Navigating Sustainable Shipping

Multi-scalar transition dynamics in the maritime shipping sector

Bach, Hanna

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Shifting away from fossil fuels in the maritime shipping sector promises to be even more difficult than turning an oil tanker. Currently, the shipping industry contributes to around 3% of the yearly global greenhouse gas emissions and is considered as one of the most challenging industries to decarbonise in line with the Paris Agreement. Given the lack of fossil free options and limited availability of other more sustainable technologies, large energy demands of ships, and a long history of established fossil fuel actors in the industry, the shipping industry is particularly resistant to change. Anchored in the field of sustainability transitions research, this thesis explores socio-technical challenges and opportunities for replacing fossil fuels with more sustainable propulsion technologies, i.e. the technologies moving a ship forwards or backwards.

The thesis is based on three empirical studies exploring multi-scalar top-down and bottom-up influences on socio-technical change in the maritime shipping sector at the global, national and community level. In addition to contributing to further empirical insights regarding socio-technical change towards decarbonisation of the maritime shipping sector, this thesis makes two main conceptual contributions. First, the thesis introduces expanded conceptualisations of top-down and bottom-up transition dynamics that goes beyond the typical regime-niche distinction and assumptions regarding policy as a main driver of socio-technical change. Second, this thesis suggests a novel conceptualisation of a global regime-induced transition trajectory to enable further understanding of sustainability transitions in sectors with strong global regimes.

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Abstract: Shifting away from fossil fuels in the maritime shipping sector promises to be even more difficult than turning an oil tanker. Anchored in the sustainability transitions literature, the overall aim of this thesis is to advance the current understanding of how multi-scalar top-down and bottom-up processes influence socio-technical change towards decarbonisation of the global maritime shipping sector. Under this broad aim, the thesis unpacks part of the complexity associated with replacing fossil fuels with more sustainable propulsion technologies at the global, national and community level. The thesis is based on three empirical studies exploring multi-scalar top-down and bottom-up influences on socio-technical change in the maritime shipping sector, a hard-to-abate sector, through document analysis, semi-structured interviews and (participant) observations. Multi-scalar top-down influences are explored in the form of international policy dynamics and the role of international and national policy in driving development and implementation of more sustainable propulsion technologies. Top-down influences are further explored in relation to how sectoral conditions associated with the shipping industry's strong global regime influence the development of grassroots innovations in the maritime shipping sector. Furthermore, multi-scalar bottom-up influences are explored through examining re-scaling processes related to frontrunner member-states of the International Maritime Organisation driving implementation of stricter global GHG regulation, how niche technology developments enforce a new configuration of the national regime for Norwegian coastal shipping, as well as the emergence and development of sail cargo initiatives as nomadic grassroots innovations.

The aggregated findings highlight how the strong global regime sets the prerequisites for how socio-technical change can unfold in the maritime shipping sector, both regarding top-down as well as bottom-up processes. The high degree of institutionalisation of the global regime is currently a barrier for implementation of sufficient policy to drive socio-technical change, while simultaneously setting the conditions for development and diffusion of niche technologies and grassroots innovations, making the shipping sector resistant to change. In addition to contributing to further empirical insights regarding socio-technical change towards decarbonisation of the maritime shipping sector, this thesis makes two main conceptual contributions. First, the thesis introduces expanded conceptualisations of top-down and bottom-up transition dynamics that goes beyond the typical regime-niche distinction and assumptions regarding policy as a main driver of socio-technical change. Second, this thesis suggests a novel conceptualisation of a global regime-induced transition trajectory to enable further understanding of sustainability transitions in sectors with strong global regimes.

Key words: Geography of sustainability transitions, socio-technical change, multi-scalarity, top-down influences, bottom-up influences, maritime shipping industry

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Coverphoto: Sail cargo ship Tres Hombres leaving Copenhagen, June 2022. In the background, a bunker barge transferring fossil ship fuel to cruise ship Azamara Pursuit. Photo by Hanna Bach.

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The pessimist complains about the wind,
the optimist expects it to change,
the realist adjusts the sails.
– William Arthur Ward

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Acknowledgements

Before a ship leaves port, a navigation plan is typically prepared to ensure that the ship is safely steered from one port to the next. There is no navigation plan for a PhD project, which at times have been frustrating since a PhD project is never just smooth sailing. Luckily, I have been surrounded by lots of excellent people who have guided and supported me through this journey in unchartered waters.

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The advantage of a PhD project, in contrast to a ship, not having a strict navigation plan is that your research can take you on an unexpected but very exiting journey. I am very grateful for all interview participants that agreed to be part of the studies included in this thesis, especially the sail cargo community for sharing your insights with me. I never expected to get the opportunity to include my interest in traditional sailing ships in my research, but I am very glad I did.

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Hanna Bach
November 26, 2024
Malmö, Sweden

Popular science summary

Most ships run on heavy fuel oil, one of the dirtiest fossil fuels available, causing the global maritime shipping sector to emit very large amounts of air polluting substances as well as greenhouse gases. Currently, the shipping industry is responsible for around 3% of the yearly global greenhouse gas emissions, which means that if the shipping industry was a country, it would be the world's sixth largest greenhouse gas emitter. Shifting away from fossil fuels in the maritime shipping sector is therefore of utmost importance to reduce negative impacts on society from climate change. However, the shift to more sustainable propulsion technologies (the combination of technologies making a ship move forwards or backwards) promises to be even more difficult than turning an oil tanker. The reasons for this are many. One main reason is the lack of suitable, more sustainable propulsion technologies to replace fossil fuels with. Another reason is the extensive energy demand of a ship, which can be compared to a power plant that in addition must carry around its own fuel. In addition, the shipping industry is a very old industry with well-established actors, norms, routines and infrastructure which make the industry very resistant to change.

This thesis explores part of the complexity associated with replacing fossil fuels in the maritime shipping sector and describes insights about how a shift to more sustainable shipping could happen. The thesis asks questions about how global, well-established structures such as regulatory frameworks and networks of actors sets conditions for how more sustainable propulsion technologies can be developed and implemented. In relation to this, the thesis investigates how top-down incentives (such as policy) as well as bottom-up initiatives (for example grassroots innovations) at the global, national and community level contribute to phasing out fossil fuels and introducing more sustainable technology options in the shipping sector, and which challenges remain.

The thesis is based on three empirical studies. One study explores how the global regulatory framework (implemented by the International Maritime Organisation) influence development and implementation of more sustainable propulsion technologies, as well as challenges for implementation of stricter regulation of global greenhouse emissions. Another study analyses the role of national policy in driving decarbonisation of the shipping industry through identification of drivers of and barriers to implementation of biofuels in the Norwegian coastal shipping sector. The final study explores multi-scalar opportunities and challenges for successful development of nomadic grassroots innovation initiatives promoting a return to traditional sail cargo ships.

Combined, the findings show that existing well-stablished structures especially at the global level currently is a barrier to the shift to more sustainable shipping. For example, given that current main global regulatory framework still supports conventional fossil fuels rather than more sustainable alternatives, existing top-down policy incentives at the global level are not able to drive development and implementation of more sustainable propulsion technologies. In contrast, clear climate policy ambitions in combination with sufficiently strict policy incentives (that supports for example emission reduction targets) have been important drivers for the introduction of more sustainable propulsion technologies in the Norwegian coastal shipping sector. In this case, policy incentives have enabled development of new solutions that goes against national and global well-established structures. Finally, the findings reveal that bottom-up grassroots innovations in the form of sail cargo initiatives struggle to gain legitimacy as well as financial and human resources, in part due to the resistance to change within the shipping industry.

Given the urgency to stop the continuous increase of greenhouse gas emissions from the shipping industry and set shipping on the course towards decarbonisation, the findings point to a need for stricter climate policy for the shipping industry at all governance levels. Furthermore, additional policy support is crucial for successful development of bottom-up initiatives with decarbonisation ambitions that goes beyond regulatory requirements. The findings also highlight a need for new explanatory models for investigation of how to achieve shifts to more sustainable solutions in sectors that are very resistant to change.

List of Papers

Paper I

Bach, H. & Hansen, T. (2023) Flickering guiding light from the International Maritime Organisation's policy mix. *Environmental Innovation and Societal Transitions*, 47 (100720)

Paper II

Bach, H. & Hansen, T. (2023) IMO off course for decarbonisation of shipping ? Three challenges for stricter policy. *Marine Policy*, 147 (105379)

Paper III

Bach, H., Mäkitie, T., Hansen, T., & Steen, M. (2021) Blending new and old in sustainability transitions : Technological alignment between fossil fuels and biofuels in Norwegian coastal shipping. *Energy Research & Social Science,* 74 (101957)

Paper IV

Bach, H. (2024) Winds of change – Nomadic grassroots innovations in the maritime shipping sector. *Geoforum,* 156 (104137)

List of Abbreviations

EU	European Union
GHG	Greenhouse Gas
GDP	Gross Domestic Product
IMO	International Maritime Organisation
LBG	Liquefied Biogas
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environmental Protection Committee
MLP	Multi-Level Perspective
NGO	Non-governmental Organisation
R&D	Research and Development
TIS	Technological Innovation System
UN	United Nations
UNFCC	United Nations Framework Convention of Climate Change

1. Introduction

Shifting away from fossil fuels in the maritime shipping sector is even more difficult than turning an oil tanker. In light of increasing global warming, reducing greenhouse gas (GHG) emissions from all industries is necessary to ensure a liveable planet for future generations, and this needs to happen quickly. The international shipping sector is a large contributor to GHG emissions, being responsible for around 3% of yearly global emissions, implying that if it were a nation, it would be the world's sixth largest GHG emitter. Furthermore, the shipping industry is classified as a hard-to-abate sector, similar to other sectors such as aviation, the steel industry and the petrochemical sector (Davis et al., 2018; Otto & Oberthür, 2024), which implies that it is considered to be particularly difficult to decarbonise for reasons such as a lack of fossil free alternatives, large energy demands, or a long history of established (fossil fuel) actors. The shipping industry meets all three of these criteria. First, there is no silver bullet fuel or other type of propulsion technology (i.e., the combination of the type of fuel or energy carrier, such as batteries, engine, drive train and propeller that makes the ship move forwards, or backwards) available to the shipping sector to replace fossil fuels. Although many options are being discussed, such as ammonia, hydrogen, methanol, battery-electric systems and wind-assisted propulsion technologies, at this point commercially available options are very limited. Secondly, the energy demand of an average ship can be compared to a power plant, with the addition of needing to carry around its own fuel. Thirdly, the shipping industry is also mature and highly institutionalised with well-established actors, norms and routines, as well as fuel infrastructures, which makes the sector extremely path-dependant.

The shift to sustainable shipping promises to be riddled with complexity. Decarbonising the shipping sector requires multiple technological solutions (DNV GL, 2019; Horvath et al., 2018), implying that experimentation and innovation in several areas of technology simultaneously is necessary. This poses a complex regulatory challenge involving multiple actors and institutions. Previous research on sustainable shipping has mainly focused on technical aspects such as life-cycle assessments of alternative fuels (Bengtsson et al., 2011; Gilbert et al., 2018; Kanchiralla et al., 2023; Nanaki & Koroneos, 2012), energy efficiency measures such as slow-steaming and weather optimised routes (E. K. Hansen et al., 2020; Poulsen et al., 2022; Rehmatulla, Calleya, et al., 2017; Rehmatulla & Smith, 2020) or wind-assisted propulsion technology add-ons to existing and new ships (Mander, 2017; Rehmatulla, Parker, et al., 2017; Stalmokaitė et al., 2022; Talluri et al., 2016). However, beyond innovation and technology development there is a need for increased understanding of the societal challenges and opportunities associated with the transition from fossil fuels to more sustainable propulsion technologies within the shipping industry. Despite this pressing need, research on these societal challenges and opportunities from a social science perspective is scarce.

Anchored in the field of sustainability transitions research, this thesis addresses these societal challenges and opportunities. The four articles included in the thesis unpacks parts of this complex industry by exploring and contrasting multi-scalar top-down and bottom-up processes that influence socio-technical change regarding the shift to more sustainable propulsion technologies. To explore top-down processes, this thesis includes investigations of the role of international and national policy regarding technology innovation and implementation. To explore bottom-up processes, this thesis includes studies of grassroots innovation activities as well as the influence of wider niche technology development and implementation on policy processes. The field of sustainability transitions offers a suitable perspective and a suite of analytical tools to explore the decarbonisation of the maritime sector and to investigate the drivers of and barriers to the implementation of alternative, sustainable propulsion technologies. More specifically, this field of study draws attention to challenges and opportunities related to several different elements of socio-technical configurations, such as institutions, markets and user practices as well as material artefacts such as fuel infrastructure. Previous sustainability transitions research has mainly focused on national case studies of transitions in the energy and road transport sectors (Köhler et al., 2019). However, despite its enormous contributions to global GHG emissions, the maritime shipping industry was, until recently, a novel empirical context of study; it has only received increasing attention in recent years. Earlier transition studies of the maritime shipping sector have, for example, focused on socio-technical scenarios for future fuels (Köhler, 2020), differences between coastal shipping segments (Bergek et al., 2021; Mäkitie et al., 2022), and national technological innovation systems for low- and zero carbon fuels for coastal shipping (Bach et al., 2020; Steen et al., 2019). Furthermore, others have studied the role of ports (Bjerkan, Hansen, et al., 2021; Bjerkan, Ryghaug, et al., 2021; Bjerkan & Ryghaug, 2021), as well as individual shipowners (Stalmokaitė et al., 2022; Stalmokaitė & Hassler, 2020; Stalmokaitė & Yliskylä-Peuralahti, 2019) in driving decarbonisation of the shipping sector.

These contributions notwithstanding, further empirical work is needed on the above themes. Moreover, there is a much called-for need to move sustainability transitions research beyond the most common national- and firm-level foci (Köhler et al., 2019). This includes *global* aspects of socio-technical change processes related to propulsion technologies as well as scale-sensitive analyses of sustainability transitions in the maritime shipping sector. Certain sectors, such as the maritime shipping, aviation, and water and sanitation sectors are seen as especially internationally or globally embedded given the internationality of value chains, actor networks, and regulatory frameworks. In the sustainability transitions literature, this is conceptualised as strong global regimes (Fuenfschilling & Binz, 2018), and such strong global regimes are assumed to influence how transitions unfold at different scales and places.

In this thesis, the influence of the shipping sector's strong global regime is explored in multi-scalar top-down and bottom-up processes at the global, national and community level, thereby contributing to a further understanding of the geography of sustainability transitions in the maritime shipping sector. Furthermore, trajectories for how socio-technical change unfolds in sectors with strong global regimes have not been extensively explored in sustainability transitions research. The novel empirical context that the maritime shipping sector represents provides an opportunity for testing whether previous conceptualisations of how socio-technical change processes typically unfolds (through upscaling of niche (technology) development from the local to national and/or global scale) remain relevant also for this globally highly institutionalised hard-to-abate sector.

Aims and research questions

Responding to the gaps outlined above, the overall aim of this thesis is to advance the current understanding of how multi-scalar top-down and bottom-up processes influence socio-technical change towards decarbonisation of the global maritime shipping sector. Under this broad aim, the thesis is more specifically concerned with drivers and barriers involved in the shift from fossil fuels to more sustainable propulsion technologies, and seeks to answer this overarching research question:

How does the strong global regime in the maritime shipping sector interact with top-down and bottom-up transition dynamics at the global, national and community level?

To operationalise the overarching research question, the following sub-questions are asked:

1. *How do global and national policies provide top-down incentives for implementation of more sustainable propulsion technologies?*
2. *In what ways do niche technology development in frontrunner countries manifest bottom-up influence on policymaking at the national and global levels?*
3. *How do bottom-up initiatives such as grassroots innovations form in the maritime shipping sector, and which multi-scalar challenges and opportunities do such initiatives face?*

While the overarching research question is answered by the thesis as a whole, the first sub-research question primarily relates to Papers I, II and III, the second sub-question relates to Papers II and III, and the third sub-question relates to Paper IV. Taken together, this collection of articles unpacks some of the complexities of the maritime shipping sector and identifies barriers to as well as opportunities for socio-technical change that enable a shift to more sustainable propulsion technologies. In turn, the findings from this empirical context advance a more complex appreciation of multi-scalar processes in the field of sustainability transitions, specifically in relation to top-down and bottom-up influences on socio-technical change in sectors with strong global regimes.

Thesis outline

This thesis consists of four scientific papers, as well as this cover essay which introduces the research context and methodological approach and presents the aggregated findings and contributions of the thesis. Following this introduction, the next chapter in the cover essay familiarises the reader with the complexity of the maritime sector. Chapter 3 introduces the conceptual foundations of the thesis, which is anchored in the sustainability transitions literature and specifically relates to two sub-research fields: the geography of sustainability transitions and policy for sustainability transitions. In chapter 4, a conceptual description of the maritime shipping sector as a socio-technical system is presented before chapter 5 goes on to discuss the methodology and research design for the three empirical studies included in the thesis. Chapter 6 provides a summary of the findings and contributions of the respective papers followed by an overarching discussion of the empirical and conceptual contributions of the thesis. Finally, some concluding remarks are presented in chapter 7.

2. Empirical background

The maritime shipping sector is one of the world's oldest industries and is characterised by a great deal of complexity, given its internationality and diversity. Before diving into the conceptual foundations for this thesis, this chapter provides descriptions of the fundamental elements of the shipping sector, in order to familiarise the reader with this 'mosaic' industry. Starting with an overview of previous propulsion technology transitions in the shipping industry, the remainder of the chapter is structured as a FAQ section providing answers about how the shipping sector is organised and regulated, as well as explaining the shipping sectors' climate impact and the possible technology options for the shift to more sustainable shipping. We will return to a conceptual overview of the socio-technical system for the maritime shipping sector in chapter 4.

Historical transitions in the maritime shipping sector

Once upon a time, majestic tall ships with white sails followed the trade winds on their routes between Europe, South America and Asia to buy and sell various goods. Today, the white sails on the horizon have been replaced by toxic smoke coming out of the chimneys of dominantly oil-fuelled ships (Bengtsson et al., 2011). This transition did not happen overnight, and as most transitions, did not follow a straight path. During the nineteenth century the introduction of the steam engine enabled faster transportation of goods and passengers, due to both a higher speed and alternative, shorter shipping routes, as ships were no longer dependant on the wind direction and speed. Furthermore, the shift from sailing ships to steamships increased the regularity and predictability of port arrivals, making more advanced logistical plans possible, to accommodate further handling of the goods (Pascali, 2014).

The steamships dominance of the high seas did not come from nowhere. Geels (2002) shows how government regulation of both business models and ship design, as well as design competition between the Great Britain and the US played important parts in the introduction of steam ships. Several regulatory change processes that started before the technological maturation of the steam engine, such as tax changes, the introduction of commercial law, and the loosening of the British navigation laws stimulated international trade, further creating conditions that helped facilitate the transition to steamships. However, as most technological transitions, steam ships did not become a success immediately upon being introduced. For example, traditional wooden hulls struggled with the weight of the heavy steam engines, and inexperience in construction methods related to the shift to iron hulls resulted in some new-built ships capsizing and ending up upside down when launched (Garrat et al., 1973; Geels, 2002). Further experimentation and regulation were needed before steamships became the dominant order for construction of new ships at the end of the nineteenth century, indicating the importance of analysing socio-technical interactions in connection to transitions from one technology to another (Geels, 2002).

Jumping forward in time, the next major technological transition in ship propulsion technologies took place with the shift from coal powered steam engines to those powered by oil, in parallel with the widespread introduction of the marine combustion engine after the second world war. Since 1950, heavy fuel oil has been the dominant ship fuel (Endresen et al., 2007). However, heavy fuel oil was not the obvious fuel choice for the shipping sector. The first combustion engines were optimised to run on diesel or petrol, so called distillate fuels from an oil refinery process. Increasing demand for these distillates left oil refineries with growing volumes of heavy fuel oil, the residual product left over from the refinery process, and no market to sell it to. The shipping sector was then offered heavy fuel oil at a very low price, initiating innovation processes to construct marine engines suitable for combustion of this residual oil (Fletcher, 1997). Apart from being cheaper, heavy fuel oil is more energy intensive, and quickly became the dominant fuel for larger ships (Endresen et al., 2007).

The shift to combustion engines and heavy fuel oil made shipping operations significantly cheaper, and the low cost of shipping spurred a drastic increase in trade volumes and thereby the number of ships in the global fleet during the twentieth century. Between 1910 and 2000 the global fleet of ships larger than 100 gross tonnes grew by approximately 66,000 ships to a total of 88,000. In the same time period, the total gross tonnage (cargo transport capacity) increased from around 37 to 558 million GT. Following this, the fuel consumption in the shipping sector increased fourfold (Endresen et al., 2007). With increasing fuel consumption comes increasing emissions, both GHGs and air pollutants. Currently, the shipping sector is responsible for around 3% of yearly global GHG emissions (IMO, 2020), and under pressure to decrease its carbon footprint and eventually decarbonise completely.

Shipping industry FAQ

What does the maritime shipping sector do and why does that matter for everyday life?

The main purpose of shipping is to transport goods or passengers from port A to port B. Every day, hundreds of thousands of containers lands in ports all over the world, having crossed the oceans between continents (when not stuck in the Suez Canal) to enable deliveries of food, clothes, toilet paper and other everyday items. As a result of increasing global trade, 90% of all goods are at some point transported on board a ship, and the distance they are transported by ship is most often the longest part of the transportation journey. The recent Covid-19 pandemic, as well as Ever Given's grounding in the Suez Canal and the ongoing rebel attacks on ships in the Red Sea has highlighted the importance of a well-functioning shipping sector. Furthermore, the six-day closing of the Suez Canal in March 2021 caused major delays for all types of goods, as ships were kept on hold outside the canal for up to eleven days, while some chose to steam around the Cape of Good Hope (prolonging their planned journey by around seven to nine days). To conclude, the shipping sector makes up a crucial part of the global transport and logistics system, and ensuring well-functioning, sustainable transportation by ship even in the future is of utmost importance.

What types of ships are there and how does a ship function?

Ships come in a variety of sizes, types and ages. Ship sizes vary, from the gigantic containerships and oil tankers longer than the Eiffel Tower is high, the 20-something meter long ferries taking commuters across the water in coastal cities, and virtually anything in between. The largest cruise ships can accommodate around 9 000 passengers and an additional 2 000 crew members, representing a village floating on the ocean. In contrast, the largest container ships, carrying more than 20 000 containers, only have a crew of around 20 people (see Figure 1). These types of ships are a familiar sight in the Öresund strait, where container ships, ferries, cruise ships, fishing vessels, as well as oil and chemical tankers pass through on a daily basis. However, the shipping sector also includes a lot of other ship types few people know exist, such as ships placing electricity cables at the bottom of the ocean, ships equipped for building large offshore wind farms, and even ships built to carry (multiple) other ships, for example, those on their way to be demolished.

In many ways, a ship is its own little world, cut off from the rest of the society. In order to sustain themselves on board, the ship needs to be able to carry food, water and fuel to last for the trip between port A and port B. It also needs to handle the accumulated waste produced on board (residual as well as sanitary) and maintain the functioning of all technical systems - all while safely navigating through the sometimes harsh conditions at sea, which can cause the ship to roll back and forth with the waves. Moving the ship in the right direction requires an engine or other propulsion system, whose power requirements vary with the size and type of ship. Given the enormous size of the largest engines that power ships with high energy demands, the industry term ‘cathedral engines’ is a very fitting one. Conventional ship engines run on fossil-based heavy fuel oil, and in addition, the typical solution to cover the ship’s electricity consumption is to have one or more electricity generators powered by the same type of fuel that is used for the ship’s propulsion.

Figure 1 Offloading of containers at the container terminal in Port of Gothenburg, Sweden
To the left, container ship Helena Schepers built 2012, 152 meters long with carrying capacity 1 036 standards containers, operating in coastal waters in northern Europe. On its port side, a small service vessel operating in the Port of Gothenburg. To the right, Milan Maersk, Tripple E-class container ship built 2017, 399 meters long with carrying capacity 18 270 standard containers, operating between China and northern Europe. Photo: Hanna Bach

The typical lifespan of a ship varies between 15 and 40 years, depending on the type of ship. In 2018, the average age of scrapped ships was 28 years (Clarksons Research, 2019). When considering developments and changes within the shipping sector, this is important to keep in mind as this has a few important implications. First, changes in technology take a relatively long time to implement due the low turn-over of ships, indicating that for the shipping industry to decarbonise in time to contribute to the Earth stay below 2 degrees global warming (as outlined in the Paris Agreement), more sustainable propulsion technologies need to be implemented as soon as possible. Second, making decisions around technology is currently a tremendous challenge due to the uncertainty regarding future fuel options and their availability. Furthermore, this implies that there will be a need to retrofit ships in the current fleet in addition to construction of new ships with alternative, sustainable propulsion technologies (International Chamber of Shipping, 2020), as the majority of the ships in the current global fleet will still constitute the largest part of the fleet in 2030 (Bullock et al., 2020).

What are the climate and environmental issues stemming from the shipping sector and where are they occurring?

The shipping sector contributes to multiple environmental and climate issues: oil spills, migration of invasive species, underwater noise pollution etc. Given that most ships are fuelled by heavy fuel oil, which is the dirtiest fossil fuel (due to being the remainder after distillation of petroleum), the emissions to air from the shipping sector contributes to air pollution as well as climate change. The combustion of heavy fuel oil causes large emissions of air pollutants such as sulphur oxides, nitrogen oxides, and particulate matter. Apart from these air pollutants contribution to decreased air quality, sulphur emissions are also a major cause of acid rain. Although promoted as the most eco-friendly form of transportation, the shipping sector currently accounts for around 3% of global GHG emissions; however, with increasing global trade, emissions are expected to increase (IMO, 2020). Even if energy efficiency gains have been accomplished (Bouman et al., 2017), the total GHG emissions are continuously increasing. In 2018, the yearly CO_2 emission from ships had increased to 1 076 million tonnes CO_2/year compared to 977 million tonnes/year in 2012 (IMO, 2020).

Considering that ships move all across the high seas, air emissions from the shipping sector constitute a global environmental and climate problem. However, regarding air quality there are some additional local effects. Higher levels of air pollution are noticeable for coastal cities and settlements along the major shipping routes, and areas close to a larger port also experience decreased air quality. Although a ship's main engine is not running when a ship is docked at a port to load and unload cargo, the emissions from its electricity generators remain and contribute to local air pollution.

How is the shipping sector regulated?

As an international sector, the shipping sector is regulated on several governance levels. The International Maritime Organisation (IMO), a specialised United Nations (UN) agency established in 1959, has responsibility for regulating international shipping. In short, IMO is a member-state-led organisation with a complex governance model, which results in the shipping sector being practically self-regulating. The first global regulations regarding air emissions from ships were implemented in 2005, focusing on air pollutants (especially sulphur). In the last 20 years, the European Union (EU) has become an increasingly important regulatory actor for the shipping sector through its environmental legislation – which, in most cases, has been stricter than the regulation implemented by the IMO. Nations, through their maritime authorities, are responsible for monitoring compliance with IMO regulations. In addition, it is possible to implement national rules for shipping in national waters and ports. Furthermore, shipping classification societies are responsible for developing maritime standards and technical specifications based on the IMO regulation, which a ship needs to comply with in order to maintain mandatory certifications.

Which actors are involved in solving the shipping sector's climate and environmental issues?

Apart from the regulatory institutions, there are several other actors involved in the shift to sustainable shipping. Shipowners and shipowner associations have been important actors which have had major impacts on the shipping industry over a long period of time, being the ones actually making investment decisions around types of ships, propulsion technologies and routes to sail. Furthermore, larger shipowner associations act as consultants for the IMO and hold observer status during IMO negotiations. In order to enable construction of new, sustainable ships, technology suppliers and shipyards also play a major role. Several external actors such as cargo owners, external investors and insurance companies are becoming increasingly important in the decarbonisation of the maritime sector, as they more and more demand sustainable transport options. The crew on board ships are essential for the daily operation and will play a crucial part in the actual handling of new, low- and zero carbon technologies on board, indicating a need to educate crews about the handling of these new technologies. Furthermore, actors involved in organisations promoting alternatives to conventional shipping, such as a return to traditional sail cargo ships that operates in their own parallel socio-technical system, can play an important role for bottom-up solutions for sustainable shipping.

What are the technology options for sustainable shipping?

Similar to other climate issues, a portfolio of solutions and technologies will be needed for the transition to sustainable shipping. Given the large energy demands of the global shipping fleet, it is estimated that a single new, low- or zero carbon fuel will not be sufficient for all ships. The shift to sustainable shipping thereby implies a complex regulatory challenge involving multiple actors and institutions engaged in experimentation and innovation within several technology areas simultaneously. Following the characteristics of the various sizes and types of ships, different ships are suitable for different options. The major factor determining viable options for a certain ship is what route it sails, specifically whether this route is following along the coast, having several options for stopovers to fuel up or recharge batteries, or travels longer distances and crossing oceans, which requires the ship to carry vast amounts of fuel. For ships with relatively short routes, battery-electric and hydrogen solutions, as well as using biodiesel in conventional engines, are all considered suitable options and are already implemented on a small scale. The major challenge for the transition to sustainable shipping, however, lies with larger ships travelling long distances. Currently, there is no consensus within the shipping sector regarding viable options; however, fuels being discussed and tested are for example ammonia, methanol, and biofuels such as biodiesel and liquefied biogas (LBG). Furthermore, additional technologies such as variants of wind-assisted propulsion are being experimented with. Given the high degree of interconnectedness with respect to the development of renewable energy systems in relation to local geographical and political context, it is likely that emerging solutions for the shipping sector (at least initially) will have spatial differences.

Past and present – what is different now?

The history of transitions in the shipping sector shows how, for the majority of time, it has been dominated by one propulsion technology and fuel at any one time (DNV GL, 2019; Horvath et al., 2018). Transitions in the shipping sector have historically been slow, and shifts have been from one technology to another, 'better' one in terms of, for example, energy density, enabling longer routes or higher speed. The current pressure to decarbonise in order to decrease the impact on climate change differs from previous drivers of transitions, such as increased range or reliable arrival and departure schedules, or lower fuel and shipping costs, as it is mostly generated by external societal pressure rather than industry-internal values or visions. Furthermore, the pending transition differs from previous technology shifts as there is no new silver-bullet fuel or other technology the shipping sector can shift to, since every potential solution has a lower energy intensity than heavy fuel oil.

3. Conceptual foundations

In this thesis, the shift to sustainable shipping is seen as a socio-technical change process that is part of a sustainability transition within the maritime shipping sector. The intention of this chapter is to present the main conceptual foundations of the sustainability transitions field that provide the background and context for the specific conceptual frameworks which the respective papers use as their points of departure. First, this chapter provides an introduction to sustainability transitions research and two main conceptual frameworks within this field. Second, two sub-fields that the thesis particularly contributes to, the geography of sustainability transitions and policy for sustainability transitions, are introduced.

Sustainability Transitions Research

The field of sustainability transitions is a relatively young but growing multi-disciplinary field which emerged in the late 1990s (Köhler et al., 2019; Markard et al., 2012) and originates from innovation studies, science and technology studies, and evolutionary economics (A. Smith et al., 2010). Sustainability transitions research finds its starting point in acknowledging that environmental and climate issues, such as climate change and biodiversity loss, constitutes grand societal challenges. These challenges are seen as a result of human overexploitation of natural resources, representing the dominance of unsustainable configurations in socio-technical systems, systems that provide specific services such as agriculture, power and heat, and transport (Markard et al., 2012). It is furthermore recognised that more innovation in new technological solutions or increased efficiency alone will not be sufficient to solve these grand societal challenges; rather, sustainability transitions research assumes that radical shifts from the current fossil-based socio-technical configurations to alternative, more sustainable socio-technical configurations, i.e., sustainability transitions, are necessary (Markard et al., 2012; A. Smith et al., 2010). Sustainability transitions are typically seen as non-linear, multi-dimensional and co-evolutionary long-term processes often spanning over decades, which engages various actors, such as policy makers, industry actors, academics and civil society (Geels, 2004, 2005; Markard et al., 2012). The future results of sustainability transitions are uncertain; however, there is an underlying normative notion of sustainability transitions research that assumes that these shifts are desired from a societal perspective and will contribute to a better future for the world's population. This implies that there is a prescriptive logic in sustainability transitions research to steer socio-technical change towards more sustainable technological solutions and socio-technical systems (Köhler et al., 2019).

In sustainability transitions research, sectors providing societal functions and services, such as electricity and water supply or transportation, are conceptualised as socio-technical systems (Markard et al., 2012). These systems consist of multiple elements interacting with each other, such as institutions (both regulations and standards as well as societal norms and practices), material artefacts (technologies, infrastructure, etc.), markets and user practices, and networks of actors engaging in knowledge sharing, which when combined in a certain way represent a specific socio-technical configuration (Geels, 2004; Markard, 2011; Weber, 2003). An example of a typical current socio-technical configuration is the combination of institutions (traffic rules, emission standards, cultural and symbolic meaning) and material artefacts (easily accessible gas stations, highways, suburban planning), etc., that uphold personal ownership of conventional fossil fuelled cars as the main socio-technical personal mobility configuration. Enabling sustainability transitions therefore encompasses more than simply replacing one technology with another and requires changes to multiple socio-technical elements simultaneously. The primary units of analysis in sustainability transitions research are the elements of socio-technical systems, and how these (need to) change in order to develop new socio-technical configurations enabling sustainability transitions (Geels, 2004).

Socio-technical systems are typically very complex with many linkages between elements, implying that, over time, the systems develop into rigid structures that are difficult to change, i.e., path-dependent and incremental (Geels, 2002; Markard & Truffer, 2008). This implies that achieving socio-technical change towards sustainability transitions requires overcoming different lock-ins, relating to for example established actor networks, institutions, markets and technologies in incumbent socio-technical systems (Arthur, 1994; Geels, 2004). In practice, this implies that multiple socio-technical elements need to change in order to develop new, more sustainable configurations of socio-technical systems. The constellation of the socio-technical system elements may vary between sectors, and there may be spatial differences in socio-technical system configurations within the same sector, indicating a need to identify which key system elements are most important to change in order to enable sustainability transitions (Geels, 2002). Furthermore, within sustainability transitions research, it is acknowledged that in order to enable sustainability transitions, development of and support for new, more sustainable socio-technical configurations (i.e., creation) needs to be complemented by withdrawal of support for and dissolving of current, often fossil-fuel-based configurations (i.e., destruction). This assumption is based on the seminal concept of 'creative destruction' in innovation introduced by Schumpeter (1950), which, in the sustainability transitions literature, has been complemented by later conceptualisations of ‘regime destabilisation’, highlighting the importance of decreasing the reproduction of incumbent regime configurations (Turnheim & Geels, 2012). However, most sustainability transitions research still focusses on creation of new socio-technical configurations, indicating that there is a need for further conceptualisation and empirical exploration of destabilisation of incumbent regimes and phase-out of unsustainable socio-technical configurations (Hebinck et al., 2022). In Papers I and II, the current status of and potential for regime destabilisation of the global regime for the international maritime shipping sector is studied through analysis of creative destruction elements in the global policy mix regulating air emissions from international shipping.

A number of different conceptual frameworks have developed within the field of sustainability transitions to help explain different aspects of how socio-technical change comes about, such as *Technological Innovation Systems (TIS)* in which the analytical focus is on drivers of and barriers to diffusion of emerging technologies (Bergek, Jacobsson, et al., 2008; Hekkert et al., 2007), the *Multi-Level Perspective (MLP) framework* that conceptualises socio-technical change as a result of interactions between three levels of socio-technical structuration, namely landscapes, regimes and niches (Geels, 2002, 2005), *transition management* which introduces practice-oriented coordinated governance models for guiding policy makers (Kemp et al., 2007; Rotmans et al., 2001), and *strategic niche management* which emphasises different support mechanisms for developing emerging niches beyond their protected environment as drivers of sustainability transitions (Kemp et al., 1998). This thesis mainly builds on concepts from the TIS literature, the MLP framework and recent geographical and configurational conceptualisations of socio-technical regimes and multi-scalar dynamics in sustainability transitions. Furthermore, the thesis builds on previous conceptualisations of policy mixes (Rogge & Reichardt, 2016) and the role of policy for sustainability transitions.

Technological Innovation Systems

The drivers of and barriers to development of new configurations of socio-technical systems have been explored in great detail in the TIS literature, in relation to national, regional as well as sectoral TISs. A TIS consists of actor networks that participate in development, diffusion and utilisation of a new technology within a certain sector, such as the maritime shipping industry, which is influenced by sector- and technology-specific institutional contexts. At the core of the TIS approach is the understanding that successful emergence and diffusion of a new technology is a result of a broader system of interconnected elements that work together to support the innovation process, rather than the capabilities of individual firms (Bergek, Hekkert, et al., 2008; Bergek, Jacobsson, et al., 2008; Hekkert et al., 2007). The TIS framework introduced by Bergek, Jacobsson, et al. (2008) highlights seven key innovation processes, or in TIS terminology, ‘functions’, such as knowledge development and diffusion, resource mobilisation, and market formation, which influence innovation in a specific sector or of a specific technological solution. Taking a processual perspective on analysis of the respective TIS functions, the framework allows for identification of drivers of and barriers to technology innovation and implementation which can guide recommendations for policymakers. Previous studies of TISs have explored a wide range of technologies, such as renewable energy (e.g., Dewald & Truffer, 2011; Foxon et al., 2010; Wieczorek et al., 2013) and transport (e.g., Hillman & Sandén, 2008; Markard et al., 2009; Suurs et al., 2010), mainly focusing on the national level (Coenen, 2015), indicating that there is a remaining research gap regarding the development of sectoral TISs. Building on the conceptualisation of TIS functions introduced by Bergek, Jacobsson, et al. (2008), Paper III connects positive and negative externalities associated with the technological alignment between fossil and bio-based ship fuels with key processes for implementation of biodiesel and LBG in the Norwegian coastal shipping sector, conceptualised as sectorial TISs.

Multi-Level Perspective

In one of the most commonly applied theoretical frameworks for sustainability transitions research, the MLP framework (Geels, 2002; Rip & Kemp, 1998), changes in socio-technical systems are seen as a result of interactions between three analytical 'levels' of structuration: landscapes, regimes, and niches. Through the MLP lens, the landscape level refers to the external, general societal context in which socio-technical configurations are embedded and which regimes and niches relate to, but have limited short-term impact on (Geels, 2002, 2004). Landscape dynamics are influenced by long-term, stable trends such as geopolitics, demographics or ideology, but also exogenous shocks such as, for example, wars or major natural disasters (Geels, 2018). A socio-technical regime is conceptualised as the 'deep structure' that represents the stability of an existing socio-technical system, i.e., the dominating configuration of a socio-technical system (Geels, 2004). It refers to the semi-coherent set of rules that "orient and coordinate the activities of the social groups that reproduce the various elements of socio-technical systems" (Geels, 2011, p. 27). For this definition, rules include, for example, shared beliefs, norms, values and routines, as well as regulation and capacities (Geels, 2004, 2011). Finally, niches are conceptualised as 'protected spaces' with extenuating circumstances that assist and enable the formation of more radical and disruptive innovations, i.e., rivalling emerging socio-technical configurations (Geels, 2002, 2004). In the original MLP conceptualisation, it was assumed that changes in landscape dynamics put pressure on existing regimes, potentially leading to a destabilisation of the regime. If this was the case, there would be an opportunity for niches to upscale and compete with the regime, and possibly overturn the existing regime (Geels, 2004). Following this, a socio-technical transition is assumed to be completed when a previous regime has been overturned by a new regime, implying a shift from “one highly structured socio-technical configuration to a new one” (Fuenfschilling & Truffer, 2014, p. 773).

The MLP framework has been criticised for a general tendency to categorise the ‘levels’ within the MLP according to the maturity of the system-specific technology and actors included in the socio-technical system. This has often resulted in an association between niches and emerging technologies, and between regimes and well-established technologies and incumbent actors. By doing so, the level of structuration of niches and regimes is assumed rather than empirically evaluated (Fuenfschilling & Truffer, 2014; A. Smith et al., 2005). Fuenfschilling and Truffer (2014) suggest a neo-institutional perspective on niches, regimes and landscapes, where the degree of institutionalisation is used to distinguish between niches, regimes and landscapes. In this conceptualisation, regimes are seen to have the highest degree of institutionalisation while niches have a very low degree of institutionalisation. Furthermore, building on concepts from the MLP framework, A. Smith et al. (2005) suggest that rather than assuming that changes in socio-technical regimes are mainly driven by niche development, overturning of regimes can be seen as a result of internal and/or external processes, implying that in addition to development of socio-technical niches in protected spaces, internal pressures as well as broader exogenous landscape pressures can be seen as drivers of reconfiguration of regimes. Differentiating between intended and unintended transitions, the authors propose two internal (‘endogenous renewal’ and ‘reorientation of trajectories’) and two external (‘emergent transformation’ and ‘purposive transition’) transition contexts that steer the direction of socio-technical change. Internal transition contexts refer to when there are sufficient capabilities and resources (conceptualised as adaptive capacity) within the current socio-technical regime, while external refers to a need for capabilities and resources from outside the incumbent regime to enable socio-technical change. Endogenous renewal is seen as an internally coordinated response within the regime to perceived threats to the regime, i.e., an intended transition, where the direction of policy and innovation activity is shaped by the incumbent socio-technical regime. This implies that socio-technical change processes are typically guided by past experiences, hence socio-technical transitions embedded in an endogenous renewal context will typically be path-dependent. In contrast, reorientation of trajectories represents a context where uncoordinated internal processes may lead to unintended, foundational changes in regime trajectories, but without resulting in major changes to the actors, networks and institutions involved in the incumbent regime. Although the reorientation is an internal response formed within the regime, the driver(s) for such reorientations may be exogenous or endogenous shocks in relation to the incumbent regime. Radical reorientations of trajectories are typically highly unpredictable. Emergent transformation represents a context which also produces unintended, uncoordinated transition processes, but which are initiated by actors and dependent on capabilities and resources that are not part of the incumbent regime. Transitions embedded in emergent transformation contexts are typically initiated through research on and development of novel technological solutions performed at universities or small (start-up) firms outside of dominant industries, and the transition processes in this context are difficult to predict. In contrast to the autonomous characteristics of emergent transformation contexts, purposive transitions contexts typically produce intended transitions drawing on external resources initiated by actors from outside the incumbent regime that share interests and societal norms. Such purposive transitions are seen as deliberate attempts to drive socio-technical change based on a ‘consensus guiding vision’, which may be aligned with government interests but is mainly driven by a diverse set of societal actors from outside the incumbent regime.

The Geography of Sustainability Transitions

The sustainability transitions literature has been criticised for initially overlooking spatial dimensions of changes in sociotechnical systems. As a response to critique regarding insufficient attention to how place-specific contexts, global regime structures and multi-scalar dynamics influence sustainability transitions, as well as the national-level bias in previous studies, a sub-research field focusing on the geography of sustainability transitions has started to form in the last decade (Binz et al., 2020; T. Hansen & Coenen, 2015; Murphy, 2015; Truffer et al., 2015). This sub-field mainly directs attention to the spaces and scales where sustainability transitions emerge and unfold (Binz et al., 2020; Coenen & Truffer, 2012). The main work on the geography of sustainability transitions has thus far focused on the geography of niche development, leaving a research gap on the geographic aspects of regime dynamics (Fuenfschilling & Binz, 2018; T. Hansen & Coenen, 2015). Furthermore, at the time of the emergence of the geography of sustainability transitions as a sub-research field, most sustainability transitions studies had an empirical focus on national-level energy transitions in Northern Europe and particularly the Netherlands. Efforts have since been made to widen the empirical scope and test theories on more diverse cases in other parts of the world, as well as on other scales such as the urban or regional (Binz et al., 2020). This has resulted in emerging bodies of literature on sustainability transitions in the global south (for a review, see U. E. Hansen et al., 2018), urban areas (e.g., Madsen & Hansen, 2019; Monstadt, 2007; Späth & Rohracher, 2011) and regions (e.g., A. Smith, 2007; Späth & Rohracher, 2010, 2012), as well as global regimes (Fuenfschilling and Binz, 2018) and multi-scalar dynamics in sustainability transitions (Bauer & Fuenfschilling, 2019; Miörner & Binz, 2021). The three studies included in this thesis mainly connect to three key themes within the literature on the geography of sustainability transitions: place-specific conditions, multi-scalarity, and the influence of global regimes. In the next section, I introduce previous contributions on place-specificity in sustainability transitions, before elaborating on multi-scalarity in sustainability transitions and lastly the role of global regime dynamics.

Place-specificity

Early contributions within the geography of sustainability transitions literature set out to further explain why transitions happen in certain places and not in others, as well as explored how and why transitions unfold more or less differently in various places, i.e., the spatial unevenness and *place-specificity of sustainability transitions* (T. Hansen & Coenen, 2015; Lawhon & Murphy, 2011). This focus on if and how geographical contexts matters resulted in a number of conceptual contributions regarding the influence of socio-spatial embedding and place-specific conditions on niche development and technology emergence, mainly through bridging concepts regarding space and place-specificity from human and economic geography with sustainability transitions theory (for a review, see T. Hansen & Coenen, 2015). Related to this, increasing attention has been directed towards the *geography of grassroots innovation.* In this literature, it is acknowledged that place-specific conditions in certain places provide favourable conditions for grassroots innovations to develop, ultimately resulting in an uneven spatial distribution of grassroots innovation initiatives (Feola & Butt, 2017; Feola & Him, 2016). Recent contributions to the literature have explored place-specific conditions such as community capacity, (volunteering) traditions and favourable political opportunities (Feola & Butt, 2017; Kratzer et al., 2022; Nicolosi et al., 2018; Nicolosi & Feola, 2016), as well as analysing the spatial distribution of grassroots innovations (Feola & Butt, 2017; Nicolosi et al., 2018). However, previous studies are mainly empirical and fail to sufficiently explain the how place-specific conditions as well as the multi-scalarity of favourable factors influence the development of grassroots innovations. As a response to this research gap, Paper IV in this thesis builds on previous bridging of concepts related to place-specific conditions from economic geography with sustainability transitions concepts to explore the geography of grassroots innovations in the maritime shipping sector, which are conceptualised as nomadic grassroots innovations due to their mobility and ability to become anchored in multiple places.

Multi-scalarity in sustainability transitions

In parallel to the development of conceptualisations of specific geographical contexts and sustainability transitions, increasing conceptual and empirical attention has also been given to *multi-scalarity in sustainability transitions*. Geographers have pointed out that there is a problematic association between the three structuration levels within the MLP framework (landscape, regime and niche) with spatial scales, where niches often are seen to emerge and develop at the local scale while regimes are anchored at the national or global scale, indicating that there is a need for further conceptualisation of how transitions unfold in space (Fuenfschilling & Binz, 2018; Hodson et al., 2016). To nuance this, it has been argued that socio-technical niches as well as regimes are multi-scalar structures that simultaneously relate to and are influenced by dynamics in multiple places and at various governance levels (Fuenfschilling & Binz, 2018; Murphy, 2015; Raven et al., 2012;

Sengers & Raven, 2015; Späth & Rohracher, 2010). This implies that niche actors can take advantage of local resources as well as broader global trends, and that regimes are reinforced or challenged by a combination of local and national pathways as well as global discourses (Coenen et al., 2012). However, given that most studies of socio-technical change have explored transition processes using national boundaries (mainly focusing on the energy and transport sectors in Germany and the Netherlands), there is a limited understanding of such multi-scalar dynamics in sustainability transitions.

A number of previous conceptual and empirical contributions regarding multi-scalarity have been made to fill this research gap, including conceptualisation of local-global interactions in niche development (Sengers & Raven, 2015), introducing spatial dimensions to the MLP framework (Hodson et al., 2016; Raven et al., 2012) and the role of global regimes in sustainability transitions (Fuenfschilling & Binz, 2018). Regarding development of niches, Sengers and Raven (2015) suggest a more scalar and spatially nuanced conceptualisation of the 'local-global niche model' originally developed by (Geels & Raven, 2006). In their conceptualisation they bridge geographic concepts from the literatures on buzz-pipelines, global production networks and policy mobilities with the original social-cognitive local-global niche model, in order to enable exploration of the spatial embeddedness as well as the (multi-)scalarity of production, transfer of knowledge and actor networks related to niche development. With regard to the MLP framework, Raven et al. (2012) propose a second generation, multi-scalar MLP framework that, in addition to the original conceptualisations of the temporal and structural scales of socio-technical change, also highlight the spatial scale. Building on the argument that all MLP levels should be seen as multi-scalar structures, they propose that the spatial dimension in the MLP framework could be seen as a relational scale that consists of networks of actors located in various places. Such a view implies that niches, regimes and landscapes are continuously produced and reproduced by interactions between actors across space and time. Furthermore, Hodson et al. (2016) propose complementing the MLP framework with dimensions of scale and (re-)scaling processes through exploration of transition activities at three scales (national, urban and hyper-local) and argue that there is a need for further understanding of how dialogue and exchange between scales, i.e., re-scaling (MacKinnon, 2010; Mansfield, 2005), contributes to sustainability transitions (at the urban scale). Re-scaling processes have been of longstanding interest in human geography and encompass the interplay between socio-institutional as well as techno-economic structures at different scales and how this interplay contributes to reconfiguration of activities and scalar boundaries for a specific phenomenon (Mansfield, 2005), such as socio-technical change (Miörner & Binz, 2021).

In order to study governance and organisation of sustainability transitions, Hodson et al. (2016) suggest a distinction between multi-scalar top-down and bottom-up influences for socio-technical change. They view top-down influences as dominant governance initiatives aimed at market formation for new, more sustainable technologies, which are typically implemented on national or urban scales. These dominant governance initiatives, i.e., institutional configurations, are presumed to outline the direction of socio-technical change as well as set the conditions for how this can unfold. Following different combinations of historically generated priorities and more current economic, environmental and social political agendas, particular institutional configurations are expected to either enable, favour or disenable market formation for more sustainable solutions. While urban institutional configurations mainly influence transition activities at the urban and hyper-local scales, national institutional configurations often influence all three scales.

In contrast, bottom-up influences are seen as alternative responses to top-down governance, which typically stems from transition activities in hyper-local spaces, such as neighbourhoods and community groups. Rather than being driven by an interest in national market formation or financial profits, hyper-local bottom-up initiatives such as grassroots innovations and other forms of civil society involvement typically engage with issues directly affecting the hyper-local space, such as energy or food supply, by forming community energy schemes and co-gardening initiatives. Developing alternatives to conventional solutions, such hyper-local bottom-up initiatives, is presumed to potentially exert influence on socio-technical change at the urban and national scales. Furthermore, these initiatives often have connections with the urban and national as well as EU and metropolitan scales, for example in relation to financial support and collaboration with other actors.

Taking this perspective allows for highlighting the various top-down and bottom-up influences that are continuously on-going in and between different scales, and how they influence transition processes. This thesis follows Hodson et al.'s (2016) distinction between top-down and bottom-up influences for sustainability transitions; however, given the international dimensions of the maritime shipping sector, I distinguish between the international, national and regional and local scales. Top-down influences are mainly explored through analysis of global and national policy in studies 1 and 2, while bottom-up influences are primarily studied through cases of niche technology development at the national scale in Study 1, and multi-scalar grassroots innovation activities in Study 3 (see Figure 2).

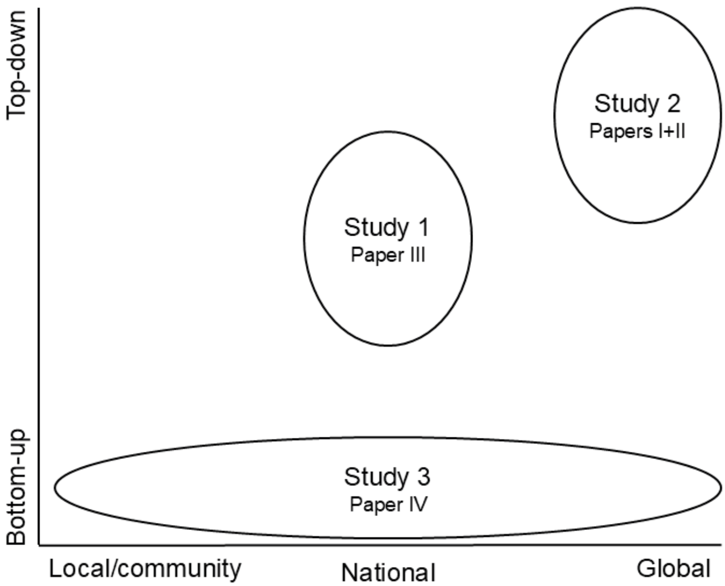

Figure 2 Overview of scale and top-down vs. bottom-up focus in the three respective studies included in the thesis

Global regime dynamics

Beyond theoretical engagement with the MLP framework, another stream of the literature on multi-scalarity in sustainability transitions takes a configurational perspective on socio-technical change, and highlights the role of global regimes in sustainability transitions. In contrast to early studies of how place-specific conditions influence transition processes differently in different places, the literature on global regimes seek to answer how and why socio-technical change processes develop similarly in different parts of the world, and how global regimes condition sustainability transitions through multi-scalar processes (Fuenfschilling & Binz, 2018; Miörner et al., 2022; Miörner & Binz, 2021). Differing from the conceptualisation of regimes in the MLP framework, the configurational perspective views socio-technical regimes as semi-coherent structures that represent the dominant institutional logic within a socio-technical system (Fuenfschilling & Truffer, 2014; Thornton et al., 2012). Calling for more spatially sensitive conceptualisations of socio-technical regimes, Fuenfschilling and Binz (2018) introduce a conceptualisation of *global socio-technical regimes* that builds on neo-institutional theory (Greenwood et al., 2008; Powell & DiMaggio, 1991) and concepts related to global production networks and value chains from human geography (Coe et al., 2004; Gereffi et al., 2005). Previous research within sociology and human geography has showed that institutionalisation of cultural-cognitive rationalities can have an international element if the degree of institutionalisation leads to diffusion of rationalities from one place or scale to another (Bunnell & Coe, 2001; Meyer et al., 1997). Certain sectors, such as large infrastructure sectors (e.g., transport, water and sanitation), are seen to be especially internationally or globally embedded following the internationality of value chains and actor networks. Therefore, it is important to understand how this embeddedness leads to development of shared standardisations of actor networks, value chains and organisational arrangements at the international or global scale, i.e., global regimes. Fuenfschilling and Binz (2018, p. 739) define global regimes as "the dominant institutional rationality in a socio-technical system, which depicts a structural pattern between actors, institutions and technologies that has reached validity beyond specific territorial contexts, and which is diffused through internationalized networks". These dominant global regime structures are likely to be institutionalised and anchored in multiple places and at different scales through incorporation of dominant institutional rationalities in national, regional and local practices, routines, and technological standards. Global regimes are believed to be strongest in socio-technical systems in which dominant rationalities are translated into international norms and technical standards, and where key actors translate these norms and standards into different contexts. This implies that in sectors with strong global regimes, the configuration of the global regime, rather than place-specific conditions, may be the main influence on the trajectories of sustainability transitions (Miörner & Binz, 2021).

Building on Fuenfschilling and Binz's (2018) conceptualisation of global regimes, Miörner and Binz (2021) introduce a framework conceptualising multi-scalar interactions between global and territorially embedded niches and regimes. In this framework, they conceptualise socio-technical change as a result of two interrelated transition mechanisms that goes beyond the conventional 'local-global niche model': (de-)institutionalisation processes in and between niches and regimes, and re-scaling of institutional rationalities between the global and various territorially embedded scales. Change is achieved through constant negotiation and translation processes between international and territorially embedded layers in socio-technical systems, both with regard to niche and regime rationalities, which may result in changes in power dynamics between actors embedded in different spatial layers of a socio-technical system.

Most previous studies have explored 'local transition trajectories', in which it is assumed that successful niche-regime interplay in territorial (mainly national level) spaces fosters upscaling of niches resulting in regime changes, which, if accumulated with other territorially embedded regimes, also influences changes in the global regime (C→D→B) (Geels, 2002; Geels & Raven, 2006). However, this assumption has been increasingly criticised for giving ontological priority to local and national levels when explaining typical trajectories for sustainability transitions. Miörner and Binz's (2021) framework allows for broader identification of how transition processes unfold spatially, for which they suggest two new trajectories: 'multi-locational diffusion' and 'global advocacy' (see Figure 3). Multi-locational diffusion refers to a trajectory where one or several territorially embedded (local) niches are directly re-scaled into becoming a global niche (C→A) rather than influencing changes in local or national regimes. It is also possible that the new global niche becomes institutionalised to such a high degree that a new global regime emerges (C→A→B). Global advocacy, in contrast, refers to when global niche developments simultaneously are re-scaled downwards to territorially embedded niches (A→C) as well as become increasingly institutionalised into global regime structures (A→B).

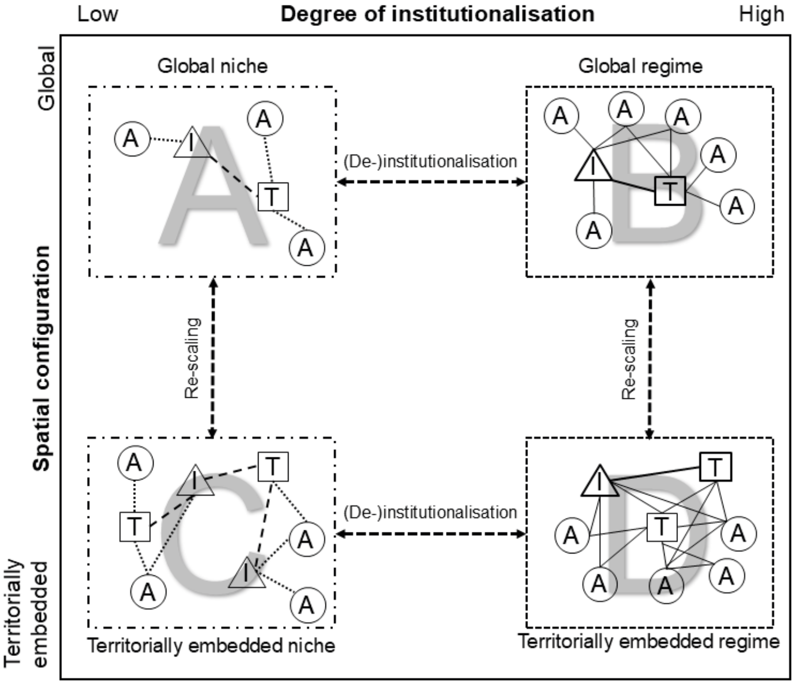

Figure 3 Conceptualisation of potential transition trajectories resulting from re-scaling and (de-) institutionalisation processes
I – Institutions, A – Actors, T – Technologies. Bold, solid lines indicate a deeply institutionalised socio-technical configuration; dotted lines represent a more emergent, less institutionalised alternative socio-technical configuration. Source: Miörner and Binz (2021)

In their empirical application of the framework, Miörner and Binz (2021) found that re-scaling of rationalities regarding proposed technologies as well as institutional rationalities across different contexts and scales were key to the global standardisation processes in the water and sanitation sector, that resulted in development of a new global regime. Additional previous empirical work on global regimes in relation to multi-scalar transition dynamics has showed how global regimes related to the chemical industry are institutionalised at the global level while also being locally embedded in Swedish companies (Bauer & Fuenfschilling, 2019).

Furthermore, Miörner et al. (2022) explore spatial diffusion of global regime dynamics in regional contexts through a case study of desalination in the San Diego region and show how global regime solutions are prevailing even in a region with high transformative potential. Similarly, Wesseling et al. (2022) show how dominant global regimes create barriers for radical innovation in the Dutch industrial heat pumps TIS despite national policy support. Yap et al. (2023) studied the emergence of a global regime for handling of space debris, highlighting the competition between national and global regimes before the establishment of a global regime.

However, given that the construction, reproduction and diffusion of global socio-technical regimes across space remains an understudied topic in sustainability transitions research, there is a need for further conceptualisation and empirical exploration of multi-scalar global regime dynamics. There is also a remaining gap regarding how global regimes are challenged by bottom-up influences such as grassroots innovations and other radical innovations. Furthermore, given that previous studies of global regimes have mainly explored socio-technical change processes in the water and sanitation sectors, there is also a need for broader exploration of other sectors with strong global regimes, such as the aviation and maritime shipping sectors. This thesis contributes to the literature on multi-scalarity and global socio-technical regimes through exploration of a novel empirical case, the maritime shipping sector, a sector that due to the intrinsic internationality of its operations has an exceptionally strong global regime. Global regime dynamics are explored specifically in relation to the technology implications of the global policy mix implemented by the IMO as explored in Paper I, the policy making dynamics associated with member-state negotiations within the IMO in Paper II, and regarding sectoral conditions for development of bottom-up initiatives in Paper IV.

Policy for Sustainability Transitions

Policy interventions directing efforts toward more sustainable socio-technical systems are seen as crucial to enable sustainability transitions (Alkemade et al., 2011; Markard, 2018; Weber & Rohracher, 2012), especially for hard-to-abate sectors (Otto & Oberthür, 2024). In contrast to conventional innovation policy, which often is aimed at maintaining and strengthening the current regime, policy for sustainability transitions strives towards a regime shift (Kemp, 1994). Furthermore, innovation policy typically targets stimulation of general innovation contributing to economic growth, while policy for sustainability transitions seek to stimulate changes and socio-technical solutions that will benefit society at large, such as GHG emission reductions that limit global warming (Alkemade et al., 2011). This implies an analytical focus on system-wide transformations rather than optimizing existing technology-centred innovation systems in ways that address market and system failures (Weber & Rohracher, 2012). However, the impact of policy interventions on the direction and speed of socio-technical change remains under-explored in sustainability transition studies (Kivimaa & Rogge, 2022; Markard et al., 2012), especially beyond exploration of national level policy.

As a response to calls for further investigation of the role of policy for sustainability transitions, the concept of *policy mixes* has been introduced in the sustainability transitions literature during the last decade (Flanagan et al., 2011; Kern et al., 2019; Kern & Howlett, 2009; Rogge et al., 2017). The term policy mix is used in numerous fields, such as innovation studies and policy analysis (Howlett & Rayner, 2007), and the definitions of policy mix terminology that have been further conceptualised in the sustainability transitions literature mainly stems from innovation studies and the policy analysis literature (Rogge & Reichardt, 2016). Put simply, a policy mix consists of a combination of different policy measures regulating a specific societal challenge, and can be explored at the local and regional, national, supra-national or global levels, as well as multi-scalar governance levels. As previously indicated, the majority of policy mix studies have explored national level policy mixes, indicating a need to analyse policy mixes on other governance levels as well as multi-scalar dimensions of policy mixes.

Furthermore, early studies of policy mixes within the economic and environmental policy literatures had a narrow focus on understanding the nature of interactions between different policy instruments (Sorrell & Sijm, 2003; Stroick & Jenson, 1999). However, Flanagan et al. (2011) argue that the concept of policy mixes includes more than simply the collected policy instruments, and that the policy mix also relates to the policy processes through which policy instruments are negotiated and implemented. Consequently, studies that limits their analytical focus to examination of how different policy instruments interact with each other should refer to this as an 'instrument mix' rather than a policy mix.

Building on this conceptualisation, Rogge and Reichardt (2016) propose an extended analytical framework for exploration of policy mixes (see Figure 4), in which they distinguish between the policy strategy and instrument mix as two separate policy mix elements. They argue that maintaining the narrow focus on policy instrument interactions and keeping explorations of policy processes separate from studies of policy mixes risks neglecting key policy mix elements or policy processes that could help explain their influence on socio-technical change processes. Therefore, Rogge and Reichardt (2016) furthermore propose that analysis of policy mixes should include policy processes (policy making and implementation) as well as the characteristics of the policy mix (consistency, coherence, credibility, and comprehensiveness).

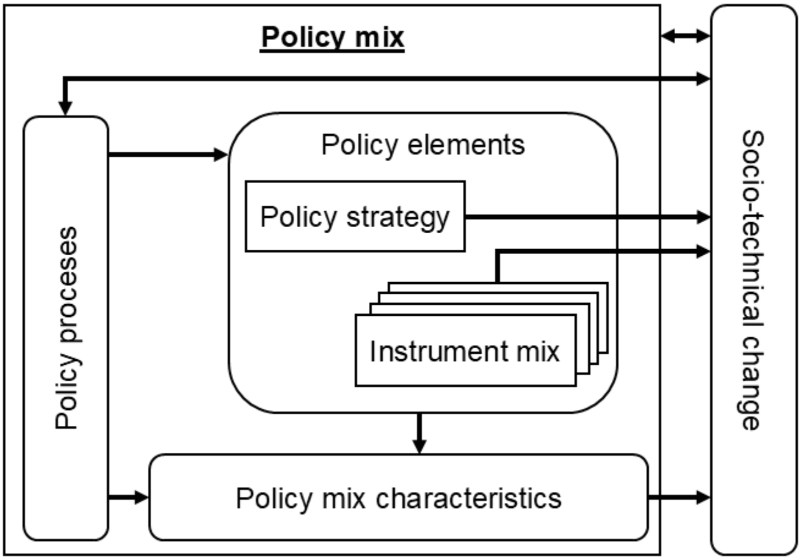

Figure 4 The extended policy mix framework for analysing interplay between the policy mix and socio-technical change
Source: Rogge and Reichardt (2016)

Policy mix elements

Long-term goals and strategies in policy making have been highlighted as important for enabling sustainability transitions (Foxon & Pearson, 2008; Quitzow, 2015a; Weber & Rohracher, 2012). Building on conceptualisations from the strategic management literature, Rogge and Reichardt (2016, p. 1623) define the first policy mix element, the *policy strategy,* as "a combination of policy objectives and the principal plans for achieving them". Policy objectives (i.e., targets), could be both long-term targets such as quantified GHG emission reduction targets (Schmidt et al., 2012), as well as visions for the future (del Río et al., 2010; Kemp & Rotmans, 2005) or process and learning objectives (Kemp, 2007; Rotmans et al., 2001), for example relating to developing strategic capacity in regulatory bodies (Quitzow, 2015b). Principal plans relate to strategic documents such as action plans, road maps and guidelines that gives direction to policy making and implementation (Rogge and Reichardt, 2016). Given that a policy strategy sets out the ambition and plan for an intended sustainability transition, an effective policy strategy can be a driver of socio-technical change by guiding actors towards investments as well as innovation and technology implementation relating to the desired socio-technical system configuration. In the TIS literature, this is conceptualised as 'direction of search', which is considered to be one of the key functions for development of TISs (Bergek, Jacobsson, et al., 2008; Hekkert et al., 2007). However, isolated policy targets and strategies, no matter how ambitious they are, have not been sufficient to drive sustainability transitions (Rogge et al., 2011; Schmidt et al., 2012), indicating that there is a need for implementation of policy instruments that enable achievement of the policy objectives (Rogge and Reichardt, 2016).

The second policy mix element in the extended policy mix framework is therefore the *policy instruments* that together constitutes the instrument mix. In this framework, policy instruments are seen as the concrete measures, such as bans, emission standards, and feed-in tariffs, as well as funding grants and subventions, that are implemented by regulatory bodies to achieve set policy targets. Previous research indicates that the type of policy instrument (for example, whether it is a regulatory, economic or soft instrument) and aiming at technology push or demand pull, have a crucial impact on the rate of innovation and socio-technical change (e.g., Jaffe et al., 2002; Johnstone et al., 2010; Requate, 2005). Typically, different types of policy instruments are needed at different stages of innovation processes, and different sectors may need different types of policy instruments depending on specific sector characteristics (Kivimaa & Kern, 2016; Pavitt, 1984), indicating that there is a need for a combination of different types of policy instruments. Given the assumption within sustainability transitions research that socio-technical change requires creation of new configurations of socio-technical systems as well as destabilisation of incumbent socio-technical regimes (Turnheim & Geels, 2012), Kivimaa and Kern (2016) argue that policy mixes for sustainability transitions should include elements of 'creative destruction'.

In practice, this implies introducing policy instruments driving implementation of new, more sustainable technologies (creation), as well as simultaneously withdrawing support for and increasingly regulating old, polluting systems (destruction). Consequently, an ideal policy mix should include a combination of different types of policy instruments, which supports both creation of socio-technical change and destruction of current, fossil-based socio-technical systems (Rogge and Reichardt, 2016; Kivimaa and Kern, 2016). To conceptually analyse the composition of instrument mixes, Kivimaa and Kern (2016) introduce a framework for exploration of 'motors of creative destruction', which builds on previous conceptualisations of 'motors of innovation' within the TIS literature (Suurs & Hekkert, 2009). They argue that given the urgency of achieving sustainability transitions, there is a need for specific attention to measures targeting active destabilisation of incumbent regimes in addition to policy instruments targeting creation of new socio-technical configurations. Building on previous conceptualisations of functions within a TIS, the framework distinguishes between four categories of destructive policy instruments targeting regime stabilisation (control policies, significant changes in regime rules, reduced support for dominant regime technologies, and changes in social networks and replacement of key actors) and seven categories of creative instruments providing support for niches (knowledge creation, development and diffusion, market formation, price-performance improvements, entrepreneurial experimentation, resource mobilisation, legitimation, and influence on the direction of search). In Paper I, we bridge Kivimaa and Kern's (2016) framework with earlier findings regarding the need for a balance between regulatory (laws and other binding regulations), economic (provision of pecuniary incentives and disincentives) and soft (voluntary measures and information provision) instrument to increase the effectiveness of policy mixes (Borrás & Edquist, 2013; Rogge & Reichardt, 2016; Schmidt & Sewerin, 2019).

Policy processes

In their extended policy mix framework, Rogge and Reichardt (2016, p. 1625) view policy processes as a combination of policy making processes and policy implementation, where the former refers to "political problem-solving processes among constrained social actors in the search for solutions to societal problems", and the latter the actual enforcement of specific policy instruments (thereby mainly relating to the instrument mix). The characteristics of the policy strategy and instrument mix are shaped by these policy processes, which determines how the policy elements develop over time and thereby influence socio-technical change (Howlett & Rayner, 2007; Kay, 2006; Majone, 1976). Given the complexity and uncertainty of sustainability transitions, policy-making processes should include elements of learning and adaption of policy, which include monitoring and evaluation of the impact of policy strategies and instruments in order to achieve an effective policy mix (Kemp, 2011; Kemp et al., 2007; Rogge & Reichardt, 2016). Policy making is seen as an inherently political process in which various types of actors are involved, which are typically resistant to change, and requires extensive negotiation to achieve radical changes in the policy mix (Unruh, 2002). This indicates that policy implementation may be hindered by lack of political consensus as well as insufficient implementation structures, causing delays in implementation or the introduction of misguided policy instruments. This may also be one of the reasons that new instruments supporting creation of niches and socio-technical change are typically simply added to existing regulatory frameworks rather than replacing instruments supporting the incumbent socio-technical regime (Kern & Howlett, 2009), and thus do not achieve creative destruction in policy mixes. In previous studies of policy processes in relation to sustainability transitions, there has been an empirical emphasis on national governments as the primary policy maker, indicating that there is a gap to be filled regarding policy mixes implemented by regulatory bodies at other governance levels such as the EU or UN agencies. This gap is addressed in Paper I.

Policy mix characteristics

Finally, Rogge and Reichardt (2016) suggest that the *characteristics* of policy mixes may impact their effectiveness and efficiency. They provide conceptualisations for four different characteristics: the *coherence* of policy processes, the *consistency* of policy elements, and the *credibility* and *comprehensiveness* of a policy mix;

proposing that a higher rate of the respective characteristics positively influences the effectiveness of a policy mix. The coherence of policy processes relates to the coherence across different policy fields and governance levels, which depends on the systematic capabilities of policy makers to implement consistent, comprehensive and credible policy mixes. Credibility refers to the legitimacy of the overall policy mix and the specific elements (policy strategy and instruments) as well as policy processes surrounding a policy mix. High credibility is associated with, for example, a strong engagement and commitment from political leadership or a clear connection between policy strategy and policy instruments. The consistency of elements refers to degree of alignment within and between policy elements and is conceptualised at three levels: consistency of the a. policy strategy, b. instrument mix, and c. overall policy mix (referring to the relationship between the policy strategy and the instrument mix). Comprehensiveness, meaning the extensiveness of the policy mix, is also assessed for the policy strategy, instrument mix and overall policy mix (Rogge & Reichardt, 2016). Despite the ascribed importance of policy mix characteristics, to date, very limited empirical work has been devoted to understanding the implications of policy mix characteristics on sustainability transitions. Recent empirical studies have found that a high degree of comprehensiveness contributes to the effectiveness of the policy mix and thereby drives innovation (Costantini et al., 2017), while less comprehensive policy mixes have been found to maintain status quo (Sanz-Hernández et al., 2020). Related to this, Reichardt and Rogge (2016) argue that a lack of comprehensiveness may be compensated by stronger presence of other policy mix characteristics such as credibility. With regard to policy mix consistency, empirical studies have shown that a higher degree of consistency increases the efficiency of policy mixes, for example when it comes to investments in technology development and implementation (Liu et al., 2024; Reichardt & Rogge, 2016; Rogge & Schleich, 2018). Based on their exploration of the consistency, coherence, comprehensiveness and credibility of vertical policy mixes in the Latvian electricity sector, Zepa and Hoffmann (2023) show discrepancies between national and local governance levels and EU policy with regard to coherence of policy processes, as well as a lack of comprehensiveness and credibility as a result of limited political consensus, which hinders a transition towards renewable electricity. However, given identified challenges regarding the operationalisation and evaluation of policy mix characteristics, such as how to assess the interplay between the respective characteristics (Rogge, 2019), there is still a need for a further conceptual and empirical understanding of the historical development of policy mix characteristics and their influence on socio-technical change.

4. Shipping as a socio-technical system

In this chapter, a conceptual overview of the key socio-technical elements of the conventional maritime shipping sector is presented, in order to highlight the complexity of this hard-to-abate sector and outline remaining research gaps. Starting with the institutions, including regulatory frameworks as well as cultural and societal norms, the chapter then moves on to the networks of actors involved in the shipping industry. Following this, an overview of the main material artefacts, technologies and infrastructure, as well as markets and user practices is presented. In addition to describing the current status of these socio-technical elements, the chapter also provides a historical perspective including changes in the socio-technical system since the implementation of the first global regulatory framework regulating emissions to air from international shipping in 2005. The chapter concludes with a comparison of the main differences between the prerequisites for previous propulsion technology shifts and the impending shift to more sustainable propulsion technologies, as well as an elaboration on the research focus for this thesis.

Socio-technical system elements

Institutions

Cultural and societal norms

Being one of the oldest professions, the culture of the shipping sector holds many traditions and well-anchored norms and values. In general, the shipping sector is seen as conservative, hierarchical and male dominated (Shea, 2005). However, shipping is an international and diverse industry, implying that values vary between nations, shipowners and captains. Shea (2005) found that the regulatory environment and the economic conditions for shipping (such as freight rates) are two major influences for the on board organisational culture. The often multi-cultural and -lingual setting for on board crews furthermore provides a challenge for developing and improving ship culture (Progoulaki & Theotokas, 2016).

Environmental and especially climate awareness has previously not been very high on the general agenda within the shipping sector. Taking comfort in the fact that the shipping sector transports around 90% of global cargo while only contributing about 3% of the yearly global GHG emissions, it has been argued that energy efficiency measures are a sufficient contribution for the shipping industry (Burel et al., 2013). However, since the introduction of the initial IMO GHG Strategy in 2018, things are starting to change: several large shipowners are stating ambitious climate ambitions and taking initiatives to implement alternative propulsion technology (Maersk, 2021; Sjöström, 2021; Stena Line, 2021). Furthermore, shipowners are increasingly acknowledging that the coming generation of crew members have higher demands when it comes to emission performance and company values, and as being an attractive employer for future generations is important to most shipowners this is a driver for change (Newman, 2020). Although the connection between organisational culture on board and safety has been researched extensively (Ek et al., 2014; Lu et al., 2016), the implications of environmental and climate awareness within the shipping sector, such as attitudes to new technology, is yet an understudied topic (Giziakis & Christodoulou, 2012; Newman, 2020; Saether et al., 2021).

Regulatory institutions

Being an international sector, the shipping sector is regulated on several governance levels. The IMO, initiated in 1948 and formally established in 1959, is one of the specialised agencies of the UN, whose aim is to regulate international shipping (IMO, 2020). As all UN specialised agencies, it is a member-state-led organisation with a complex governance model. The key feature to investigate in order to understand how the IMO functions, and also differs from other UN bodies, is how power structures mainly are influenced by individual nations' registered tonnage (representing the goods-carrying capacity of a fleet of ships) rather than national population or GDP (Corbett et al., 2020). This results in the shipping sector being practically self-regulating (The International Federation of Shipmasters' Associations, 2014). Furthermore, due mainly to tax reasons, shipowners often register their ship(s) in countries with open registration (such as Panama and the Bahamas) – a phenomenon called 'flag of convenience'.[1] This implies that the mandates do not truly represent the geographical location of shipowners, and that some small states hold disproportional clout in negotiations (Corbett et al., 2020).

In the first years, the IMO's main responsibility was to ensure safety at sea by establishing traffic rules, requirements for safety equipment, a global search and rescue system, etc. While this still remains the main focus, the organisation's responsibilities have been expanded. Article 1(a) of the IMO Convention states that

[1] A term stemming from the tradition, and legal requirement, of displaying the flag of the nation which the ship is registered in at the aft (the rear end) of the ship.

the purposes of the organisation are “to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships”. The IMO began work with environmental regulation during the 1970’s with the formation of the Marine Environmental Protection Committee (MEPC), which developed the International Convention for the Prevention of Pollution from Ships (MARPOL) (IMO, 2019).

Although signed in 1973, MARPOL did not come into force until 1983, at the time constituted by one annex on the prevention of oil pollution. In the following years, additional annexes were added, covering prevention of pollution by noxious liquid substances, harmful substances, as well as sewage and garbage from ships. With regard to air emissions from ships, the regulatory process was initiated in parallel with the Kyoto Protocol negotiations in 1997. The Kyoto Protocol established that IMO shall be responsible for regulatory action on GHG emission reduction from international shipping (UNFCCC, 1997), and processes to draft a new annex of MARPOL were initiated later in 1997. This annex, now known as Annex VI – Prevention of Air Pollution from Ships (hereafter MARPOL Annex VI), aimed to regulate emissions of GHG and air polluting substances like sulphur oxides and nitrogen oxides. Several member states (for example, Norway) had already been raising the issue of acid rain due to emissions from shipping to the IMO for a number of years, and with the initiation of a new annex, air pollution became institutionalised through regulation. The negotiations regarding the type and level of regulation at the IMO was a lengthy process. Finally, eight years later, MARPOL Annex VI came into force in 2005. Initially, regulation focused on limiting emission of air pollutants (mainly sulphur and nitrogen oxides). In 2013, a number of instruments aiming to improve the energy efficiency of individual ships was introduced as a first attempt at regulating GHG emissions from ships. These measures came into force in 2015; however, to date, they still only apply to certain types of vessels, reflecting the challenge of regulating the diverse global fleet (Resolution MEPC.203(62)).

The Paris agreement, signed in 2015, replaces the Kyoto Protocol, and sets the ambition for global climate action to keep the global warming well below a 2°C increase from pre-industrial levels, and to attempt limiting the increase to 1.5°C. Although the Paris agreement solely requires nations to take action to decrease their GHG emissions, it calls upon the IMO to voluntarily implement regulation for international GHG emission from ships (UNFCCC, 2015). An IMO working group on GHG emissions from ships was formed in 2008, with the task of proposing emission-reduction measures. Following up on the Paris Agreement, the work of the GHG working group accelerated, and an Initial IMO GHG Strategy was presented in 2018 and further updated in 2023 (Bullock et al., 2020; IMO, 2018, 2023). The updated strategy states the ambition to reduce the CO_2 emissions/transport work by 40% (compared to 2008), as well a 20% reduction of total annual GHG emissions by 2030. More long-term, the strategy sets reduction targets for at least 70% (aiming for 80%) reduction of total annual GHG emissions by 2040 and net-zero GHG emissions from international shipping by or around 2050 (IMO, 2023). From 1 January 2018, large ships are obligated to report their GHG emissions to the IMO DCS database (Resolution MEPC.278(70)), and a few short-term measures addressing GHG have been decided upon and partially implemented since then (IMO, 2018; Resolution MEPC.336(76)).

The EU has become an increasingly important regulatory actor for the shipping sector in the last 20 years through its environmental legislation. The European shipowners affected by EU regulation control 39.5 % of the global fleet, and shipping makes up 76% of EU's external trade and 32% of its internal trade (European Community Shipowners' Association, 2020). Although not a member of IMO, the European Commission holds observation status during IMO negotiations and has influence through the EU member states, which are all members of IMO (Nengye & Maes, 2010). Furthermore, regulatory processes within the EU seemingly have an impact on IMO regulation, as EU legislation typically is stricter (at least initially), which drives sharpening of international regulation (J. J. Smith & Tanveer Ahmad, 2018). Apart from incorporating IMO regulation in the EU regulatory framework, the EU has also implemented additional regional measures such as regulating sulphur emissions in ports (Directive 2012/33) and the EU Monitoring, Reporting and Verification (MRV) scheme for CO_2 emissions from the shipping sector (Regulation 2015/757). The EU are currently accelerating their policy work around regulating shipping emissions, mainly by including shipping in the EU Emission Trading Scheme (Directive 2003/87). The European Green Deal furthermore includes several measures enabling cargo owners and consumers to put pressure on shipping companies to decrease their emissions (European Community Shipowner's Associations, 2020). Furthermore, national maritime authorities have the mandate to implement regional measures such as environmentally differentiated fairway fees and mandatory use of shore power supply (Vierth & Johansson, 2020). Ports, both publicly as well as privately owned, also have the possibility to introduce measures addressing ships emissions, for example, differentiated harbour fees (Styhre et al., 2019).

Furthermore, in addition to being responsible for implementing IMO regulation in the national regulatory framework, national maritime authorities (or in IMO terms, 'flag states') have the possibility to implement national legislation regulating shipping in national waters and ports. Flag states are also responsible for ensuring regulatory compliance on board nationally registered ships, as well as ships calling at the nation's ports (Hoffmann et al., 2020). Classification societies are non-governmental organisations (NGOs) that are responsible for developing maritime standards and technical specifications, based on IMO regulation. They are also responsible for issuing mandatory and voluntary certificates as instructed by the IMO. Individual classification societies may be granted observer status at IMO negotiations, and the International Association of Classification Societies has acted as a consultant for the IMO since 1969 (Chircop, 2019).

Networks of actors

Shipowners and shipowner associations have been important actors which have had major impact on the shipping industry for a long time, and are granted observer status during IMO negotiations (Chircop, 2019). In addition, larger shipowner associations, such as the European Community Shipowners' Associations and the International Chamber of Shipping, act as consultants for the IMO, collecting material for IMO Committees (Corbett et al., 2020). Shipowner associations also function as knowledge networks, providing opportunities for diffusion of new technology. Ships' crews are self-evidently essential for operating the ships. With the implementation of alternative propulsion technology, crews play a crucial part in the actual handling of the new systems and will need education to widen their competence. Among technology suppliers there is an ongoing shift: new suppliers specialized in specific low- and zero-carbon solutions are entering the shipping sector, while conventional suppliers either decide to expand their services to include new technology or continue their business as usual (Steen et al., 2019).

Several external actors are becoming increasingly important in the decarbonisation of the maritime sector, such as cargo owners who are progressively placing requests and show willingness to pay for climate neutral shipping (Poulsen et al., 2016). For example, strong customer demand for zero-emission transport of luxury goods such as fairtrade coffee and cacao has created a window of opportunity for traditional sail cargo ships to make a return in the modern world (De Beukelaer, 2023). Furthermore, external investors are starting to include climate initiatives in their investment assessments, and insurance companies are also increasingly investigating how climate change and alternative propulsion technology will affect insurance policies (Scott, 2019).

Material artefacts

Technology

The large two-stroke combustion engine fuelled with heavy fuel oil has been the dominant technology for the shipping sector since the 1950s. Technology development has historically been focused around improving engine efficiency and decreasing fuel consumption, as well as hull optimization aimed at decreasing friction – initially motivated by keeping fuel costs low, and later also required by the regulatory framework (International Chamber of Shipping, 2020). In light of the implementation of MARPOL Annex VI, Liquefied Natural Gas (LNG) has gained traction as a ship fuel in the last decade. However, LNG is a fossil fuel which emits CO_2 (although less than heavy fuel oil) as well as methane (an even more potent GHG), implying that in order to achieve decarbonisation of the shipping sector alternative low- and zero-carbon propulsion technologies are necessary. Within the shipping sector, there is consensus that there will be a need for several types of future fuels to cover the great energy demand of the global fleet (DNV GL, 2019; Osterkamp et al., 2021). Currently, pilot testing, experimentation and small-scale implementation of several new (and old) types of alternative propulsion are ongoing; for example, wind-assisted propulsion and sailing ships, hydrogen, ammonia, methanol, LBG, battery-electric systems, etc. (DNV GL, 2019). In parallel, the work around energy efficiency for conventional propulsion is ongoing, and the overall carbon intensity for global shipping has improved by 29% since 2008. However, since 2015 the pace of carbon intensity reduction has decreased to an average annual decrease of between 1% and 2%, and the total emissions from the shipping sector is continuously increasing (IMO, 2020).

Infrastructure

In the last century, the global shipping fleet has grown not only in number of ships, but also in terms of cargo capacity, further establishing the shipping sector as a large socio-technical system enabling globalisation (Hughes, 1987; Levinson, 2016). The typical lifespan of a ship varies between 15 to 40 years, depending on the type of ship. In 2018, the average age of scrapped ships was 28 years (Clarksons Research, 2019). This has two main implications for the socio-technical system: first, technology changes take a relatively long time to implement due to the low turn-over, decreasing the speed of transitions (Bullock et al., 2020). Second, making decisions about propulsion technologies is currently a tremendous challenge due to uncertainty regarding future fuel options and their availability. Furthermore, this implies that there will be a need to retrofit ships within the current fleet in addition to construction of new ships with alternative, sustainable propulsion technology (International Chamber of Shipping, 2020), as the majority of the ships in the current global fleet will still constitute the largest part of the fleet in 2030 (Bullock et al., 2020).

When MARPOL Annex VI, the first international regulatory framework governing emissions to air from international shipping, came into force in 2005, heavy fuel oil had already been the dominant ship fuel for more than 50 years and bunker infrastructure was well established, implying a great risk of technological lock-in (Unruh, 2000, 2002). The new regulation of air emissions was the first to require changes in the infrastructure system, especially through the increasingly strict regulation of fuel sulphur content, which called for distribution of low-sulphur fuels. The increased interest in LNG requires construction of new types of ship engines as well as bunker infrastructure – which is currently a rapidly growing process (SEA-

LNG, 2021). Since LNG had already been used as fuel for ships carrying LNG as cargo, engine and fuel storage systems were already available for diffusion to other ships, which can be seen as a case of path dependency (Klitkou et al., 2015; Steen et al., 2019). The shift to multiple alternative propulsion technologies beyond LNG constitutes a major challenge when it comes to fuel production as well as distribution infrastructure. Countries and regions with different geographical contexts and access to (mainly natural) resources have varying challenges and opportunities for implementing alternative solutions. Historically, it has been shown that transitions often start out smaller in scale: among the first steam ships were, for example, steam tugs in harbours (Geels, 2002). This is also reflected in current transitions, such as the experiments with alternative propulsion for car- and passenger road ferries in Norway (Bach et al., 2020; Sjøtun, 2019). To summarize: following the need for various fuels, bunker infrastructure and ship propulsions systems, it is likely that several socio-technical configurations will develop around the shipping sector in the future.

Markets and user practices

As the main purpose of shipping is to transport goods, the maritime industry is naturally interdependent on the markets of these various types of cargo; for example, as the need for different types of ships (such as container, tanker, bulk cargo) varies over time, or the development of shipping rates (Levinson, 2016). This is especially the case for the oil market, which is intertwined with the shipping sector in several ways. Apart from using heavy fuel oil as fuel and thereby being dependent on fuel market fluctuations and the availability of bunker infrastructure, the majority of global oil is transported by ship. A large part of the oil is traded on the so-called spot market, which implies that a tanker ship may get the order to steam towards port A, only to be redirected to port B upon arrival at port A, as their cargo has been purchased by a new company (Prochazka et al., 2019). Furthermore, flows of goods have increasingly become an important aspect of route planning since ships are no longer dependent on wind direction and speed nor the access to fuel. In the decades before the implementation of MARPOL Annex VI, access to fuel was rarely an issue (Endresen et al., 2007). With the implementation of alternative fuels, it is likely that there will be some tension between access to fuel infrastructure and cargo flows when planning shipping routes. The implementation of new fuels will also require new practices around handling of fuels and technical systems on board, implying a need for increased knowledge regarding several types of systems as well as education of crews (Steen et al., 2019).

Differences between previous and current transitions

Returning to the historical overview of transitions in the shipping sector presented in the beginning of chapter 2, there are some important reflections to be made regarding differences between previous transitions and the impending transitions in ship propulsion technologies. First, the directionality for impending transitions differs immensely from historical transitions. Historically, important drivers have been increased speed, reliable arrival and departure schedules, increased range and fuel cost reductions (Endresen et al., 2007; Geels, 2002). In contrast, the pressure to decarbonise shipping emanates from a societal pressure for climate change mitigation, indicating a need for a different type of policy incentives to enable socio-technical change with regard to propulsion technologies. In relation to this, the societal pressure for decarbonisation of the maritime shipping sector includes an element of urgency that has not been present during previous technology shifts. Taking the long lifespans of ships into consideration, it is evident that implementation of more sustainable propulsion technologies needs to be expedited in order to enable the achievement of decarbonisation in line with the Paris Agreement.

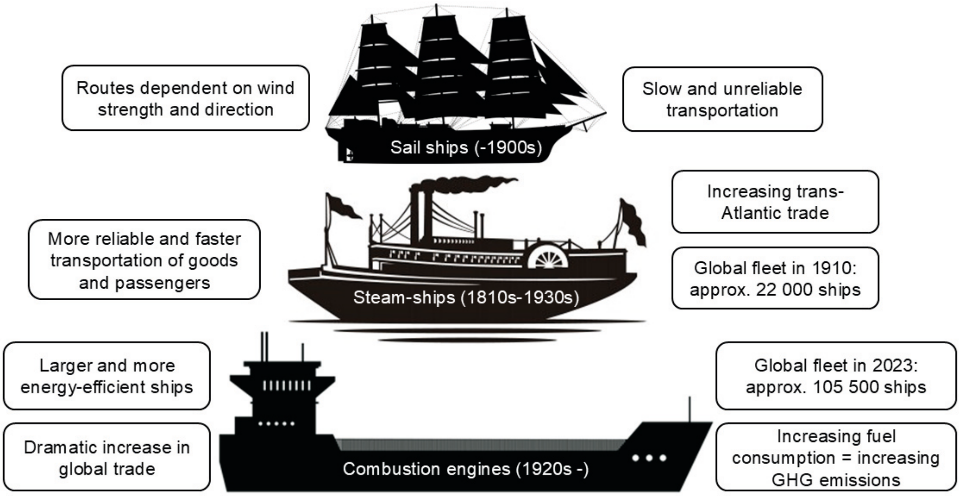

Figure 5 Overview of historical transitions in the shipping sector from early 19th century to 20th century (ships not to exact scale)

Second, the scale and degree of institutionalisation of the shipping sector has increased dramatically since the transition from sail ships to steamships (see Figure 5). In the past, the global fleet included far fewer, and smaller, ships. With the introduction of the steam engine, the growth of the global fleet began to increase (Geels, 2002). By the time the transition to diesel and heavy fuel oil started, the global fleet had grown remarkably and included around 20 000 ships – but was still small compared to today (Endresen et al., 2007). Following more efficient modes of cargo handling, such as container systems, international trade grew explosively during the 1970s, bringing more and more ships onto the oceans (Levinson, 2016). Presently, 90% of the world's trade is at one point transported by any of the approximately 105 500 ships within the global fleet (DNV, 2024a). This implies that the scale of the global fleet, both in terms of number of ships and their cargo capacity, is much larger now and will require great amounts of alternative fuels.

Third, there is no silver bullet propulsion technology to replace fossil fuels, as none of the more sustainable propulsion technologies will be available in sufficient quantities. This implies that there is a need for portfolio of propulsion technologies, such as hydrogen, methanol, and wind assisted propulsion solutions. Shifting from one main propulsion technology to multiple solutions promises to be very complex with regard to regulatory as well as practical aspects of innovation and implementation processes. Furthermore, it is projected that the price of more sustainable propulsion technologies will be significantly higher than conventional fossil fuels (Solakivi et al., 2022), implying that the shift to more sustainable propulsion technologies is associated with increasing investment as well as operation costs, in contrast to the reduced costs following the shift to combustion engines running on heavy fuel oil.

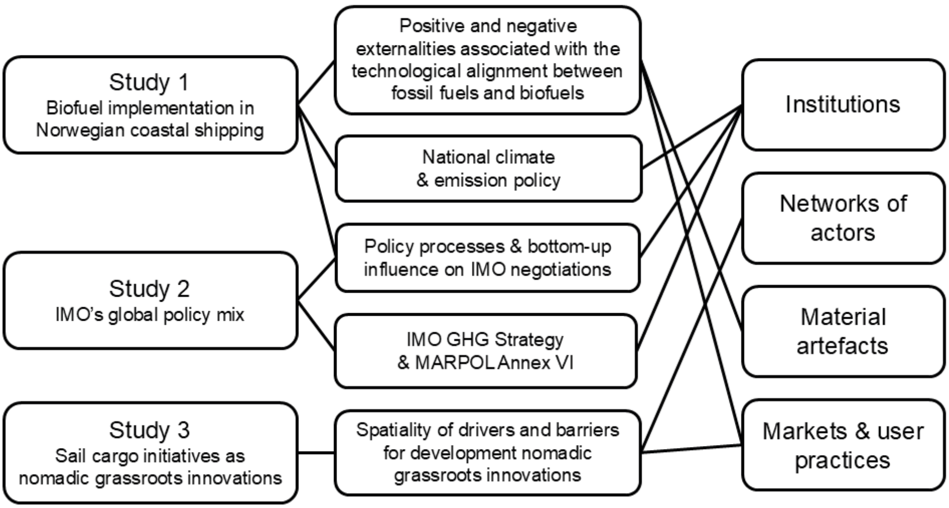

Figure 6 Overview of empircal focus regarding the respective socio-technical elements in the thesis' three studies

This thesis unpacks parts of the complexity associated with the socio-technical system of the maritime shipping sector, and studies how multi-scalar top-down and bottom-up processes influence socio-technical change towards decarbonisation of the global maritime shipping sector. Based on three empirical studies, which will be presented in more detail in the next chapter, this thesis explores changes within all four key socio-technical system elements: institutions, networks of actors, material artefacts, and markets and user practices. While the first study takes a TIS perspective and thereby explores the socio-technical system as a whole, the study primarily focuses on socio-technical change in relation to institutions and material artefacts (see Figure 6). The second study is concerned with institutional developments, while the third study focuses on networks of actors as well as markets and user practices.

5. Methodology

In this section, I present an overview of the methodological approach for three empirical studies that the papers in this thesis are based on; more detailed descriptions of the respective methodological approaches can be found in the papers. My research takes a predominantly qualitative starting point, and the research design includes document analysis, semi-structured interviews, and participant observations in various combinations. As sketched out in the previous chapter, I investigate socio-technical change processes in relation to the institutions, networks of actors, material artefacts, and market and user practices that are part of socio-technical configurations in the maritime shipping industry.

Positionality

When starting my research on the shift to sustainable shipping, I already had some prior knowledge of the maritime shipping sector, both from maritime navigation studies, as well as working and sailing on various types of ships, including traditional sailing ships and coastal sightseeing boats, in parallel to my studies in environmental and sustainability science. During my time at sea, the environmental and sustainability issues associated with the continued use of conventional fossil fuels, as well as the challenges of shifting to more sustainable propulsion technologies, were right before my eyes. Eventually, these experiences contributed to my motivation for pursuing a PhD project focused on the shift to sustainable shipping. Throughout the project, my previous experiences have proven beneficial in multiple ways. First, having a practical understanding of how maritime law and regulations are organised and enforced has helped tremendously in the parts of my research focused on policy at national (Study 1) and international (Study 2) levels, while practical knowledge from working on board different types of ships has been beneficial regarding understanding socio-technical challenges with implementing new, alternative propulsion systems (Study 1). In addition, being familiar with the peculiarities associated with operating around century-old traditional sailing ships, such as the sail cargo ships studied in the third study, allowed for a unique insight into potential challenges these initiatives face, as well as facilitating trust building with interview respondents.

Furthermore, my normative standpoint is that it is necessary to shift to more sustainable propulsion technologies as well as decrease shipping volumes in order to decrease GHG emissions from the maritime shipping sector and thereby contribute to preserving a liveable planet for future generations. This standpoint has influenced the choices made regarding the focus of the three empirical studies that the papers of this thesis are based on, and the research questions asked, in two main ways. First, given that I perceive that there is, in addition to technology innovation, an urgent need to identify socio-technical barriers to as well as drivers for transitions from conventional fossil fuels to alternative, more sustainable propulsion technologies, the first two studies explore how international and national policy influences implementation of specific propulsion technologies. Exploring this from a normative standpoint allows for identification of barriers to and drivers for a shift to more sustainable shipping, while also identifying shortcomings in policy processes that can be improved upon. Second, about half-way through this PhD project, it became clear to me that current policy incentives are insufficient to drive implementation of more sustainable propulsion technologies, and I became increasingly frustrated with the slow progress towards more sustainable propulsion technologies in the shipping sector. This led to a desire to explore sustainability initiatives outside of the conventional shipping industry, in order to identify examples of initiatives that go beyond regulatory requirements as well as give hope for the future. Ultimately, this desire contributed to the decision to study grassroots initiatives which are proposing a return to traditional sail cargo ships in the third and final study of this thesis. This allowed for identification of alternative sustainable shipping pathways that can inspire radical innovation in the maritime shipping industry both in relation to propulsion technologies as well as changing shipping patterns and decreasing shipping volumes.

While taking a normative standpoint provides opportunities to identify of previously understudied topics and is typical for sustainability transitions studies, it is also associated with risks, such as confirmation bias and positive or negative bias towards specific opinions, narratives or socio-technical solutions. Throughout this PhD project, I have applied strategies to mitigate the risk of potential biases by including rigorous empirical material from multiple data sources in each study, as well as through validation and triangulation between data sources, such as confirming results from document analysis with interview respondents and cross-checking between multiple organisations or types of actors.

Philosophical underpinnings

The research in this thesis is guided by the philosophy of science perspective critical realism. This perspective was popularised in human geography by Sayer (1985, 1992), and has become an influential philosophical perspective within the field

(Pratt, 1995; Yeung, 1997). Critical realism has also been pointed to as a relevant philosophical perspective for sustainability transitions research (Geels, 2022; Papachristos, 2018; Sorrell, 2018; Svensson & Nikoleris, 2018). Within the critical realism perspective, a core principle is that the world exists independently of our theories and knowledge of it, implying that our experience of certain empirical objects should not be confused with the actual object (Bhaskar, 1975). A simple illustration of this is that the shift in thinking from the Earth being flat to the Earth being a sphere did not in fact change the actual shape of the planet (Sayer, 2000). Following this notion, critical realists distinguish between transitive (theories about objects) and the intransitive (the actual objects) dimensions. The transitive dimension encompasses our subjective experiences of reality, manifested in the scholarly concepts and theories researchers use to explain the world. This would include concepts and theories explaining socio-technical change and the geography of sustainability transitions in this thesis. In contrast, the intransitive dimension represents the 'real world' as independent from these concepts and theories (Bhaskar, 1975). In line with previous critical realists, I recognise that a researcher's understanding of the world is inevitably always subjective, relative and constructed by the individual (Stutchbury, 2022), implying that research results can be fallible and that our knowledge of the world should be subject to constant revision (Pratt, 1995). Likewise, interview participants share their perceptions of this 'real world' based on their experiences, intentions and understandings. Yet, the critical realist position is that the researcher should always strive to get as close to 'objectivity' as possible, by including multiple methods and fallible data sources that can be triangulated (Sayer, 2000).

Another core principle within critical realism is that in order to understand why and how an event has occurred, it is insufficient to solely study the event in isolation. Rather, it is assumed that observable events occur as a result of various structural interactions. As these structures are at times not directly observable (Lawani, 2021), critical realists apply a stratified ontological perspective in which reality consists of three levels/domains: the *empirical*, the *actual* and the *real* (Bhaskar, 1978). From a critical realist point of view, knowledge about a certain phenomenon, such as the shift away from fossil fuels to more sustainable propulsion technologies in the maritime shipping sector, is stratified around these three domains. However, the domains should be viewed as separate, yet nested, layers which "are ordered, not just jumbled up together" (Collier, 1994, p. 46). The *empirical* domain includes people's experiences and observations, i.e., interpretations, of events, and is considered a sub-set of the *actual* domain, which represents the events that occur as a result of causal powers associated with the deep structures and underlying causal mechanisms that constitute the *real* domain (Lawani, 2021; Sayer, 2000). The *actual* domain lies below the surface and thereby exists whether it is being observed or not – but can be explored through observations and interviews (Stutchbury, 2022), as in this thesis. In contrast, the physical, social, psychological, or conceptual structures and mechanisms that constitute the *real* domain cannot be directly observed (Mingers & Standing, 2017; Sayer, 2000). This implies that the *real* domain, i.e., the structures that influence the *actual* and the *empirical* domains, must be understood through a process of retroduction. In practice, this means that the researcher should go back and forth between the collected empirical material and previous conceptual explanations of the studied phenomena; i.e., apply an iterative research approach, to enable identification of underlying structures and mechanisms that could help explain why an event unfolded in a particular way (Stutchbury, 2022). In doing so, researchers are able to relate events studied in the empirical domain to the actual and real domains, which requires researchers to develop and test conceptual explanations of causality. This ultimately allows for theory development as it is possible for the researcher to revisit and reconfigure existing theories and concepts (Maxwell, 2012). For example, in Study 2, the *empirical* and *actual* domains have been explored through interviews discussing respondents' views on how certain (combinations of) policy instruments have provided (dis-)incentives for investments in particular propulsion technologies. Through retroduction, these explorations have contributed to identification of underlying structures in the *real* domain that relates to the shipping industry's strong global regime, thereby contributing to advancing our conceptual and empirical understanding of socio-technical change in sectors with strong global regimes.

The critical realist view of causality differs from alternative, more deterministic perspectives in other philosophies of science in that causality is not seen as equal to regularity of events. Rather, causality is associated with the causal powers of the structures and mechanisms in the *real* domain as well as human agency (Sayer, 2000). It is furthermore argued that underlying structures and mechanisms are context dependent, implying that they will be different across time and space, and that the same causal powers will not always lead to the same effect in different contexts (Reed, 2005). In addition, the critical realist approach highlights the subjectivity in the identification and assessment of causal mechanisms, as this is dependent on the researcher's interpretation (Stutchbury, 2022). Although critical realism does not stipulate using certain methods, Sayer (2000) argues strongly that qualitative methods are well-suited for critical realist research. He highlights that the intensive nature of qualitative work is favourable for abstraction of causal mechanisms and developing a further understanding of how certain objects or events occur in specific places.

Research Design

My research takes a predominantly qualitative starting point, complemented by quantitative elements; the main research design includes document analysis, semi-structured interviews, and participant observations in various combinations in the three studies and the papers included in the thesis (see Table 1 for an overview).

The predominantly qualitative approach was chosen as it allows for in-depth analysis of (ongoing) change processes (Sayer, 1992), as well as utilising an iterative research approach which can contribute to theory development (Sayer, 1992, 2000).

Table 1 Overview of methods and material for the three empirical studies included in the thesis

	Study 1	Study 2	Study 3
Researchers	GREENFLEET Research team	H. Bach & T. Hansen	H. Bach
Empirical context	Biofuel implementation in the Norwegian coastal shipping sector	IMO's global policy mix regulating emissions to air from international shipping	Multi-national bottom-up sail cargo initiatives operating internationally
Conceptual frame	Technological Innovation Systems	Policy mix characteristics	Grassroots innovations for sustainability transitions
Methods and material	74 semi-structured interviews with shipowners, shipyards, technology suppliers, public agencies, and local governments; average length 70 minutes (range 25-120 mins) Firm survey including 334 Norwegian shipowners surveying their priorities and expectations regarding implementation of more sustainable propulsion technologies Bibliometric analysis of Norwegian publications covering novel propulsion technologies Patent analysis of patents related to novel propulsion technologies acquired by actors related to the Norwegian coastal shipping sector Document analysis of European funded R&D projects related to alternative propulsion technologies and the Norwegian coastal shipping sector	8 semi-structured interviews with shipowners, shipowner associations, national maritime authority, classification society and the IMO; average length 60 mins (range 49-93 mins) 16 legislative text and policy documents Observations from 24 webinars and industry conferences	19 semi-structured interviews with founders and members of grassroots innovation initiatives, cargo costumers, and intermediaries; average length 62 mins (range 19-166 mins) 10 field visits in combination with interviews and including unstructured field observations 85 texts including blog entries, reports, press releases, newsletters and news articles Digital observations of social media posts

Study 1: Biofuel implementation in Norwegian coastal shipping

The first study for this thesis is a case study of technology implementation in the Norwegian coastal shipping sector, which provides the basis for Paper III. The study is part of a larger study conducted within the research project *Greening the Fleet – Sustainability transitions in the maritime shipping* sector *(GREENFLEET).* The larger study was initiated in 2015 and ran until 2020, I began my involvement in the project in January 2019.

Case selection

This study zooms in on the Norwegian coastal shipping sector to investigate the status of implementation of four alternative propulsion solutions: biodiesel, LBG, battery-electric and hydrogen. The exploration of the first two of these technologies – biodiesel and LBG – forms the basis of Paper III; the others are reported on in other publications by the project team (see Bach et al., 2020; Steen et al., 2019). Applying a TIS perspective, Paper III presents assessments of the status of implementation of biodiesel and LBG, respectively. Following their high GHG emission reduction ambitions in public policy, as well as work to implement alternative propulsion technologies, certain countries such as Norway and Denmark are considered front-runner countries for the shift to sustainable shipping. For example, the Norwegian government has set a national 50% GHG emissions reduction (compared to 2005) target for maritime transport by 2030, whereas the IMO at the time of the study only aimed for a 50% reduction (compared to 2008) by 2050.[2] To reach their targets, the Norwegian government has also implemented policy instruments to support innovation and implementation of alternative, more sustainable propulsion technologies. This national context, therefore, offers the opportunity to study ongoing technology innovation and implementation processes that can contribute to knowledge building and potentially accelerate similar transitions in other regions or globally.

Furthermore, studying the implementation status of biofuels (biodiesel and LBG) offers the opportunity to explore sectoral cross-technology externalities stemming from technological alignment with their fossil fuel equivalents (different forms of marine diesel oils and LNG). Biofuels are believed to play an important role (at least short-term) in reducing GHG emissions from the maritime shipping sector and have been forecasted to amount to around 20% of the future fuel mix for international shipping (DNV GL, 2019; Kirstein et al., 2018); therefore it is important to explore processes around their implementation and how this relates to structures surrounding existing technologies. Through exploration of positive and negative externalities for different aspects of the two respective TISs, the study provides

[2] As part of the revision of the IMO GHG Strategy presented in July 2023, the emission reduction targets were revised and now aims for net-zero GHG emissions by or around 2050 (IMO, 2023).

further insight into the connection between emerging and existing technologies in innovation processes related to sustainability transitions.

Data collection

The main material for the first study consists of interview data from 74 semi-structured interviews performed over four years (2015-2019), of which 17 interviews in particular have informed the findings in Paper III. Most of the larger sample of interviews covered a broad range of topics related to implementation of low- and zero-carbon propulsion technologies in Norwegian coastal shipping in general, while 4 interviews were specifically focused on biofuels, and 13 interviews covered multiple technologies including biofuels. Following a purposive sampling approach, a broad variety of senior level representatives of key actors within the Norwegian coastal shipping sector were approached. The main advantage of purposive sampling is the opportunity to target key informants with specialist knowledge and experience, enabling the collection of relevant empirical material. However, this sampling approach has a subjective element, as it relies on researcher assessment of the relevance of potential interview respondents, as well as snowball referral from other respondents. This may result in biased material, impacting the research quality negatively (Crouse & Lowe, 2018; Oliver, 2006). To reduce the risk of bias and its potential impact on the validity to of the research, it is recommended to perform triangulation between multiple sources of empirical material (Maxwell, 2012). In Paper III, the interview data were therefore supplemented by and triangulated with additional sources of material: (1) a bibliometric analysis of Norwegian publications covering novel propulsion technologies (Heiberg, 2017a); (2) an analysis of EU funded research and development (R&D) projects between 1998 and 2017 (Tsouri, 2018); (3) an analysis of patents applied for biofuel related technology by Norwegian actors (Heiberg, 2017b); as well as (4) a firm survey answered by representatives from 334 Norwegian shipowners that was conducted as part of the larger study (see Appendix A). While all these sources shed light on the structural dimensions and functions within the biofuel TISs, the bibliometric analysis and patent analysis were specifically performed to identify crucial actors and networks that influence activities related to two TIS functions; knowledge development and diffusion, as well as the direction of search.

The final set of interviewees included representatives from firms (e.g., shipowners, shipyards, ship designers, technology suppliers, and fuel producers), public agencies, interest organisations, research institutes, universities, and non-governmental organisations that represent all aspects of the socio-technical systems for the respective biofuels (see Appendix A for a full list of interview respondents). The respondents representing firms were typically CEOs, CTOs or managers responsible for research and innovations and/or business development. Additional interviews with experts on specific technologies and/or standardisation processes were conducted with representatives from research and development institutions and knowledge-intensive business services (e.g., consultancies). Respondents from public agencies were managers of public support programs or public transport services, while representatives for NGOs and industry associations were mainly directors and/or managers responsible for the maritime sector or a specific propulsion technology. Of the 17 interviews that have especially informed the findings in Paper III, 3 were conducted with public support agencies, 2 with other public organisations, 1 with an industry association, 2 with fuel producers, 1 with a technology supplier, 2 with R&D institutions, 1 with a ship-designer, as well as with 5 shipowners.

The interviews were conducted by my co-authors for Paper III and other colleagues in the GREENFLEET research team from 2015-2019, and during most of the interviews two or three researchers were present. The majority of the interviews were conducted in person while some interviews took place over telephone or online meetings, especially in the later stages of data collection. The length of the interviews varied from 25 to 120 minutes and averaged 70 minutes. All informants were given information about the purpose of the research and notified that their answers would be anonymised in interview requests sent via email. Following acceptance of interview requests, respondents were asked for consent to record and transcribe the interview. Semi-structured interview guides based on the TIS analytic framework, were prepared and tailored to each type of key actor interviewed (see Appendix A for an example). While allowing flexibility for preparation of context-sensitive interview guides, semi-structured interviews still follow a similar structure, which ensures collection of comparable material for the study (Roulston & Choi, 2018). The conversational nature and openness of semi-structured interviews provides benefits such as enabling interview respondents to elaborate on their experiences and insights in great detail, as well as creating space for the respondent to expand on unforeseen interesting topics. Furthermore, semi-structured interviews allow the researcher to ask spontaneous follow-up questions during the interview, contributing to more in-depth answers from the respondents (Valentine, 2005).

Furthermore, the interview guides were updated during the project as new insights were gained and additional questions arose. After the main round of interviews were concluded in October 2018, three further interviews were conducted during spring 2019 to gain additional insights on the current status of implementation of biofuels in the Norwegian coastal shipping sector, until saturation was achieved. Most of the interviews were recorded and later transcribed, and for interviews not recorded extensive notes were taken during and directly after the interviews. Depending on the language preference of the international research team, interviews were conducted in either Norwegian or English.

Process of analysis

Once transcribed, the interview material was manually coded according to the categories (TIS functions) in the analytical framework as well as by technology type (biodiesel and LBG) in the coding software NVivo. Several researchers in the GREENFLEET team participated in coding of the interview material, and to ensure consistency in coding within the team, an elaborate descriptive code book (see Appendix A) was developed and used to support coding by individual researchers. Furthermore, a pilot round of at least two researchers coding the same sample of interview material was conducted to compare coding between researchers in order to ensure validity and avoidance of definitional drift (Saldaña, 2009), which revealed a high consistency, and further coding was therefore divided among the researchers to be coded individually. For Paper III, I was specifically responsible for the empirical analysis, which included extraction of relevant empirical material relating to the paper's focus from the coded material for the larger study as well as analysis of this material. Although most of the relevant coded material was in Norwegian, I felt comfortable taking the lead on the empirical analysis given the similarities between Norwegian and my native language (Swedish) and previous experience from working with Norwegian colleagues. In case of uncertainty regarding how to interpret proverbs or other sentiments, I was supported by Norwegian-speaking project members.

The first step in the analysis was to make assessments of the current status of six TIS functions; knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation, market formation, legitimation and resource mobilisation. Based on a combination of the data sources mentioned above, all of us authors discussed the strengths and weaknesses of each TIS function until we arrived at a consensus, and ultimately appointed each TIS function a score on a three-point ordinal scale (weak – intermediate – strong). Thereafter, the second step of the analysis included exploration of positive and negative externalities for each TIS function. Insights from these analyses were thereafter combined to make an overall assessment of the implementation status for biodiesel and LBG in Norwegian coastal shipping, as well as the influence of positive and negative externalities connected with technological alignment between biofuels and their fossil fuel equivalents on biofuels innovation and implementation in this sector (see Table 2 for an illustrative example).

Table 2 Illustrative example of functional analysis and identification of externalities regarding the TIS function 'Resource mobilisation'

	Biodiesel TIS	*LBG TIS*
Strengths	Previous public co-funding for biodiesel operations of car- and passenger road ferry	Public funding support for gas engines, LBG production and infrastructure available from most public support agencies (although focused on road transport sector) Long-term contracts between shipowners and fuel producers reduce risk for upscaling LBG production and secures fuel availability
Weaknesses	Currently excluded from public funding support for sustainable fuels due to low sustainability score Uncertain fuel availability Higher fuel price than fossil diesel	Although eligible for public funding support and green public procurement, LBG often disfavoured due to lower sustainability score than battery-electric and hydrogen propulsion solutions Higher fuel price than LNG
Functionality assessment	Weak	Intermediate
Sectoral cross-technology externalities	Potential to use existing distribution infrastructure, however very limited availability of biodiesel in ports currently	Uses part of existing distribution infrastructure Take advantage of existing technological knowledge bases for LNG Recent entry of large established firms increases investments in LBG production and implementation
Effect from externalities	Neutral effect	Minor positive effect

Study 2: The International Maritime Organisation's global policy mix

Partly in parallel with study 1, in the late autumn of 2020 I initiated a second study on the global policy mix regulating emissions to air from international shipping implemented by the IMO, which provides the basis for Papers I and II in this thesis.

Case selection

Given that maritime shipping is an inherently global industry, it is crucial to understand policy making dynamics within international shipping's main regulatory body; the IMO, as well as the influence of the development of the regulatory framework (i.e., policy mix) that governs emissions to air from international shipping on implementation of alternative, more sustainable propulsion technologies. The second study in this thesis, therefore, explores the consistency and comprehensiveness of the IMO's global policy mix, as well as dynamics in the policy making processes which hinder implementation of stricter GHG regulation.

Since the majority of the ships in the global fleet[3] constantly have to comply with policy instruments implemented by the IMO, this international policy mix provides the main regulatory setting for the maritime shipping sector. Considering that this has contributed to standardisation of infrastructures such as port facilities and fuel supply as well as institutionalisation of norms and practices, this indicates that the shipping sector has a strong global regime.

Similar to sustainability transitions research in general, previous research on policy mix characteristics has been empirically focused on national policy mixes through national or regional case studies. The global scope of the IMO's policy mix offers a novel empirical focus for policy mix research, as well as the opportunity to study regulatory challenges in sectors with strong global regimes. A sole main regulatory body can be assumed to be able to implement a consistent and comprehensive policy mix, and the IMO's global policy mix therefore provides an interesting case for exploring policy mix characteristics. Previously implemented international regulations on air polluting substances has proven to be very effective, considering for example the 77% reduction in sulphur oxide emissions since the implementation of a sulphur cap for ship fuels in 2020 (Ovcina Mandra, 2022). This implies that effective international regulation of GHG emissions implemented by the IMO could be a strong driver for the shift to sustainable shipping.

Data collection

The main material for the second study consists of participant observations, document analysis of policy documents and legislative texts, as well as semi-structured interviews with key actors. The document analysis is the main data source for Paper I, while the interview material provides the basis for Paper II. Leading up to the beginning of this study, I started to attend webinars and other industry events in order to gain an overview of recent technology developments in the shipping industry, as well as identify research gaps and find inspiration for paper ideas. In total, I attended 66 webinars and (mainly online) industry conferences between May 2020 and December 2022 (see Appendix B). These events were selected as they represent forums for debate within the sector, which attract a variety of actors involved in the maritime shipping sector. In addition to individual events, I followed multiple webinar series and reoccurring events, including a series covering different aspects of the shipping sector's green transition hosted by the Swedish Shipowners Association, a webinar series on finance, innovation and transitions within the shipping sector hosted by the European Community Shipowners' Association, as well the annual meetings of the Danish and Swedish shipowners' associations. These webinar series provided an overview of current debates, as well as more

[3] Exceptions include military ships and ships smaller than 500 gross tonnes. The latter represents 1 % of the global cargo capacity and mainly operate within national waters (Equasis, 2022), implying that they may be subject to national emission reduction regulations.

in-depth details regarding certain aspects of the shift to more sustainable propulsion technologies.

Later in the study these *participant observations* were also used to identify key actors to invite to interviews, as well as triangulation and validation of findings from document analysis (Maxwell, 2012; Oliver, 2006). The attended events were organised by a wide range of industry actors, including, for example, classification societies, shipowner associations and maritime competence centres. Presenters and audiences represented a broad variety of actors relating to different elements of the shipping sector's socio-technical system, including fuel producers, technology suppliers, crew members working on ships and policy makers, in addition to the actors mentioned above. This provided the opportunity to observe the interaction between the presenters and the audience, for example during Q&A sessions, as well as formed a good basis for identification of potential interview respondents given the diversity of actors. Given that the first part of the study was conducted in a time characterised by lockdowns and remote working due to the Covid-19 pandemic, the majority of these events were held online, which had the advantage that some, mainly international, events that would have been difficult to attend in person due to time and financial constraints were now accessible for free or a low cost. Although the online format of the majority of the events prohibited extensive networking with other participants, noting down the presenters and participants allowed for identification of key actors to approach with interview requests for this second study. Once the world started to open up again, I also participated in a few in-person events, including a three-day international combined academic and industry conference in Copenhagen and a one-day event in Gothenburg organised by the Swedish Shipowner's Association. Lunch and coffee breaks during these events allowed for informal conversations with other participants, where I could ask questions, share what I was working on and listen to their reflections on the topic of the presentations we had just heard.

During and closely after the events I took notes regarding both the content of different presentations, and reflections on questions that I found intriguing, potential research gaps and other ideas for my own research (also beyond this second study). I also saved presentation slides if they were made available, and in the later stages of the study, presentation slides and notes from relevant industry webinars and conferences covering insights regarding policy processes at the IMO were used to triangulate and validate the findings from the document analysis of policy documents and legislative texts in Paper I. For example, a series of webinars hosted by a classification society presenting summaries and analysis of the latest IMO negotiations and new regulations was particularly helpful for analysis of the newer policy instruments targeting GHG emissions. The collected observations ensured that the analysis covered all policy instruments as well as policy objectives implemented by the IMO, and that the interpretation of the function and type of policy instruments (economic, regulatory or soft instruments targeting specific creative and destructive processes) was accurate. Furthermore, in combination with data from interviews, observations of events hosted by shipowner associations and maritime competence centres particularly informed insights into the technology implications of the implemented policy mix throughout different time periods.

The second source of data for study 2 is a *document analysis* that was initiated in November 2020, which provides the core data for Paper I. The main purpose of the document analysis was to identify and map policy mix elements (policy instruments and policy objectives in strategic documents) and outline timelines for the implementation of policy instruments, as well as developments in the policy strategy throughout three time periods (2004-2011, 2012-2017, and 2018-2023). Identification of policy instruments was made through analysis of the full length of legislative texts in MARPOL Annex VI, which regulates prevention of air pollution from ships, as well as resolutions and amendments to the different chapters of MARPOL Annex VI since its implementation in 2005. This was furthermore triangulated with summaries and interpretation of these legislative texts published by IMO member states. The analysis of the development of policy objectives for the IMO's policy strategy was based on various strategic documents published by the IMO, including for example High-Level Action Plans that were published every two years, Strategic Plans for the Organization published every six years, as well as the IMO Initial GHG Strategy published in 2018 (see Appendix B).

Finally, seven *semi-structured interviews* were conducted in order to gain insights regarding the technology implications of the development of the policy mix throughout the three time periods, as well as to triangulate and validate the findings from the document analysis for Paper I. Furthermore, the interviews provide the core data for the analysis of policy making challenges at IMO level presented in Paper II. The interviews took place during a two-week period in June 2021, directly after the 76th MEPC meeting, during which the first short-term measures for GHG reduction were added to MARPOL Annex VI. For two of the interviews, I was accompanied by my co-author, while I conducted the remaining five interviews myself due to time constraints.

Following a purposive sampling approach, eight[4] interview respondents in total participated in the study, all identified during the previously described participant observations. The respondents included the Secretary General of the International Chamber of Shipping (an international shipowner association), a principal consultant for international regulatory affairs at the Norwegian classification society DNV, the international liaison officer for climate and marine environment at the Swedish Transport Agency, and the senior policy advisor for safety and climate at the Swedish Shipowners' Association. Furthermore, a technical officer from the

[4] One of the interviews included two respondents from the same organisation that were experts in regulation of air polluting substances and GHGs respectively.

Marine Environment Division at the IMO secretariat as well as three shipowner representatives were also interviewed. The interviews with the three Swedish-speaking respondents were conducted in Swedish, while the remainder of the interviews were conducted in English. Although both my co-author and I speak or understand Danish and Norwegian, interviews with Danish and Norwegian respondents were conducted in English to avoid the risk of misinterpretation during the interviews and when transcribing them (which I performed). This implies that Swedish speaking respondents, and the native English speaker, had the advantage of speaking their native language during the interview, potentially allowing for more in-depth or nuanced answers. However, given the fact that the other respondents work in an international context, the risk for language limitations during interviews conducted in English was perceived as minor. The length of the interviews ranged from 49 to 93 minutes, with an average length of 60 minutes. Based on recordings of the interviews, respondents' replies were transcribed to allow for manual coding, which is further described in the next section.

All informants were initially approached with an email stating that the purpose of the research was to explore the development and effects of IMO regulation of air pollution and GHG, and that the interviews would complement document analysis of policy instruments and processes. To ensure that we reached respondents with the right competences, the interview request also included a description of the key themes that were covered by the interview questions. Upon accepting the interview request, the respondents were also asked for consent to record and transcribe the interview, which all respondents agreed to. Information about the project and confirmation of the respondent's consent to participate in the study and the recording of the interview were repeated during the beginning of each interview. The respondents were given the option of being anonymised in publications based on the study; however, all respondents agreed to be introduced by title and organisation. Furthermore, direct quotes from interviews that are included in the final versions of the papers have been approved by the respective interview respondents. Although interview requests were in some cases forwarded to someone else within the organisation other than our initial contact person, all approached organisations except for one agreed to be part of the study. The key persons targeted for interviews typically held office jobs and were easy to approach by email to set up online interviews (due to the Covid-19 pandemic). Although there was limited small talk and other possibilities for icebreaker activities, given that home offices and digital meetings were well institutionalised at this time, I experienced that the interviews went well. The interviews followed semi-structured interview guides that were partly tailored to the specific type of actor interviewed, and focused, for example, on the policy processes surrounding IMO negotiations, how the current policy mix had influenced decision making for shipowners, and if they saw any specific propulsion technology being (indirectly) favoured by the current policy mix (see Appendix B for the full interview guide). Furthermore, as preparation for the interview, the participants received an email a few days before, containing figures showing timelines for the implementation of policy objectives and instruments since 2005 (see Appendix B). These figures functioned as prompts as they were also shared on the screen during the interviews, and in relation to this, questions were asked regarding the balance between regulation aimed at air pollution vs. climate change mitigation, whether they could identify particular turning points in the development of regulation, and the extensiveness and consistency of the current policy mix. Furthermore, these figures offered an opportunity for triangulation and validation of the findings from the document analysis since the respondents were asked if they thought any policy instruments or themes for the policy strategy were missing. Given that the focus for the study covers a nearly 20-year period, it was important to acknowledge that interview respondents might struggle to remember events that happened years ago. My perception is that anchoring the discussion in the two figures as prompts contributed to refreshing the respondents' memories, contributing to historical validity (Budach, 2012). Some of the respondents also commented on the function of the prompt: "*Looking at this, I come to think of that the sulphur rules for our emission control area in 2015 had a much larger impact on our operational costs than the newest global rules implemented in 2020*" as one of the shipowner representatives expressed during the interview. In addition, the prompts also gave structure to the interviews which contributed to a good flow in the conversations.

Process of analysis

Processing of data was conducted in two steps. First, the document analysis was completed through manual coding of all documents based on a prepared code book in Nvivo, and thereafter followed coding of the transcribed interview material based on the conceptual framework for Paper I, as well as inductive coding of key themes identified in the transcribed interview material (which has mainly informed Paper II). The coding was performed by me, with support from discussions with my co-author. With regard to the document analysis, the purpose of the coding was to identify the type of policy instruments that were included in the instrument mix, and the code book (see Appendix B) was based on the conceptual framework presented in Paper I. Given that previous operationalisations of policy mix characteristics are scarce, it became increasingly clear during the coding process that these previous operationalisations were insufficient to understand the complexity of the consistency and comprehensiveness of the IMO's global policy mix. Paper I therefore provides suggestions for further operationalisation of policy mix consistency and comprehensiveness that are based on insights from the coding process, representing an iterative research process (Merriam, 1998). Taking an iterative approach allows the researcher to go back and forth between theory and the collected empirical material to develop a comprehensive understanding of the study object (Alvesson et al., 2022; Srivastava & Hopwood, 2009). This furthermore enables identification of potential differences between theoretical assumptions and the studied empirical case which can inform theory development (Alvesson & Kärreman, 2011).

Based on the code book, each statement concerning specific policy instruments was coded with the implementation year, the type of air emission the instrument is regulating (air polluting substances and GHGs) and the type of policy instrument (regulatory, economic or soft instrument, targeting creative or destructive processes). Furthermore, to enable assessment of the instrument mix consistency, statements were coded as to whether they indicated existing synergies or conflicts with other policy instruments at the time of their implementation, as well as if the instrument was a replacement or addition to an existing instrument. A similar process was applied to identification of policy objectives, where statements in strategy documents were coded with the policy topic(s) (air pollution vs. climate change mitigation) covered, as well as the degree of concretisation of the policy objective to assessment of the comprehensiveness of the policy strategy. In addition, similar to the instrument mix, statements indicating existing synergies or conflicts between policy objectives were coded. Through extraction from the coded material, a database with all identified policy instruments and policy objectives was created, in which the coded information for each policy instrument and objective is presented in a collected way. Based on discussions with my co-author, some of the assessments were calibrated. Coding of the interview material also followed the same code book as the coding of policy elements, in order to triangulate the findings from the document analysis as well as to gain further insights into the technology implications of specific instruments. In addition, inductive coding of key themes relating to policy processes and challenges for policy making at IMO level was performed, which provides the core data for Paper II.

Study 3: Sail cargo initiatives as nomadic grassroots innovations

The third and final study of this thesis was initiated during the spring of 2022, and was conducted through participant observations, semi-structured interviews and document analysis. Drawing inspiration from digital ethnography approaches, the study furthermore includes analysis of social media posts and newsletters issued by nine sail cargo initiatives.

Case selection

Throughout the first and second study, it became increasingly clear to me that it will take time before regulation becomes a strong driver in the shift to sustainable shipping. From this realisation, a curiosity about what could be the most radical alternative grew increasingly strong, and given the urgency of decarbonisation of the international shipping industry I decided that I wanted to contrast the top-down pressures from policy identified in the first two studies with bottom-up initiatives that have decarbonisation ambitions beyond regulatory requirements. I first heard of traditional sail cargo initiatives, which is the empirical focus of Study 3 and Paper IV, through a social media post in 2016 where the new owners of the traditional sailing ship Hawila, which used to be owned by the sail training association I was previously involved in, announced their plans to convert the ship from a sail training (passenger) ship back to its original purpose as a sailing cargo ship. Since then, I have followed that sail cargo initiative sporadically and at the time of the initiation of this third study during early spring 2022, I drew inspiration from methodological approaches within digital ethnography (Coleman, 2010; Hampton, 2017; Ulmer & Cohen, 2016) and identified further sail cargo initiatives through a snowball approach, by going through the social media followers of the first identified sail cargo initiative.

Based on this exploration, I identified 15 sail cargo initiatives at different stages, ranging from recently initiated or still renovating or building their sail cargo ships, to already operating. Out of these 15 initiatives, 6 were basing their operations on very small ships with extremely limited cargo capacity only operating in coastal areas or rivers, or mainly operating as passenger vessels while also taking a small amount of cargo on board. A decision was therefore made to focus on the nine remaining initiatives, which have a clearer focus on cargo operations and are, or are planning to, operate internationally. These nine initiatives all have ships with a cargo capacity larger than 35 gross tonnes (see Figure 7), which, compared to conventional cargo ships, is equivalent to a handful of standard 20-foot shipping containers.

Figure 7 Sail cargo ship De Tukker (built 1912) in Den Helder, the Netherlands, June 2023
Photo: Hanna Bach

Although it took time and effort to reach the selected nine sail cargo initiatives due to limited access to internet when they are sailing, all of them finally agreed to be part of the study. In addition to exploring on-going processes, the study takes an historical perspective and analyses development of sail cargo initiatives in three stages: initiation, operations, and upscaling and diversification. The initiatives are currently in various stages, four are in the initiation phase and constructing or renovating sail cargo ships, while five initiatives are already operating.

Study 3 uses the conceptual lens of grassroots innovations to explore drivers of and barriers to the development of sail cargo initiatives. Previous research on grassroots innovations have been focused on place-based initiatives such as transition towns, energy communities or maker spaces, and there are very few examples of studies of grassroots innovations in the transport sector. Furthermore, previous studies lack insight regarding the global aspects of grassroots innovation and non-place-based conditions that influence the development of grassroots initiatives. Exploring sail cargo initiatives therefore offers the opportunity to study a novel empirical context for grassroots innovations research, which contributes to insights regarding grassroots innovations relating to international sectors with strong global regimes as well as the factors that influence development of grassroots initiatives beyond place-specific conditions.

Data collection

The main material for study 3 was collected through digital and participant observations, semi-structured interviews, and document analysis. These material sources were combined in the analysis (described in the next section). At the beginning of the study, material was mainly collected through *digital observations* of the initiatives' social media accounts (primarily Instagram), as mentioned above, initially for identifying sail cargo initiatives, and later on also to get an overview of the initiatives' activities and structures. In addition, listening to interviews with representatives from sail cargo initiatives in various podcasts, as well as watching videos from sail cargo initiative's YouTube channels, TED Talks, etc. also contributed to increasing my understanding of the development of sail cargo initiatives, and allowed for identification of potential interview respondents. Furthermore, continuously collecting *documents* such as newsletters, blog entries and social media posts as well as news articles, business plans and life cycle analysis reports, etc. allowed for gaining an historical perspective on the development of the initiatives and their progress during the course of the study. This material was later also utilised for triangulation and validation of field observations and interview data.

I have also conducted unstructured *observations in the physical field*, in combination with conducting interviews with key representatives from sail cargo initiatives and other key actors such as cargo costumers. Field visits were conducted in June, July and August 2022 as well as in June and November 2023, and include observations of cargo off-loading, preparations for departure for the upcoming trans-Atlantic cargo run, visits to cargo costumers (restaurant and chocolate factory) and renovation activities at shipyards (see Table 3). Field observations contributed to gaining further understanding of the sail cargo initiatives' everyday operations and the opportunities and challenges related to this.

Table 3 Overview of interviews and field observations for Study 3

	Interviews	Field observations
Sail cargo initiatives		
Blue Schooner Company	Captain/founder, online, September 2023	-
Brigantes	Founder + manager of café and coffee roastery, at shipyard and café, November 2023	Renovation of ship at shipyard and tour of the Brigantes café and coffee roastery in Trapani, Sicily November 2023
Fairtransport	Captain/co-founder + 3 crew members, on board ship, June 2022	Cargo off-loading in Copenhagen, June 2022 + observations of market stand for their own products during traditional sail ships festival in their home port Den Helder, the Netherlands, June 2023
EcoClipper	Captain/founder, at shipyard July 2022 + on board ship June 2023	Renovation of the activities at shipyard in Franeker, the Netherlands in July 2022 + promotional activities at traditional sail ships festival in their home port Den Helder, the Netherlands, June 2023
Kaap Kargo	Co-founder, on board June 2023	Preparations of the ship for departure at forthcoming sail cargo hub harbour in central Amsterdam, the Netherlands, June 2023
Les Frères de la Côte	Founder, on board June 2023	Renovation of the ship in forthcoming sail cargo hub harbour in central Amsterdam, the Netherlands, June 2023
Hawila Project	Co-founder/captain, Lund University, November 2023	Two-day learning camp focused on sustainable travel and cargo shipping including tour of the ship (under renovation), shipyard and other key infrastructure in Holbæk, Denmark, September 2023
Sailcargo Inc.	Co-founder + two crew members, July 2022	Renovation of the ship in Harlingen, the Netherlands, July 2022
Timbercoast	Captain/founder, on board ship, August 2022 + follow-up interview online May 2023	Preparations of the ship for departure in Hamburg, Germany
Cargo costumers		
Chocolate Makers	Director/co-founder, at factory, June 2023	Chocolate factory tour in Amsterdam, June 2023
New Dawn Traders	Director/founder, online, May 2023	-
Sabotøren	Manager, at restaurant, June 2022	Cargo off-loading and visit to restaurant in Copenhagen, June 2022
Educational institute		
Enkhuizen Nautical College	Director, online, July 2023	-

In human geography research, observations are considered important to reveal patterns of human-environment interactions (Watson & Till, 2018). Given that one aim of the study was to explore the spatiality of factors that influence the development of sail cargo initiatives, these observations allowed for informal conversations with other crew members during tours of the ships, observations of how crew members interacted with each other, cargo costumers and other actors in different places (in the paper conceptualised as home and host localities[5]), which contributed to increasing my understanding of what the sail cargo initiatives need from these different places to enable their development. Observing infrastructure in ports and shipyards (see Figure 8) furthermore provided the opportunity to observe how well aligned the infrastructure was to sail cargo operations and how potential challenges were solved. During and directly after the field visits, I wrote extensive notes reflecting on both the content of interviews and informal conversations, as well as impressions from the observations, which were also complemented by photos taken during the visit (Byrne, 2021).

Figure 8 Traditional slipway in Holbæk, Denmark
Photo: Hanna Bach

Finally, in total 19 *semi-structured interviews* with key informants were conducted to further explore the development of sail cargo initiatives. In contrast to the two previous studies, key informants from the sail cargo initiatives explored in Paper IV spend most of their time working on the ships rather than in offices and are therefore off-grid for long periods of time. Hence, although initial contact was attempted by email, in many cases this did not yield any results. Instead, my first physical contact

[5] Home localities represent places where the ships have their physical home ports and the initiatives' offices are located, and host localities are the ports they return to for cargo operations or construction, renovation and maintenance of the ships.

with the sail cargo initiatives took place during an (semi-) unannounced[6] field visit to a cargo-offloading event in central Copenhagen (see Figure 9), which was advertised on social media. After first observing and thereafter participating in the cargo offloading, once the offloading was completed, I approached one of the crewmembers (identified by a t-shirt with the organisation's logo) who introduced me to the captain, who is also one of the founders of that sail cargo initiative, and he agreed to be interviewed on the spot. Thereafter followed some spontaneous snowball sampling, as it was suggested that I talk to other crew members, who agreed to interviews on the same day or later during their stay in Copenhagen.

Figure 9 Offloading of natural wine in central Copenhagen, Denmark, June 2022
Photo: Hanna Bach

During some of the other field visits, I also participated in maintenance work on board the ships and a climate action camp focused on sustainable transport and sail cargo, providing opportunities for informal conversations with various crew members which in addition to further enhancing my understanding also functioned as a trust building exercise. Having sailed on various traditional sailing ships between the age of 16 and 25, although in relation to sail training and not cargo, I came into this project with some previous knowledge about how these ships are operated. Taking part in everyday activities during field visits, and asking questions about the ship's technical systems and operational aspects during tours of the ship served as a good icebreaker and appears to have been beneficial with regard to building trust with interviewees. In some cases, the established trust based on my

[6] When talking to the captain it was revealed that he had received my email and thought that he had given me a positive reply to my interview request, however this had not reached me.

previous experience and network led to additional interviews beyond what was originally planned, as for example during the field visit to Sailcargo Inc.'s renovation of their newly acquired ship in Harlingen, the Netherlands, where I was approached by one of the crew members after informal conversations over lunch revealed that we had mutual connections to previous crew members. During the first field visits, I also obtained recommendations for who else to talk to within other sail cargo initiatives as well as access to phone numbers and personal email addresses to the recommended people, which was crucial for establishing contact with the other initiatives I visited during the study and for scheduling online interviews with the remaining initiatives. A similar pattern of combined purposive and snowball sampling occurred during other field visits, where I had one or two interviews planned beforehand, but was recommended other people to talk to once I was there, or even approached by those who were willing to be interviewed. Furthermore, I generally asked interviewees for contact details and recommendations regarding who they thought I should talk to within their own or other sail cargo initiatives, as well as cargo costumers and other actors.

Although establishing contact with the sail cargo initiatives was time consuming and took a lot of effort, the final interview sample include representatives from all nine identified sail cargo initiatives with ships with a larger cargo capacity than 35 gross tonnes. In total, I conducted 19 interviews in two stages, of which ten interviews were with co-founders or directors of sail cargo initiatives, five with crew members, and four with other actors such as representatives of cargo costumers and educational institutions. Two other representatives of cargo costumers were approached with interview requests multiple times but never replied. The nine interviews in the first stage (June to August 2022) were of an exploratory nature and in addition to identification of key challenges and opportunities for the development of sail cargo initiatives these interviews also allowed for identification of a suitable theoretical framing of the study. The exploratory interviews followed semi-structured interview guides that covered a variety of themes, such as the main drivers of and barriers to sail cargo operations, motivation for working with sail cargo, cooperation with other sail cargo initiatives, business models, regulation, access to financial and human resources, and the relation between sail cargo operations and conventional shipping (see Appendix C). The second round of interviews was conducted between May and November 2023, for which the interview guides were adopted to be more tailored to the conceptual framing of sail cargo initiatives as grassroots innovations. In addition to the initial themes, the updated version of the interview included questions more specifically focusing on the spatiality of the various factors that influence the development of sail cargo initiatives. In addition, to complement gaps in the initial interview material, I conducted follow-up interviews with two of the four initiatives interviewed during 2022. Most of the interviews (14) were conducted during field visits, while the remaining five were conducted through online meetings. Given the internationality of the interview respondents, all interviews were conducted in English, which is also the main working language for all sail cargo initiatives. The interviews ranged from 19 to 166 minutes long, with an average length of 62 minutes, and were recorded and later transcribed.

For interviews that were planned beforehand, the interview respondents received information about the research project and the purpose of the interview as well as my personal background as a tall ship sailor through emails, text messages, or short introductory phone calls. For the initial contact, I decided to be transparent about my personal background in the hope that this would contribute to gaining trust with individuals from the sail cargo community, which appears to have been a successful strategy. Upon acceptance of the interview request, the respondents were also asked for consent to record the interview to enable transcription, which they all agreed to. For spontaneous interviews, the interview respondents were instead given this information verbally before being asked for consent to be interviewed and recorded. All respondents were also asked for consent to include their title and organisation in the published research. Before starting planned interviews, the purpose and focus of the study was repeated, and all respondents were asked to repeat their consent to the interview once the recording had started. Given that the sail cargo community is a relatively small and tightly knit community, I was careful to point out that rather than identifying personal conflicts, rivalry between initiatives or relaying sensitive information to other initiatives, the main purpose of the study was to get different perspectives on the drivers and challenges for initiating and developing sail cargo initiatives, which would be synthesised in a research paper. I also stated differences between an interview with a journalist (something that most respondents were used to) and a researcher, to set appropriate expectations in terms of what the interview material would be used for as well as the timeline for publication. As a response to the participants' expressions of hope that my research would contribute to further recognition of sail cargo initiatives, I explained that the research would be accessibly for the public once published and that, if time allowed, I planned to do further dissemination of the research such as presentations at conferences. Finally, I also informed the respondents that direct quotes which were included in the final paper would be checked with them and that they would have the opportunity to indicate if I had interpreted them correctly.

Process of analysis

Study 3 followed an iterative and abductive research approach (Dubois & Gadde, 2002; Merriam, 1998) where the empirical material guided the identification of a suitable conceptual framing, as well as played a generative role in further conceptualisation of the geography of grassroots innovations (Alvesson & Kärreman, 2011; Clark, 1998). After transcription of the first round of exploratory interviews, there followed a period of reading a variety of sustainability transitions studies with different conceptual approaches to niche development. During this period, I continuously reflected on the empirical material as cases of different conceptualisations before arriving at grassroots innovation as the most suitable framework, given that I identified a research gap regarding the geography of grassroots innovations for which my exploration of the sail cargo initiatives could contribute with further understanding of the spatiality of factors influencing the development of grassroots innovations.

Following completion of the data collection, the interview material and the various text sources presented earlier were coded in Nvivo based on a code book developed from the analytical framework presented in Paper IV (see Appendix C). The main purpose of the analysis was to explore which socio-technical elements are needed for emergence and development of sail cargo initiatives as nomadic grassroots innovations, as well as the places and scales where these factors are present, throughout three stages of development (initiation, operations, and upscaling and diversification). Relevant statements were therefore coded to indicate which development stage(s) they referred to, the type of socio-technical element(s) that were mentioned, as well as the places and scales the socio-technical elements were present in. Given that the analysis revealed that the spatiality of factors needed for development of sail cargo initiatives differ from typical place-based grassroots innovations explored in previous research, the empirical material thereafter took a generative role in the development of a novel conceptualisation of sail cargo initiatives as a case of *nomadic* grassroots innovations.

Summary

Reflecting on the methodology

Studying on-going socio-technical change processes is challenging in multiple ways, but especially so given the slow speed of these processes and the uncertainty of how socio-technical change will unfold (Sovacool & Hess, 2017; Stirling, 2011). Furthermore, socio-technical change processes do not exist in a temporal vacuum, rather they are influenced by previous events, existing structures and actor networks, resulting in path-dependency. In order to take longitudinal aspects into account, all three studies in this thesis have a temporal element, exploring developments over several years.

Inevitably, every research project has limitations and shortcomings. Studies that extensively utilise interview data rely on the interview respondents' willingness to share their insights, and are exposed to potential bias given respondents' selective memory and personal interpretations of events. While interviewing additional or other types of actors may have resulted in different findings, especially for the second study, the balance between shared and individual perspectives in the interview material for the respective studies indicate a relevant sample of informants. Furthermore, to ensure a high level of credibility and validity in the findings, the studies are based on and triangulated with extensive empirical material collected through a combination of mainly qualitative methods. Moreover, I have collected empirical material throughout the entirety of the PhD project, which has contributed to a cumulative understanding of socio-technical change processes in the maritime shipping sector.

Overview of studies

Although the three studies have been presented in chronological order in this chapter, in the next chapter the findings and contributions of this thesis will be presented paper by paper in a thematic order. Papers I and II present findings from the second study of this thesis, Paper III is part of the first study, while Paper IV presents the results from Study 3 (see Figure 10). The papers are included in this thematic order to in the first two papers introduce the main, international regulatory context (implemented by the IMO) that provides top-down influence on socio-technical change in the global shipping sector. The third paper zooms in on the national level through a case study of Norwegian coastal shipping, which highlights technology implications from top-down policy interventions as well as bottom-up influences from niche technology developments. Finally, as a contrast to the highly institutionalised and slow processes within the conventional shipping sector, unconventional bottom-up initiatives in the form of grassroots innovations are explored through the case of traditional sail cargo initiatives.

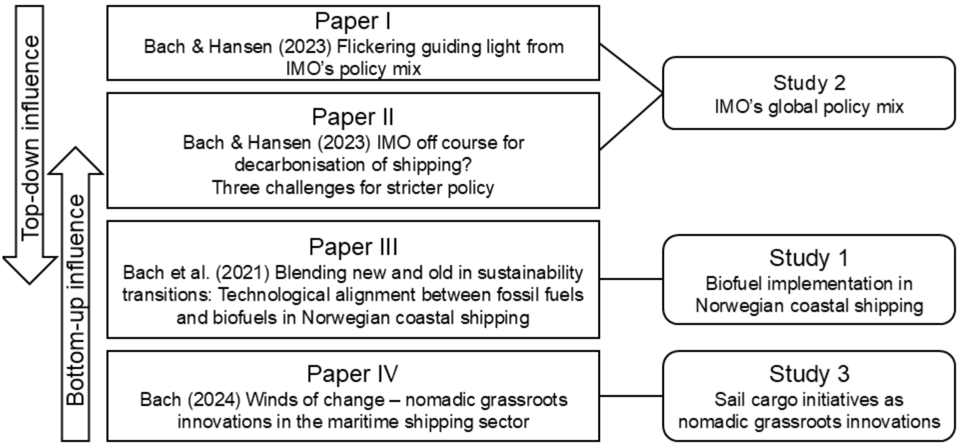

Figure 10 Overview of the four papers that are the outcomes of the three empircal studies included in the thesis

6. Findings and contributions

In this penultimate chapter of the thesis, I will discuss the findings and contributions from my research, reflect on the limitations of the project and suggest areas for future research. The chapter begins with an overview of the articles included in the thesis, presenting the main conceptual and empirical contributions of the individual papers. In the following section, the aggregated findings and contributions of the thesis are presented. Lastly, the chapter ends with reflections on the boundary conditions of the three studies included in this thesis and potential avenues for future research.

Overview of articles

Through the lens of policy mix characteristics, **Paper I** presents a temporal analysis of the consistency, i.e., how well different parts of the policy mix fits together, and comprehensiveness, i.e., how extensive the policy mix is, of the global policy mix targeting emissions to air from international shipping. The paper analyses the consistency and comprehensiveness of IMO's policy targets and regulatory framework (i.e., policy strategy and instrument mix constituting the global policy mix for international shipping), as well as the technology implications resulting from these characteristics, throughout three time periods (2004-2011, 2012-2017, 2018-2023). Our contribution to the policy mix literature through Paper I is twofold. First, following the limited previous empirical exploration of policy mix characteristics, we provide further conceptualisations of consistency and comprehensiveness, which we argue contributes to advancing the current understanding of the effectiveness of the policy mix. Second, the global policy mix regulating international shipping provides a novel empirical scope given that previous policy mix studies have only explored national level policy mixes.

Building on previous conceptualisations of policy mix characteristics, the paper aims to elaborate on the conceptualisations and operationalisation of consistency and comprehensiveness at the levels of instrument mix, policy strategy and the overall policy mix. Given the limited number of previous studies of policy mix characteristics and their impact on sustainability transitions, there is a need for further refinement of the conceptualisations of policy mix characteristics as well as additional empirical studies. Responding to this gap, we provide improved conceptualisations of consistency and comprehensiveness, highlighting the complexity in the relation between different levels of consistency and the importance of determining factors for the degree of comprehensiveness for all policy elements (instrument mix, policy strategy and overall policy mix). Regarding consistency: based on the empirical analysis we suggest that the fit between the instrument mix and policy strategy determines whether a high degree of consistency in the policy strategy and the instrument mix result in a high degree of consistency also in the overall policy mix. This differs from previous suggestions that strong consistency of the policy strategy and instrument mix contributes to a high degree of consistency for the overall policy mix (Rogge & Reichardt, 2016), and indicates the importance of analysing all parts of the policy mix rather than solely investigating policy instruments. Given the need for a diverse set of policy instruments to drive innovation and sustainability transitions, we bring in Kivimaa and Kern's (2016) typology of policy instruments targeting creative and destructive processes for assessment of the level of comprehensiveness of the instrument mix. In addition, previous research suggests that a balance between regulatory (based on laws and binding regulations), economic (provision of pecuniary incentives and disincentives) and soft (voluntary measures and information provision) policy instruments strengthens the effect of policy mixes. Following this, the comprehensiveness of the instrument mix is assessed based on the distribution of regulatory, economic and soft instruments, as well as the use of instruments targeting creative and destructive processes. We furthermore introduce the level of concretisation of policy objectives and the breadth of policy topics (the extent to which the policy strategy addresses all relevant themes given the analytical focus, for example all GHGs) in the assessment of the comprehensiveness of the policy strategy, suggesting that this contributes to a further understanding of the effectiveness of the policy mix. We argue that including an assessment of the level of concretisation of policy targets over time, such as a shift from generic to specific targets for GHG emissions reduction, contributes to further understanding of the comprehensiveness of the policy strategy as well as the overall policy mix. Finally, in addition to the level of concretisation of policy targets over time, we suggest that overall policy mix comprehensiveness is determined by the extent to which policy targets are addressed by a broad portfolio of policy instruments (regulatory, economic and soft instruments targeting both creative and destructive processes).

The empirical analysis, mainly based on document analysis which was complemented by and triangulated with participant observations and semi-structured interviews, shows that although it could be assumed that a sole main regulatory body such as the IMO should be able to implement a consistent and comprehensive policy mix, the IMO has failed to implement sufficient policy instruments to reach their own GHG emissions reduction targets. By applying the conceptual lens of policy mix characteristics to the global policy mix for decarbonisation of international shipping we can therefore highlight the shortcomings of global governance bodies such as the IMO. Following an historical focus on regulation of air polluting substances and the policy making challenges outlined in Paper II, the IMO's current overall policy mix lacks consistency and comprehensiveness, implying that policy measures that drive development and implementation of alternative, more sustainable propulsion technologies are missing. Given that it is possible to comply with current GHG emissions regulation without application of alternative propulsion solutions, the main technology implication of the current policy mix is a continued socio-technical lock-in around fossil fuels. This partly because of the continued use of conventional ship fuels such as heavy fuel oil, but also due to the increasing adoption of low-sulphur oil and LNG as ship fuels. Our findings therefore point to a need for implementation of stricter GHG emissions regulation through introduction of policy instruments providing economic incentives for decarbonisation and disincentives for the use of fossil fuels to balance the large number of regulatory instruments, such as R&D funding, emission trading schemes and feed-in tariffs. In addition, there is a need for a broader portfolio of instruments targeting creative and destructive processes, especially more disruptive instruments aimed at limiting the use of fossil fuels such as more stringent emission performance standards. Furthermore, the policy instruments within the existing regulatory framework, such as instruments targeting energy efficiency measures, needs to be updated to match with the level of ambition regarding GHG emissions reduction stated in the IMO's GHG strategy.

Building on the analysis of policy mix characteristics in Paper I, **Paper II** in this thesis further explores policy processes surrounding negotiations and implementation of climate mitigation policy at the IMO. The paper targets a broader audience beyond the sustainability transitions community, and the format of a 'short communication' paper allows for contributing to further empirical understanding of policy processes within the IMO as well as societal engagement explaining regulatory challenges for implementing stricter climate policy for the international shipping sector. Given that the GHG emissions from international shipping continuously increase, it is obvious that the IMO's efforts to regulate GHG emissions are insufficient and that they have failed to implement suitable policy instruments to achieve the emission reduction targets in the IMO GHG Strategy, as well as decarbonisation of the shipping industry in line with the Paris Agreement. Based mainly on interview data from the second study of the thesis, our findings pinpoint three main barriers to designing and implementing an effective, consistent, and comprehensive policy mix for the international shipping sector: lack of capacity within the IMO to regulate multiple and emerging technologies, uncertainty around the IMO's regulatory mandate, and lack of political consensus during negotiations. The paper thereby provides insights into how sectors with one main regulatory body are governed, and the findings highlight that, while it could be assumed that such regulatory bodies should have the capacity to implement consistent and comprehensive policy mixes, one should be careful not to overestimate this capability. Furthermore, our findings suggests that the regulatory capacity and mandates of the regulatory body as well as the character of decision-making processes has an impact on the effectiveness of the policy mix. This implies that if the IMO is to play a more progressive role in mitigating GHG emissions from international shipping, there is a need to consider reforming decision-making processes to implement policy instruments that ensure GHG emission reduction in line with current and future, more ambitious emission reduction targets.

In contrast to the attention to international policy in Paper I and Paper II, **Paper III** zooms in on national-level governance through the case of the coastal shipping sector in Norway. The paper analyses socio-technical challenges and opportunities for the implementation of biofuels, specifically biodiesel and LBG, as part of a sustainability transition within the maritime shipping sector. Through exploration of how the technological alignment between fossil fuels and biofuels, as well as the existing sectoral maritime context, impact the development of TISs for biodiesel and LBG in the Norwegian coastal shipping sector, the paper aims to contribute to the understanding of sectoral cross-technology externalities, meaning self-reinforcing mechanisms increasing or decreasing the attractiveness of a technology (Onufrey & Bergek, 2015), in relation to sustainability transitions. Furthermore, based on this exploration we provide a development of the TIS framework through discussing the effects of sectoral cross-technology externalities on the functionality of a TIS.

Applying the conceptual lens of TIS allows for comparative and extensive assessment of the key functions of the innovation system surrounding a specific technology in a certain geographical area or in general, which enables an overall assessment of the current status of technology implementation. In this paper, we explore two national TISs, for biodiesel and LBG, based on 17 interviews with key stakeholders such as shipowners, technology suppliers, shipyards and policy makers. The paper uses six TIS functions (*knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation, market formation, legitimation,* and *resource mobilisation*) developed by Bergek et al. (2008) and Hekkert et al. (2007) as the conceptual starting point. TIS functions represent different dimensions that influence innovation system development, and through assessment of the performance of the respective functions we can gain an understanding of these development processes and the overall functionality of the TIS. However, rather than analysing the seventh core function introduced by Bergek et al. (2008), *development of positive externalities*, as a separate function, we analyse the effect of positive and negative externalities stemming from the interchangeability between fossil fuels and biofuels on each of the six core functions. Given that technological capabilities, institutions, and physical infrastructures in a sector have developed along with and thereby been shaped by established conventional technologies, technological alignment between established and novel technologies in a certain sector may influence innovation in different ways. On the one hand, it is believed that alignment with existing technologies within a sector may have a positive impact on innovation (Dolata, 2009; A. Smith

& Raven, 2012), especially if interchangeability between technologies or fuels allows for using the same infrastructure or gradual drop-in of, as for example in this case, biodiesel into conventional fossil diesel. These positive externalities could thereby reduce the length of formative innovation phases and enable rapid implementation of novel technologies (Bento & Wilson, 2016). On the other hand, misalignment with conventional technologies may hinder establishment of radical novel technologies and result in a continued lock-in on fossil fuels, which constitutes negative externalities that hamper sustainability transitions (Dolata, 2009; Loorbach et al., 2010; A. Smith & Raven, 2012; Unruh, 2000).

Sectoral cross-technology externalities have been pointed out to have particular relevance for hard-to-abate sectors with high path-dependency, such as the maritime shipping sector (Dolata, 2009). However, our findings highlight that in the case of Norwegian coastal shipping, despite several positive externalities resulting from technological alignment, neither the biodiesel or LBG TISs have developed successfully. Instead, legitimacy concerns regarding upscaling potential and fuel costs are substantial barriers to implementation of biodiesel and LBG in the Norwegian coastal shipping sector. Furthermore, our analysis also reveals negative cross-technology externalities, such as competition with the road transport sector regarding fuel availability, and ineligibility for public financial support to cover increased fuel costs due to policy demands for zero emission propulsion technologies, which especially impact the biodiesel TIS. The paper thereby showcases how policy interventions at the national scale, such as green public procurement and emission standards, can further the development of specific technologies while hampering the development of others. In addition, Paper III contributes to further insights regarding the positive and negative externalities connected with technological alignment with conventional technologies, by showing that although there are positive externalities associated with a high degree of alignment and interchangeability with established technologies, these positive externalities do not always accelerate innovation and technology implementation. Rather, our findings indicate that "low-hanging" solutions which contribute to sustainability transitions may still not be adopted due to a general low performance of the TIS. This further indicates that other, more radical and transformative technologies or solutions may be favoured by policy makers and industry actors to be implemented instead.

In light of the insufficient policy incitements for driving decarbonisation of the maritime shipping sector, **Paper IV** explores decarbonisation initiatives at the community level through nine cases of sail cargo initiatives promoting a return to traditional sail cargo ships. Conceptualising these initiatives as grassroots innovations, the paper aims to contribute to a more nuanced understanding of the spatiality of grassroots innovation activities and thereby contribute to the literature on the geography of grassroots innovations, a recent yet under-researched theme in the grassroots innovations for sustainability transitions literature (Feola & Butt, 2017; Kratzer et al., 2022). This is done through empirical exploration of the spatiality and multi-scalarity of factors such as financial resources, access to infrastructure, policy and regulation, and networks of actors, that contribute to the development of sail cargo initiatives. Based on this exploration, a conceptualisation of *nomadic grassroots innovations* is developed, suggesting that nomadic grassroots innovations differ from place-based grassroots innovations in that they are anchored in multiple places conceptualised as *host localities*, to which they return to perform their main activities, while also being based in *home localities* where, for example, offices and key infrastructure are located.

Maritime shipping provides a novel empirical context for grassroots innovations research, which allows for a broader perspective on grassroots innovation activities. In previous literature, grassroots innovations are seen as place-based phenomena, locally rooted in specific places, implying that they are difficult to diffuse to other places given their dependence on place-specific conditions (Håkansson, 2017; Kratzer et al., 2022). Following this, Paper IV aims to gain an understanding of how nomadic characteristics impact the development, upscaling and diffusion of grassroots initiatives, and how place-based grassroots innovations can adopt nomadic characteristics to overcome diffusion challenges related to place-specificity. Based on field observations, semi-structured interviews with key stakeholders and document analysis, the paper investigates the spatiality of factors impacting development of sail cargo initiatives throughout three stages (initiation, operations, and upscaling and diffusion). The findings suggest that the spatiality of sail cargo initiatives differs from place-based grassroots innovations throughout all stages of development given that they are anchored in multiple places and depend on socio-technical elements from all scales for their development. Furthermore, the nomadic characteristics imply that such grassroots innovations are not solely dependent on place-specific conditions for their development, but rather can take advantage of their mobility and ability to become anchored in multiple places, which is beneficial with regard to gaining access to key infrastructure and human as well as financial resources. However, being nomadic also comes with certain challenges for grassroots innovations; for example in relation to temporariness, multi-scalar complexity and lack of spatial proximity within and between initiatives. Following this, three main lessons for addressing the diffusion challenges associated with place-specificity for place-based grassroots innovations are: applying strategies for developing social cohesion through multi-scalar networks, utilising (costumer) demand for alternative solutions, and taking favourable sector conditions as a starting point when designing grassroots innovations.

Contributions of the thesis

This thesis aims to *advance the current understanding of how multi-scalar top-down and bottom-up processes influence socio-technical change towards decarbonisation of the global maritime shipping sector*. To explore top-down processes, the thesis includes investigations of the role of international and national policy regarding technology innovation and implementation, which specifically addresses the first sub-research question of this thesis. To explore bottom-up processes, the thesis includes explorations of the influence of wider niche technology development and implementation on policy processes, as well as studies of grassroots innovation activities, which specifically addresses the second and third sub-research questions respectively. In doing so, the thesis specifically contributes to a further understanding of socio-technical change processes in relation to institutions, networks of actors, material artefacts, and markets and user practices in sectors with strong global regimes. In the next sections, the aggregated findings and conclusions from the papers included in this thesis are presented, starting with insights regarding socio-technical transitions in the maritime shipping sector, followed by a discussion of the theoretical contributions of this thesis as well as an outlook for future research.

Socio-technical transitions in the maritime shipping sector

International policy dynamics

Maritime shipping is an inherently international industry with a strong global regime. The main regulatory framework governing international shipping is implemented by the IMO, implying that there is at least a theoretical possibility to develop an effective policy mix driving decarbonisation in the shipping sector. However, the exploration of policy processes surrounding the negotiations and implementation of GHG emissions policy at the IMO in Paper II and the analysis of the consistency and comprehensiveness of the IMO's policy mix in Paper I show that the IMO has failed to establish sufficient policy instruments to achieve decarbonisation of international shipping. In Paper II, three main challenges (lack of capacity within the IMO to regulate multiple and emerging technologies, uncertainty around the IMO's regulatory mandate, and lack of political consensus during negotiations) for implementation of more consistent, comprehensive and stricter regulation of GHG emissions from international shipping are highlighted. First, the analysis shows that the IMO administrative organisation, as well as the member-state committees, lack capacity and experience with regulating multiple and emerging technologies. Historically, the IMO has taken a reactive policy approach and mainly regulated fossil-oil-based ship fuels, indicating that there is limited experience with governing innovation and novel technologies among the member-state delegations participating in negotiations at MEPC meetings. Furthermore, interview data revealed that the current administrative organisation at the IMO headquarters (with around 300 staff members) lacks the financial and human resources to administer policy instruments driving development of more sustainable propulsion technologies, such as financial support for research and development activities.

Second, also related to IMO's history as a technical organisation regulating technical specifications of how ships should be operated, interview data revealed that there is uncertainty around IMO's regulatory mandate. Given that the IMO has not yet implemented forward-looking regulation, certain member-states question whether policy instruments such as market-based incentives for emission reduction could be implemented within the regulatory framework as it is currently organised. Statements from member-states questioning IMO's regulatory mandate are likely to have stalled negotiations, and indicate that these types of attitudes among member-states might also be a hinder for further negotiations and implementation of stricter GHG emission regulations. Although it was decided during the 81st meeting of the IMO Marine Environment Protection Committee in March 2024 that an economic instrument, including a GHG emission pricing mechanism, should be implemented in 2027, negotiations regarding the actual design of the policy instrument was postponed to 2025 (DNV, 2024b), signalling that negotiations remain slow and that there is no consensus regarding the implementation of market-based measures.

Third and finally, according to our interviewees, the main challenge for implementing stricter GHG regulation at the IMO level is the lack of political consensus among member-states. Our findings indicate that consensus on implementation of stricter policy instruments targeting GHG emissions is hindered by: a. a discrepancy in ambition between member-state delegations participating in general climate negotiations associated with the UN Framework Convention on Climate Change (UNFCCC) and IMO negotiations, where member-states typically are less ambitious when discussing shipping specifically; b. the strong leverage of big shipowner nations from the Global South (due to flag of convenience registrations), which often oppose stricter GHG regulation due to concerns about losing sources of income; and c. delays in decision-making processes due to digital, shorter meetings during the Covid-19 pandemic. Although the latter was a minor and temporary factor, any delays in negotiations of stricter regulations are problematic given the urgency of climate change mitigation in the shipping sector.

As a result of these policy making challenges, the current policy mix targeting emissions to air implemented by the IMO is insufficient to drive a decarbonisation of the maritime shipping industry in line with the IMO's own emission reduction targets as well as the Paris Agreement. In Paper I, an analysis the development of the IMO's policy mix since the implementation of the first policy measures targeting emissions to air from ships in 2005 is presented. Specifically, the consistency (how well different parts of the policy mix fit together) and comprehensiveness (how extensive the policy mix is) of the policy strategy, instrument mix and overall policy mix is assessed for three time periods (2004-2011, 2012-2017, and 2018-2023). While the IMO's policy strategy has developed from being heavily focused on air polluting substances to mainly including policy objectives regarding GHG emission reduction, and the attention to GHG emissions has been further sharpened since publication of Papers I and II following revision of the IMO GHG Strategy in July 2023, the emission reduction ambitions has not yet trickled down to the instrument mix.

The current instrument mix consists of very similar policy instruments, mainly regulatory, with some soft instruments but no economic instruments. Furthermore, there are very few policy instruments targeting GHG emissions compared to the large number of instruments targeting air polluting substances, implying that the instrument mix has a strong consistency but lacks comprehensiveness. Given the discrepancy between the policy strategy and the instrument mix, and the lack of a comprehensive instrument mix, shipping is not yet on course to achieve the emission reductions outlined in the IMO GHG strategy. Furthermore, the current emission reduction targets are insufficient to live up to maritime shipping's contribution to limiting global warming to no more than 2˚C as outlined in the Paris Agreement. Following this, there is a need for both more ambitious policy objectives as well as a more effective instrument mix. Furthermore, it also appears that it is difficult to achieve elements of creative destruction in the global policy mix implemented by the IMO. This suggests that hard-to-abate sectors with one main regulator and highly institutionalised global regimes, such as the aviation and shipping sectors, in addition to challenges regarding identifying suitable alternative, more sustainable fuels and technologies, also face policymaking challenges with regard to implementing effective policy mixes that are able to guide socio-technical change.

At this point, it is still unclear which alternative propulsion technologies will be viable options in the future, and findings from Paper I show that the current global policy mix is insufficient to provide incentives for shipowner investments in alternative, more sustainable propulsion technologies, implying a continued socio-technical lock-in on conventional fossil fuels. According to the IMO's organisational norms, policy instruments implemented by the IMO should be technology neutral; however, the analysis in Paper I shows that beyond conventional oil-based fossil fuels, the current policy mix also favours ships using LNG as their fuel. Following the introduction of policy instruments regulating emission of air polluting substances (mainly sulphur and nitrogen oxides) from international shipping in the early 2000s and the continued stringency of these regulations, there has been an increasing uptake of LNG as a ship fuel due to its low level of air pollution emissions. Implementation of technical standards regarding the use of LNG as a ship fuel, while not implementing any policy instruments regulating methane emissions, has further enabled increased uptake of LNG in international shipping. Although using LNG as a ship fuel results in lesser carbon emissions, in addition to less contribution to air pollution, methane emissions increase, and according to the latest available data methane emissions from international shipping have increased with 151-155% between 2012 and 2018, with in total 148 kt emissions/year in 2018 (IMO, 2020). Emissions are expected to continue to increase exponentially as the additional 911 LNG-powered ships that have been ordered since 2018 (when 123 LNG-powered ships were operating) gradually starts operating, which is directly contradictory to the GHG emission reduction targets in the IMO GHG Strategy. Given the long lifespans of ships (15-40 years), this further strengthens the socio-technical lock-in on fossil fuels, and points to a need for policy instruments regulating not only CO_2 emissions but all GHG emissions from ships. Furthermore, lack of recognition of alternative, more sustainable propulsion technologies represented by, for example, the lack of technical standards for such fuels provides a substantial hinder for implementation of new technologies.

Although additional instruments targeting GHG emissions have been implemented in the last few years, these instruments lack emission factors for alternative fossil free fuels, implying that shipowners that invest in more sustainable propulsion technologies are not rewarded for these investments. This points to a need for policy mixes that restrict the use of conventional fossil fuels while simultaneously promoting uptake of more sustainable propulsion technologies. Given the remaining uncertainty regarding viable future technology options for different segments within the shipping industry, introducing economic instruments such as CO_2 pricing mechanisms offers the opportunity to increase the operational cost for fossil fuels while redirecting incoming funds to research and development of more sustainable propulsion solutions. However, economic instruments alone will not be sufficient to drive socio-technical change within the maritime shipping sector, and needs to be combined with other types of policy incentives such as regulatory and soft policy instruments.

Looking at the global orders for new ships that will be delivered up to 2028, it is clear that the portfolio of propulsion technologies has started to diversify, given recent orders for ships powered by methanol, hydrogen and ammonia. Out of the total the cargo capacity (tonnage) currently ordered, 49% will be powered by alternative fuels (DNV, 2024a). During 2023, 138 methanol-powered ships were ordered (see Figure 11), compared to 130 LNG-powered ships (a significant decrease from the 222 ordered ships during 2022), potentially indicating that LNG is no longer seen as the main alternative fuel. Methanol as a ship fuel has the advantage that it can be used in slightly modified conventional combustion engines and be stored in the same or similar tanks as conventional oil-based fuels on board ships. However, the majority of the methanol produced currently is also based on fossil fuels and it is unclear if volumes of renewable methanol will match demand as new ships start operating. Although regulatory expectations for potential stricter regulation in the future is likely part of the explanation for this diversification, interview data and observations for Papers I and II suggest that other incentives such as costumer demand for sustainable shipping, competitive advantage potential and motivations for being part of the solution are the more prominent drivers for shipowners to invest in alternative propulsion technologies.

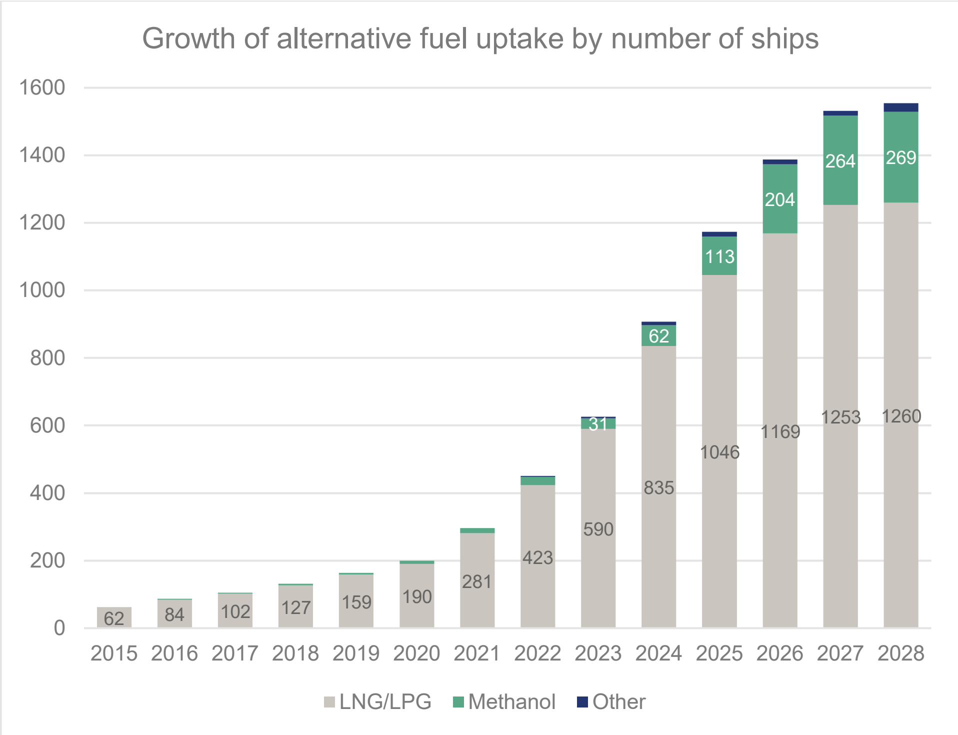

Figure 11 Number of ships with alternative propulsion technologies ordered for delivery 2015-28

LNG – Liqufied natural gas, LPG – liquefied petrol gas, other – ammonia & hydrogen. Years beyond 2023 indicate the total number of ships operating on the respective propulsion technologies after expected deliveries of new ships. Source: DNV's Alternative Fuels Insight platform

The role of national policy

Given the slow progress and challenges with implementing stricter GHG emission reduction policy at the international level through IMO negotiations, regulating shipping at the national level could be an important driver for testing and implementing technology on a smaller scale, which can later be upscaled for oceangoing ships. In Paper III, insights into how national policy, and specifically green public procurement, has influenced implementation of biodiesel and LBG in the Norwegian coastal shipping sector are presented, in the context of being interchangeable with their fossil fuel equivalents (marine gas oil/marine diesel oil and LNG, respectively). The analysis shows that even though there are several positive externalities resulting from technological alignment between marine fossil fuels and biofuels, these are overruled by the directionality of public policy promoting implementation of zero-emission technology, such as battery-electric and hydrogen solutions, rather than biofuels. During the last two decades, the Norwegian government and regional administrations have enforced more and more stringent emission regulations for ship operations in domestic harbours and coastal waters. In addition, to support technological development, publicly awarded so-called 'development contracts' have been used to support the development of more sustainable propulsion solutions in combination with public procurement of medium-sized car- and passenger road ferries. Additional policy instruments to achieve emission reduction include financial support available from multiple public funding agencies for R&D activities, as well as implementation of alternative fuel infrastructure.

Over the years, the analysis shows that there has been a shift from general emission reduction requirements to specific demands for low- and zero-carbon emissions in both national and regional policy objectives as well as public procurement regulations, which has excluded biodiesel and LBG given their still high (but fossil free) carbon emissions, as well as uncertainties regarding fuel availability and cost. In combination with the availability of cheap electricity in large parts of Norway, this has resulted in a more rapid technology implementation of battery-electric and hydrogen propulsion solutions in the Norwegian coastal shipping sector (Bach et al., 2020). A similar pattern has been observed also within green public procurement of road transport in Sweden (Aldenius, 2018; Aldenius & Khan, 2017). This implies that although biofuels initially were seen as "low hanging fruits" given positive sectoral cross-technology externalities such as using the same conventional bunker infrastructure and engines that already exist, the decreasing policy support for these technologies has resulted in a lack of legitimacy for biofuels and a low rate of implementation, while other propulsion technologies have been favoured. Paper III therefore contributes to advancing our understanding of sectoral cross-technology externalities by highlighting how even multiple positive externalities resulting from a high degree of alignment and interchangeability with established technologies do not necessarily contribute to faster technological innovation and implementation. This implies that while biofuels may benefit from the positive externalities connected with technology alignment with existing fuels, high expectations of the upscaling potential for biofuel implementation also risks prolonging the use of fossil fuels, especially if implementation of biofuels is unsuccessful.

Although there is an advantage of strong directionality in national policy with regard to accelerating technology implementation, favouring of certain technologies over others risks hindering innovation and development related to other solutions that are needed in the anticipated portfolio of alternative propulsion solutions. Given the characteristics of different types of ships, some are more suitable than others to certain alternative propulsion technologies, due to their differences in size (energy demand and storage capacity) and routes (close to shore or offshore, speed expectations, fuel infrastructure in ports). For example, a car- and passenger road ferry operating on a short route between two fixed ports is well suited for battery-electric propulsion as it can charge the batteries when loading and off-loading. A ship operating on longer routes between irregular ports, on the other hand, has a larger energy demand and spends a longer time between ports, and is therefore not suited for battery-electric propulsion, and instead requires the possibility of taking on the same alternative fuel in (most of) the ports it docks in. Given that projected fuel availability forecasts show that no single alternative fuel option will be available in sufficient amounts to replace current ship fuel demand, it is important to not prematurely exclude propulsion technologies that could be crucial in the required fuel mix or function as transition fuels to other, more sustainable fuels that will be available in the future. National policy makers thereby face similar challenges as identified for IMO negotiations, regarding navigating support for and regulation of multiple emerging propulsion technologies simultaneously. Given the different preconditions for supporting alternative propulsion technologies in various countries, due to different abilities in providing public financial support as well as access to natural resources for production of cheap renewable electricity or different types of alternative fuels, it is likely that we will see national variations of the favoured technology solutions for domestic coastal shipping; however, this needs to be further explored in research on sustainable shipping. This implies that national policy has the potential to not only influence technology choices within the domestic coastal shipping sector, but also for international shipping if certain fuels or other propulsion technologies are available only in specific ports, influencing shipowners to make technology choices based on fuel availability along their ships' routes.

Furthermore, given its ambitious national emission reduction targets and strict policy instruments, Norway is considered a frontrunner in sustainable shipping, which is also evident when looking at, for example, the rapid implementation of battery-electric solution in coastal ferries and experimentation with hydrogen propulsion solutions (Bach et al., 2020) as well as the continuously increasing implementation of fuel infrastructure for more sustainable propulsion technologies in Norwegian ports (Steen et al., 2024). Previous research has shown that frontrunner countries often play crucial roles in driving IMO negotiations regarding more ambitious emission reduction targets and stricter policy instruments (Cragila et al., 2020), while also showcasing that shifting to more sustainable propulsion technologies is possible (Bach et al., 2020). In addition, Norway and other frontrunner countries such as Denmark and Sweden are considered influential member-states of the IMO, as they continuously draft and submit policy proposals and engage in other efforts to drive implementation of climate change mitigation policy (Psaraftis & Kontovas, 2020). This further indicates that national policy dynamics play an important role beyond national borders.

Initiatives beyond policy requirements

Given the flickering guiding light from international policy and the limited impact of national policy, there is also a need for bottom-up initiatives striving to develop and implement sustainable propulsion solutions that go beyond regulatory requirements. Although regulation on different governance levels has the potential to be a strong driver for decarbonisation of the maritime shipping sector, it is clear that the current global policy mix and limited national policy incentives are insufficient given the urgency of achieving emission reductions. Therefore, community-initiated bottom-up processes such as grassroots innovations could play an important role in exploring unconventional propulsion solutions that go beyond policy requirements. Previous conceptualisations of grassroots innovations describe them as locally rooted place-based phenomena, which are dependent on and utilise place-specific conditions, resulting in challenges for diffusing a particular grassroots innovation solution to other places (Håkansson, 2018; Kratzer et al., 2022). Paper IV challenges the definition of grassroots innovations as solely locally rooted in specific places and introduces a conceptualisation of nomadic grassroots innovations.

Based on empirical analysis of three development stages, *initiation, operations,* and *upscaling and diversification*, Paper IV explores the spatiality of socio-technical elements contributing to the development of sail cargo initiatives as nomadic grassroots innovations. The analysis shows that while nomadic characteristics of sail cargo initiatives are present for all development stages, the spatiality differs between the respective stages. It appears that sail cargo initiatives are more anchored in their home localities when building or renovating ships during the initiation stage, compared to when they start operating and the nomadic aspects are actualised with the mobility between home and host localities. In the *upscaling or diversification* stage, sail cargo initiatives become more locally anchored again during further construction or renovation processes, while also continuing their nomadic operations. The analysis furthermore indicates that nomadic grassroots innovations can utilise their mobility in order to gain access to key material artefacts to further their development, either by deciding on a home locality based on access to infrastructure etc., or through temporary relocation. However, relocation is also associated with challenges such as, for example, losing connection to elements and networks in the home locality, as well as establishing new networks in the host locality.

Furthermore, sail cargo initiatives at all stages are also dependent on socio-technical elements from all scales (*local and regional*, *national*, and *international*) for their development. For example, being anchored in multiple places and part of multi-scalar networks, sail cargo initiatives can benefit from having access to larger populations of potential investors, costumers, crew members, intermediaries, etc. than typical place-based grassroots innovations. However, having to take multiple national and international regulatory contexts into consideration, both with regard to ship and trade regulations, requires greater efforts compared to operating in one place – especially if regulatory frameworks and institutions do not recognise the grassroots innovation's technology or solution (anymore). This indicates that one of the main challenges for development and diffusion of sail cargo initiatives, similar to grassroots innovations in general, is obtaining legitimacy for their activities, both in relation to regulatory institutions, and also from external investors, cargo owners, producers and individual consumers.

Given that sail cargo initiatives operate outside of the conventional shipping context and its global value chains and path dependency, which has been argued to hinder niche development (Pettit et al., 2018), the analysis of the sail cargo initiatives offers insights into the formation of alternative niches in the maritime shipping sector. First, the analysis showcases the need in the conventional shipping sector for further bottom-up initiatives with higher decarbonisation ambitions than regulatory requirements, which contributes to achieving a shift to sustainable shipping. Second, the findings reveal that consumer demand plays a crucial role in driving development and implementation of additional sail cargo initiatives, indicating that consumer demand for low- and zero-carbon emission shipping could be a strong driver in the conventional shipping sector also. This further implies that there is a need for policy attention to cargo owners and their decarbonisation targets in order to drive decarbonisation of the maritime shipping industry.

The stability of the current global regime is one of the main barriers to sustainability transitions in the maritime shipping sector. By offering an alternative to conventional shipping, the sail cargo initiatives studied in Paper IV challenge the current global regime for the international shipping sector. However, it is not likely that these traditional sail cargo initiatives will be able to upscale to such an extent that they will overturn the current global regime. Rather, these sail cargo initiatives can be seen as inspirational examples for decarbonisation efforts, both with regard to community or firm initiatives to invest in propulsion solutions that go beyond the regulatory demands, as well as drawing attention to more modern designs of wind-assisted propulsion technologies such as Flettner rotors, airplane wing-like solid sails and Dynarigs that can be added to new and existing ships to decrease fuel consumption, or even used to design mainly wind-propelled modern sail cargo ships.

Theoretical contributions

To date, transition studies have been focused on national-level case studies and geographically centred around northern Europe. The intrinsic trans-nationality and mobility that is the core of the maritime shipping sector makes this sector an interesting case for testing whether the typical conceptual assumptions regarding how socio-technical change and sustainability transition processes unfold taken from previous national case studies of transitions in the energy, mobility and water sectors also apply to an international sector with a strong global regime. Previous conceptualisations and empirical explorations of sustainability transitions suggest that transitions typically occur as a result of successful development and upscaling of niche technologies that eventually outcompete incumbent socio-technical regime configurations. However, sectors with strong global regimes are assumed to be extraordinarily resistant to change, indicating that this transition trajectory is unlikely to be achievable in the maritime shipping sector. Furthermore, the shipping sector's highly institutionalised global regime implies that this sector is an interesting case for further exploration of multi-scalar transition dynamics in top-down as well as bottom-up processes. In addition to contributing to a further understanding of socio-technical change towards sustainability transitions in hard-to-abate sectors, the thesis therefore also contributes to the literature on the geography of sustainability transitions. Based on the exploration of how the maritime shipping sector's strong global regime interacts with top-down and bottom-up transition dynamics at the global, national and community level, this thesis specifically contributes to the literature on multi-scalarity and global socio-technical regimes.

Multi-scalar top-down and bottom-up transition dynamics

Based on exploration of multi-scalar top-down and bottom-up influences for socio-technical change in the maritime shipping sector, this thesis contributes to the literature on multi-scalarity in sustainability transitions. Exploring top-down as well as bottom-up influences is a rare approach within sustainability transitions research, as previous research typically focuses on either top-down (exploring, for example, the influence of global regimes or policy on socio-technical change) or bottom-up processes (such as social movements, grassroots innovations or niche technology development). By including top-down as well as bottom-up influences, the thesis specifically contributes to further insights regarding how re-scaling processes hinder or enable sustainability transitions.

Previous conceptual contributions regarding the geography of sustainability transitions have suggested complementing the MLP levels (niche, regime, and landscape) with spatial scales, such as the international, national, urban, and hyper-local scales, to enable exploration of rescaling processes between the respective scales (Hodson et al., 2016). Furthermore, Hodson et al. (2016) suggest distinguishing between top-down and bottom-up influences for sustainability transitions. They see top-down influences as dominant governance initiatives aimed at market formation for new, more sustainable technologies. Such governance initiatives are typically implemented at national or urban scales. While urban governance initiatives mainly influence activities at the urban and hyper-local scales, national governance often influences the national as well as the urban and hyper-local scales. In contrast, bottom-up initiatives are conceptualised as alternative responses to top-down governance, typically represented by transition activities such as grassroots innovations at the hyper-local scale.

The aggregated findings from the three studies in this thesis highlight both top-down and bottom-up re-scaling processes (see Figure 12). In the maritime shipping sector, top-down as well as bottom-up influences occur between all scales, thereby contributing to re-scaling processes, i.e., the interplay between and reconfiguration of socio-institutional as well as techno-economic structures at different scales (Mansfield, 2005). Top-down influences are mainly observed from the international to the national and regional and local scales, as well as from the national to the regional and regional and local scale. Multi-scalar top-down influences are manifested in the impact of the IMO's global policy mix on: a. the influence of technological alignment between fossil (established global and national regime) and biobased fuels for implementation of the latter as examined in Study 1; b. the technology implications in the international shipping industry presented in Study 2; and c. the sectoral conditions for the development of grassroots innovations in the maritime shipping sector, such as the sail cargo initiatives studied in Study 3.

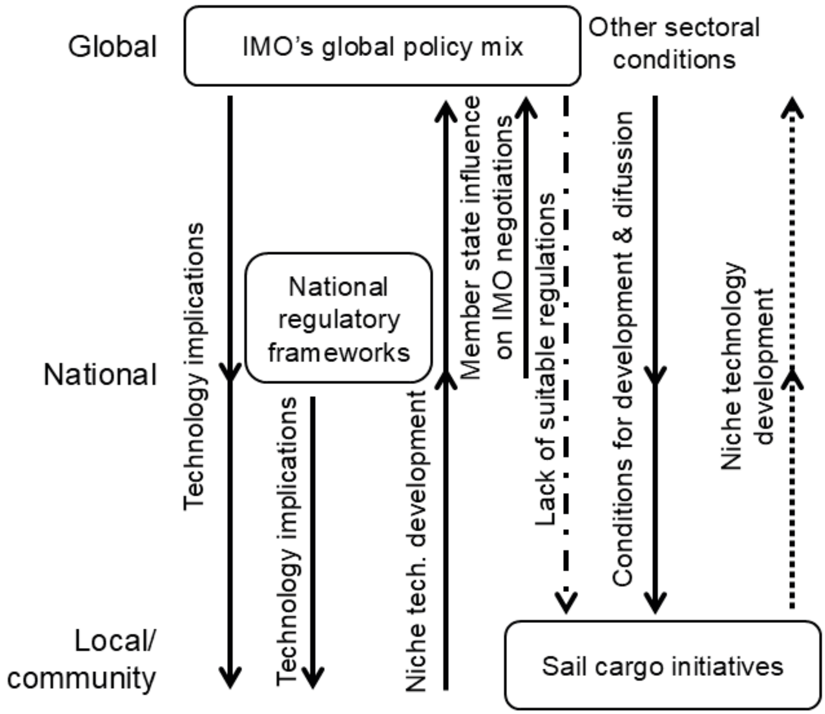

Figure 12 Overview of top-down and bottom-up influences identified in the thesis' three studies

Furthermore, Study 1 also explores top-down influences from national policy, i.e., the national territorially embedded regime, on development of territorially embedded niches in the Norwegian coastal shipping sector. Multi-scalar bottom-up influences for sustainability transitions in the maritime shipping sector are observed in interactions between the local and regional, national as well international scales, and are showcased through a. how niche technology developments enforce a new territorially embedded regime in Study 1, b. re-scaling processes related to frontrunner member states driving implementation of stricter global GHG regulation during IMO negotiations (Studies 1 and 2), and c. the multi-scalar dynamics of emergence and development of sail cargo initiatives as nomadic grassroots innovations (Study 3).

The combined findings from the three studies point to a need for a broader conceptualisation of top-down and bottom-up influences for sustainability transitions. Given that observations of top-down influences in the maritime shipping sector go beyond dominant governance initiatives at the national level, the findings from this thesis challenge Hodson et al.'s (2016) assumption that national governance initiatives aimed towards market formation are the main top-down influence. I thereby suggest an expansion of Hodson et al. (2016) definitions, which in addition to governance initiatives at the national level acknowledges governance initiatives at other scales as well as further top-down structures associated with additional socio-technical elements such as material artefacts, networks of actors, and norms and practices that constitute sectoral conditions. This would enable a more systematic exploration of how the global or national socio-technical regime configuration exerts top-down pressure on transition activities at the lower scales. Furthermore, the findings from Study 3 highlight how grassroots innovations are not only rooted at the hyper-local scale, but rather are dependent on and take advantage of multi-scalar resources and networks in addition to being anchored in multiple localities. Taken together with the observation of bottom-up influences from the national to the international scale regarding IMO negotiations, the findings from this thesis further challenges Hodson et al.'s (2016) assumption that bottom-up influences typically stem from transition activities at the hyper-local scale. Following this, I suggest that bottom-up influences should be seen as multifaceted given their interplay with multiple scales, and thereby should be explored for additional scales beyond the hyper-local. This implies that although top-down influences are associated with regime pressures, bottom-up influences should be seen as more than niche development, and include how the interaction between socio-technical configurations at different scales exert bottom-up influences on socio-technical regimes.

Transition trajectories in sectors with strong global regimes

Previous studies of how transitions unfold in sectors with strong global regimes are scarce, as most previous studies have explored 'local-global niche development' trajectories. Such a trajectory assumes that successful niche-regime interplay, mainly between the local and national level, fosters upscaling of niches, ultimately resulting in changes to the incumbent regime at the national scale. If multiple national-level regimes undergo the same transition, these might influence changes in the global regime (Geels, 2002; Geels & Raven, 2006). This 'local-global niche development' trajectory assumes that socio-technical change is dependent on place-specific conditions that favours niche development; however, Miörner and Binz (2021) argue that for certain sectors, the strong global regime, rather than place-specific conditions, may be the main influence on the trajectories of sustainability transitions.

The findings of this thesis indicate that this appears to be the case for the maritime shipping sector, given how the current global regime, mainly manifested through the IMO's global policy mix, currently reinforces a continued socio-technical lock-in around fossil fuels rather than promotes a shift to more sustainable propulsion technologies. Furthermore, the findings highlight the so far limited influence on changes within the global regime from niche technology development and bottom-up influence from frontrunner member-states on policy processes within the IMO. This indicates that niche development alone is insufficient to drive transformative socio-technical change in the shipping industry, implying a need for different transition trajectories for sectors with strong global regimes, which supports Miörner and Binz's (2021) call for conceptualisations of additional transition trajectories. They suggest conceptualisations of two additional multi-scalar transition trajectories, 'multi-locational diffusion' and 'global advocacy', which challenge previous theoretical assumptions that sustainability transitions mainly unfold through upscaling of territorially embedded niche technologies. The 'multi-locational diffusion' trajectory highlights how one or multiple territorially embedded (typically at the local scale), can be directly re-scaled into a new global niche, which in itself could be institutionalised to such a high degree that a new global regime emerges. In contrast, the 'global advocacy' trajectory refers to dual processes in which global niche developments are re-scaled downwards, influencing changes in territorially embedded niches while simultaneously also potentially becoming increasingly institutionalised into global regime structures (Miörner & Binz, 2021).

The findings of this thesis do not identify any indications of direct re-scaling of local niche developments to the global regime or emergence of global niches in the maritime shipping sector. Given that such external pressures on the global regimes described in previous conceptualisations of transitions trajectories appear to be insufficient or non-existent in the maritime shipping sector, in which the strong global regime is a obstacle to the shift to more sustainable propulsion technologies, I see a need for increased attention to internal change processes within global regimes. Based on insights from the findings of this thesis, and building on A. Smith et al.'s (2005) conceptualisation of internal adaptive capacity within socio-technical regimes, I suggest a conceptualisation of a fourth, potential *global regime-induced* multi-scalar transition trajectory for sectors with strong global regimes, which highlights the influence of regimes on socio-technical change and how changing the global regime can drive change processes at other scales as well (see Table 4).

Table 4 Overview of potential transition trajectories

Local-global niche development	***Territorially embedded niche*** *→ territorially embedded regime → global regime* Socio-technical change starts with development of territorially embedded niches, which can be upscaled and influence territorially embedded regimes and eventually overturn the global regime if supported by favourable (place-specific) conditions (Geels, 2002; Geels & Raven, 2006).
Multi-locational diffusion	***Territorially embedded niche*** *→ global niche (→ global regime)* Socio-technical change processes start with niche developments typically at the (territorially embedded) local scale, which can be directly re-scaled to a global niche. Potentially, the new global niche could also be institutionalised to such a high degree that it influences a new global regime (Miörner & Binz, 2021).
Global advocacy	***Global niche*** *→ territorially embedded niche* ***Global niche*** *→ global regime* Establishment of global niches can influence emergence of territorially embedded niches as well as simultaneously prompt changes within the global regime (Miörner & Binz, 2021).
Global regime-induced	***Global regime*** *→ territorially embedded regime (→ territorially embedded niche)* ***Global regime*** *→ global niche (→ territorially embedded niche)* Conditions for socio-technical change is dictated by the strong global regime, which is resistant to influence from re-scaling of territorially embedded or global niche developments. Socio-technical change therefore requires internal adaptive capacity within the global regime itself to enable changes to the regime. The new global regime hypothetically influences socio-technical change within territorially embedded regimes as well as global niches, which in turn can influence changes in territorially embedded niches.

The aggregated findings from the three studies in this thesis point to the fact that the maritime shipping sector has an exceptionally strong global regime, which historically has been resistant to change. This strong global regime exerts pressure on territorially embedded regimes at the regional, national and local levels as well as development of both territorially embedded and global niches. While implementation of stricter global regulation of air polluting substances from international shipping has been successful, the current global policy mix regulating GHG emissions is insufficient to provide incentives for implementation of more sustainable propulsion technologies, implying that the current global regime is a barrier to the shift to sustainable shipping. So far, bottom-up influences, such as territorially embedded as well as global niche development, and member-state influence on IMO negotiations regarding implementation of stricter GHG policy, has not been enough to put pressure on the fossil-fuel-centred global regime to change. Rather, findings from Study 2 point to the fact that the current regime is continuously reproduced given that influential IMO member states still see conventional fossil fuels as the main propulsion technology, implying that their shared interests, values and problem-solving routines remain centred around conventional propulsion technologies. This furthermore implies that the previously assumed transition trajectories, where regimes typically are overturned through upscaling and diffusion of niche technologies, does not appear to be sufficient to overturn the global regime in the maritime shipping sector. While this highlights that hard-to-abate sectors with strong global regimes likely are even more path-dependant and resistant to change than other sectors, this also points to a need to find alternative strategies for changing the global regime. Given that the strong global regime sets the conditions for how transitions can happen in the maritime shipping sector, changes to the global regime are necessary to enable a shift to more sustainable propulsion technologies at the global as well as national and local or community scales. Rather than focusing on different types of influence from territorially embedded and global niches to territorially embedded and global regimes, I suggest that a *global regime-induced* multi-scalar transition trajectory for sectors with strong global regimes should encompass increased attention to the internal adaptive capacity of the global regime. Internal adaptive capacity refers to the incumbent socio-technical regime having sufficient capabilities and resources to achieve changes in the regime within itself (A. Smith et al., 2005). Given the strong influence of the high degree of institutionalisation in strong global regimes on multi-scalar transition dynamics, internal adaptive capacity within the regime is important to enable a shift to a more sustainable regime configuration that can drive niche technology development and implementation at the global, national and local or community level (see Figure 13).

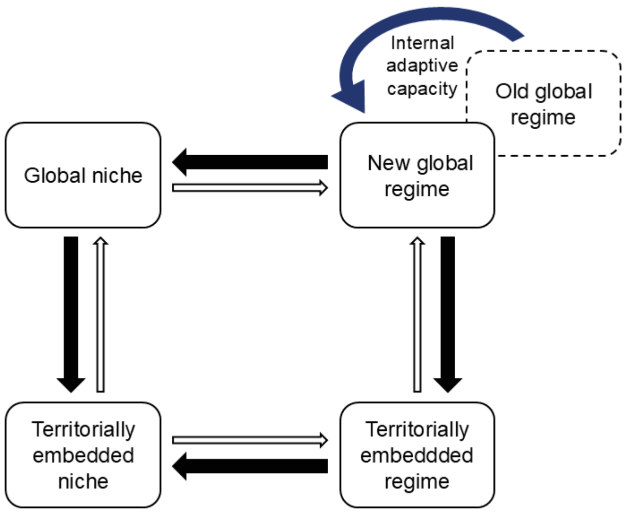

Figure 13 A global regime-induced transition trajectory for sectors with strong global regimes
Further developed based on Miörner and Binz (2021).

In the maritime shipping sector, the internal adaptive capacity of the global regime can be related to the financial and human resources of the IMO's administrative organisation (the IMO Secretariat), as well as the readiness of IMO member states to reach political consensus during negotiations regarding implementation of stricter GHG regulations. Furthermore, beyond regulatory aspects, the adaptive capacity of major shipowners, fuel producers, cargo costumers and other influential regime actors to adopt more sustainable propulsion technologies also influences the internal adaptive capacity of the global regime, although this has not been extensively explored in this thesis. Findings from the second study in this thesis highlight that there are multiple challenges for increasing the internal adaptive capacity within the IMO to enable implementation of stricter GHG regulation; however, given the successful implementation of regulation of air polluting substances, there is great potential for transformative socio-technical change in the maritime shipping sector if sufficient GHG regulation is implemented. Furthermore, findings from Study 1 point to how changes within the national regime configuration towards favouring low- and zero-carbon propulsion technologies have been a driver of niche development in the Norwegian coastal shipping sector, further showcasing the potential of regime pressure to drive socio-technical change towards sustainability transitions. This successful regime change indicates that the incumbent socio-technical regime at national level in Norway had sufficient internal adaptive capacity to implement stricter GHG regulation for coastal shipping, which furthermore points to the fact that socio-technical regimes at the national scale likely have larger internal adaptive capacity than global regimes. Consequently, it can be assumed that with increasing scale comes increasing complexity, which is challenging for development of internal adaptive capacity within global regimes. These insights contribute to a further understanding of how transitions unfold in sectors with strong global regimes and highlight the importance of considering *global regime-induced* transition trajectories for such sectors.

Limitations and future research

In the following, final section of this chapter, I reflect on the boundary conditions of the three studies included in this thesis, which on the one hand highlight limitations of the research, but also, on the other hand, emphasize the continued need for further exploration of the ongoing shift towards more sustainable propulsion technologies as well as sustainability transitions in sectors with strong global regimes. Considering that the main conceptual frameworks for explaining how sustainability transitions unfold have been developed based on empirical exploration of national case studies, there is a continued need for deepening our understanding of how sustainability transitions unfold in sectors with strong global regimes such as the steel industry, and the aviation and petrochemical sectors. Future research could further explore strategies for destabilisation of incumbent global regimes and develop complementary conceptualisations of transition trajectories in sectors with strong global regimes, both with regards to the internal adaptive capacity of incumbent regimes as well as external pressures driving regime changes.

Although exploring both top-down and bottom-up influences on socio-technical change towards more sustainable propulsion technologies offers the opportunity to gain more comprehensive insights regarding decarbonisation of the maritime shipping sector, limiting the focus of the thesis to either one of these would have enabled more in-depth exploration of the particular influences. Considering that the majority of previous research on sustainability transitions in the shipping industry has explored top-down influences, there is especially a need for further research on bottom-up influences. However, given the scarcity of previous research on the interaction between top-down and bottom-up influence on sustainability transitions, future efforts ought to engage with further exploration and conceptualisation of top-down as well as bottom-up influences on socio-technical change. Such continued explorations could also consider top-down influences beyond governance initiatives; for instance, the institutional impact of established fossil fuel infrastructure, as well as bottom-up initiatives from conventional shipowners.

This thesis includes a case study of a frontrunner nation (Norway) to study the role of national policy in driving implementation of more sustainable propulsion technologies. However, not all nations are frontrunners, and many are instead at earlier stages, where we are likely to observe different patterns of interplay between contextual, place-specific conditions and national policy in driving socio-technical change. In contrast to frontrunners, countries considered laggards are more likely to copy already established socio-technical solutions, rather than engage in innovation and early stages of technology development. Differences in capacity between frontrunners and laggards to engage in such activities can be explained by variations in institutional infrastructures, financial resources, knowledge networks, etc., highlighting a need to further explore implementation of more sustainable propulsion technologies also in countries in earlier stages of technology adoption. Furthermore, the dynamics between member states during IMO negotiations are complex and the influence on negotiations are likely to vary across member states depending on the type of actors included in delegations, national climate mitigation agendas, the role of the shipping industry for the nation's economy, and status of implementation of alternative, more sustainable propulsion technologies. Future research that considers additional national cases is therefore also of the utmost importance to develop a further understanding of the complexity of the dynamics between member states during IMO negotiations, and how this effects the internal adaptive capacity for socio-technical change within the IMO.

Moreover, in recent years, the EU has become an increasingly important regulatory actor for the maritime shipping sector following the gradual inclusion of shipping in the EU emission trading scheme, the FuelEU maritime regulation, and other policy measures within the EU Commission's Fit for 55 legislative package. Given that these policy measures were still under discussion at the time Study 2 was conducted (and are still not yet fully implemented), EU policy was excluded from this thesis, but is important to consider in future research. This delimitation invites future research on the role of EU policy in driving socio-technical change in the shipping industry, for example in relation to if and how the differences in organisational structure between the EU and the IMO enable implementation of different types of policy measures, such as economic or regulatory policy instruments targeting creative and/or destructive processes. Considering previous examples of how EU regulation of air polluting substances drove implementation of similar regulations at the IMO, future research ought to engage with policy process interactions between these two governance levels to gain a further understanding of bottom-up influence driving socio-technical change within the shipping industry's strong global regime.

Given the increased multi-scalar regulatory complexity for the shipping industry following recent policy developments at EU level, it is also relevant to explore the technology implications of multi-scalar policy mixes, including policy elements from the IMO, the EU and other supra-national organisations, and national-level policy mixes. In addition, this also encourages future research on cross-country comparisons between national policy mixes to explore spatial variations of the interaction between policy measures and technology development and implementation. Such spatial variations could be expected as a result of, for example, differences in institutional infrastructures and access to natural resources for fuel or electricity production, and are likely to result in adoption of different sustainable propulsion technologies. Understanding these spatial variations could provide further insight into governance-related top-down influences on socio-technical change in the maritime shipping sector, as well as which factors contribute to implementation of a successful policy mix.

Finally, the third study in this thesis showcases the potential for individual actors to drive socio-technical change towards decarbonisation of the shipping industry. Given the inability of the current global policy mix to drive socio-technical change in the maritime shipping sector, there is a need to further explore if and how individual actors such as grassroots activists, shipowners, technology suppliers, fuel producers and cargo owners engage in socio-technical change processes that go beyond regulatory requirements. Furthermore, it is also relevant to consider how policy at different scales can support such efforts.

7. Concluding remarks

This thesis set out to advance the current understanding of how multi-scalar top-down and bottom-up processes influence socio-technical change towards decarbonisation of the global maritime shipping sector. To this end, I posed the following overarching research question to be answered by the aggregated findings from the thesis: *how does the strong global regime in the maritime shipping sector interact with top-down and bottom-up transition dynamics at the global, national and community level?* Empirically, this thesis has addressed this overarching research question through exploration of multi-scalar top-down influences in the form of international policy dynamics (Study 2) and the role of international and national policy in driving development and implementation of more sustainable propulsion technologies (Study 1 and 2). In addition, top-down influences are explored in relation to the sectoral conditions associated with the shipping industry's strong global regime, which influence the development of grassroots innovations in the maritime shipping sector (Study 3). Furthermore, multi-scalar bottom-up influences are explored through examining re-scaling processes related to frontrunner member-states driving implementation of stricter IMO GHG regulation (Study 2), how niche technology developments enforce a new configuration of the national regime for Norwegian coastal shipping (Study 1), as well as the emergence and development of sail cargo initiatives as nomadic grassroots innovations (Study 3).

In addition to contributing to further empirical insights regarding socio-technical change towards decarbonisation of the global maritime shipping sector, this thesis also contributes to advancing the current understanding of sustainability transitions in sectors with strong global regimes as well as multi-scalar top-down and bottom-up transition dynamics. The aggregated findings highlight how the strong global regime sets the prerequisites for how socio-technical change can unfold in the maritime shipping sector, both regarding top-down as well as bottom-up processes. With regard to top-down processes, the analysis reveals that policy incentives, both at the global and national scale, are currently insufficient to drive decarbonisation of the maritime shipping sector. Given that the current global policy mix reinforces the socio-technical lock-in on fossil ship fuels rather than incentivises development and implementation of more sustainable propulsion technologies, the global shipping industry is off course for reaching the level of decarbonisation needed to achieve the emission reduction targets set in the IMO GHG Strategy as well as the

Paris Agreement. Furthermore, the findings reveal that bottom-up influences from IMO member states play an important role in the policy dynamics during negotiations for implementation of stricter global GHG policy, indicating a multi-scalar interplay also for bottom-up influences. In addition, bottom-up initiatives such as nomadic grassroots innovations in the maritime shipping sector are dependent on and utilise multi-scalar socio-technical elements for their development. Although their multi-scalar interactions, for example, grant sail cargo initiatives access to larger populations of grassroots actors, they struggle with gaining legitimacy as well as diffusing and upscaling their niche activities. The findings thereby point to the importance of considering the multi-scalarity of top-down as well as bottom-up influences on socio-technical change rather than assuming that policy incentives will be sufficient to drive technology development and implementation. Furthermore, the findings indicate that socio-technical change in the maritime shipping sector is unlikely to unfold solely based on niche development given the resistance to change within the global regime. This highlights a need for further conceptualisations for how sustainability transitions can unfold in sectors with strong global regimes.

In this thesis, two main conceptual contributions are presented. First, I argue that there is a need to expand current conceptualisations of what encompasses top-down and bottom-up influence on sustainability transitions. For this, I suggest complementing previous conceptualisations of top-down influence as predominantly governance initiatives by acknowledging other top-down structures associated with additional socio-technical elements such as material artefacts, networks of actors, and norms and practices that constitute sectoral conditions. Furthermore, I suggest that rather than only being associated with niche development at the hyper-local scale, bottom-up influences should be seen as multifaceted and multi-scalar given the interplay between multiple scales with regards to, for example, policy processes. Second, I suggest introducing a global regime-induced transition trajectory to further develop our understanding of sustainability transitions in sectors with strong global regimes. Rather than expecting sustainability transitions to unfold through re-scaling of niche (technology) developments, the global-regime-induced trajectory highlights the importance of internal adaptive capacity to change the socio-technical configuration within the global regime itself. Given that sectors with strong global regimes are typically resistant to change due to the high degree of institutionalisation of the global regime, I suggest that increased attention should be given to strategies for changing the global regime through internal processes. If a successful re-configuration of the global regime is achieved, this is expected to drive socio-technical change through top-down re-scaling processes influencing regimes and niches at all scales.

Policy implications

The aggregated findings from the three studies in this thesis highlight the importance of policy initiatives to steer the shipping sector on the right course towards decarbonisation. Although there are many potential policy implications of the findings in this thesis, as a complement to the more concrete policy implications related to policy processes within the IMO and the Norwegian coastal shipping sector, as well as bottom-up initiatives presented in previous sections, in this section I highlight overarching implications that are important for policymakers to consider.

In a way, the most effective strategy to decrease GHG emissions from the maritime shipping sector would be to ship less. Being a hard-to-abate sector, the shift to more sustainable propulsion technologies promises to be a slow process, especially given the lack of silver bullet solutions, the complexity of shifting to several new technologies and the uncertainty regarding availability, price and life cycle emissions of alternative propulsion technologies. In order to achieve the crucial rapid reduction of GHG emissions needed to enable decarbonisation in line with the Paris Agreement, there is therefore a need for policy incentives to decrease maritime shipping operations. During the last century, following increased energy efficiency, the cost of maritime shipping has been relatively low – contributing to globalisation of value chains. With regard to climate change, this has, however, had negative impacts as the GHG emission from maritime shipping has continuously increased over the same time period. Furthermore, the low cost of maritime transport enables 'unnecessary' shipping, such as the shipping of fish fished in the North Atlantic to Asia for preparation before being shipped back to be sold in, for example, Scandinavian supermarkets (Skjåstad Lysvold, 2019), partly because the cost of labour and transport to Asia is less than the cost of labour in Scandinavia. Therefore, I argue that decreasing maritime shipping operations relates to eliminating 'unnecessary' shipping, as well as the need for a general decrease in (over)consumption and consequently maritime transport.

In the current economic system, the most effective incentive to decrease shipping volumes and streamline shipping operations in a way that reduces GHG emissions is presumably to increase the cost of shipping for the consumer as well as for the shipowner. This could be achieved, for example, through implementation of global or regional fossil fuel levies, emission trading schemes or other economic policy instruments. The impending implementation of more sustainable alternative propulsion technologies is also likely to contribute to increasing costs of shipping given the expected higher fuel price of alternatives such as hydrogen and methanol. In addition, it is also crucial to remove fossil fuel subsidies in all sectors to even out the price difference between conventional fossil fuels and alternative, more sustainable propulsion technologies. Incoming funds from economic policy instruments ought to be directed towards supporting development and implementation of more sustainable propulsion technologies to further contribute to decarbonisation of the maritime shipping sector.

A decrease in maritime shipping operations would alter the world as we know it. Rather than a continuation of current globalisation trends, we can presume that less shipping would imply an increasing regionalisation of value chains and trade patterns. Given that spatial variations are expected regarding implementation of alternative, more sustainable propulsion technologies depending on access to natural resources, existing knowledge networks, etc., regionalisation of value chains and trade patterns could furthermore contribute to establishment of new fuel infrastructures serving ships on specific routes. Paradoxically, around 30% of current shipping operations are related to transport of fossil fuels, including heavy fuel oil, LNG, and marine gas/diesel oil for use as ship fuel. Implementation of more sustainable propulsion technologies in combination with reducing shipping operations would thereby contribute to lowering GHG emissions from the shipping industry in dual ways, both in relation to a decreased need for transporting fossil fuels and the direct reduction of operational emissions. In addition, the anticipated phase-out of fossil fuels in other sectors will further contribute to a reduced need for transporting fossil fuels by ship.

Sustainable shipping on the horizon?

This thesis unpacks part of the complexity associated with decarbonising the global maritime shipping sector. Combined, the collected material from the three studies in this thesis tells a story of how enabling socio-technical change in the maritime shipping sector requires top-down as well as bottom-up influences. Although shifting away from fossil fuels in this hard-to-abate sector is a slow-moving process, some small, hopeful steps ahead have been taken since the start of this PhD project. In 2023, the Initial IMO GHG Strategy from 2018 was updated to include more ambitious GHG reduction targets, aiming for net-zero emissions from international shipping by or around 2050 (IMO, 2023). Although still insufficient to drive full decarbonisation, additional policy instruments addressing GHG emissions have been decided upon by the IMO, and further mid-term measures are expected to be settled on during the next MEPC meeting in April 2025. During the last MEPC meeting in October 2024, the Secretary General of the IMO reportedly jokingly stated that delegates will be locked in the room until they have reached an agreement on implementation of mid-term economic measures at the next meeting. Technology suppliers such as engine manufacturers are taking initiative to develop new solutions for implementation of more sustainable propulsion technologies to meet the increasing demand from shipowners. Furthermore, an increasing number of different types of ships are now running on hydrogen, methanol and battery-electric propulsion systems as well as more modern versions of wind-assisted propulsion, either as the sole propulsion technology or as part of a hybrid solution. However, although positive improvements have been made during the course of this PhD project, current efforts are still insufficient to drive the urgently needed shift to more sustainable propulsion technologies, and the transition trajectories remains uncertain. Ultimately, the maritime industry continues to be a hard-to-abate sector, and the findings of this thesis highlight that the shift to sustainable shipping will indeed be more difficult than turning an oil tanker.

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Appendices

Appendix A: Supplementary materials for Study 1

Overview of interview respondents

* Indicates interviews that especially informed Paper III

	Organization type	Market segment	Technology focus	Year	Number and position of informants	Duration in minutes
1	NGO	Generic	Generic	2015	1 – Advisor maritime	60
2	Industry association	Generic	Generic	2015	1 – Director (Head of Environment)	30
3	Industry association	Generic	Generic	2015	1 – Head of Maritime Branch	60
4	Classification company	Generic	Generic	2015	1 – Programme Director	60
5	Public authority	Coastal ferry	Generic	2016	1 – Senior advisor	60
6*	Public authority	Generic	Generic	2016	1 – Senior engineer	60
7	Ship yard	Coastal ferry/fishing	Generic	2017	1 – CEO	75
8*	Public support agency	Generic	Generic	2017	2 – Market Dir. Transport, Senior advisor	85
9*	R&D	Generic	BE	2017	1 – Research scientist	95
10	Technology supplier	Generic	BE	2017	1 – Head of Strategy and Business Develoment	90
11*	Ship owner	Coastal ferry	Generic	2017	2 – CEO, CTO	50
12	R&D	Generic	Generic	2017	1 – Assoc. Professor	80
13	R&D	Generic	Generic	2017	1 – Senior research scientist	70
14	Fuel producer	Generic	Biofuels	2017	1 – COO	70
15	Public authority	Generic	Generic	2017	3 – Senior engineer	80
16	Classification company	Generic	Generic	2017	1 – Principal engineer	65
17	Technology supplier	Generic	BE	2017	1 – VP Business development	80
18*	Public support agency	Generic	Generic	2017	1 – Manager	80

19*	Public support agency	Generic	Generic	2017	1 – Special advisor	80
20	Technology supplier	Generic	H2	2017	2 – CEO, CTO	90
21	Public authority	Generic	Generic	2017	2 – Senior advisor (x2)	60
22	Cluster organization	Generic	Generic	2017	2 – CEO, Advisor	75
23	Ship owner	Freight	Generic	2017	1 – CEO	65
24	Technology supplier	Generic	Generic/ BE	2017	1 – Managing Director	70
25	Technology supplier	Generic	Generic/ BE	2017	2 – CEO, Manager Sales and Business Development	75
26	Ship owner	Offshore supply	Generic	2017	1 – Senior Project Engineer	80
27	Public authority	Generic	Generic	2017	2 – Senior engineer (x2)	75
28*	Ship owner	Offshore supply	Generic	2017	1 – VP Technology & Development	85
29	Ship yard	Generic	Generic	2017	1 – CEO	70
30	Ship design	Generic	Generic	2017	1 – CEO	85
31	R&D	Generic	H2/BE	2017	1 – Research scientist	80
32*	Technology supplier	Generic	Generic/ BE	2017	1 – Director Engineering & Projects	80
33	Ship owner	Freight	Generic	2017	2 – CEO, Engineer	80
34	Technology supplier	Generic	BE	2017	1 – CEO	75
35	Ship owner	Freight	Generic	2017	1 - VP Newbuilding and Projects	35
36	Public authority	Coastal ferry	Generic	2017	2 – Managing Director, Special advisor	65
37	Fuel producer	Generic	H2	2017	2 – Analyst, Chief Project Officer	75
38	Industry association	Freight	Generic	2017	1 – CEO	80
39*	Ship owner	Coastal ferry	Generic	2017	1 – CTO	60
40	Ship owner	Fishing	Generic	2017	1 – General Manager	60
41	Ship owner	Aquaculture	Generic	2018	1 – CEO	45
42	R&D	Generic		2018	2 – Professor, Head of Department	100
43	Industry association	Fishing	Generic	2018	1 – CEO	60
44*	Ship owner	Offshore supply	Generic	2018	1 – HSEQ Environmental Engineer	60
45*	Ship design	Generic	Generic	2018	1 – Design Manager	85
46	Technology supplier	Generic	Generic/ BE	2018	2 – IP Manager, Business Development & Strategy Manager	80
47	Ship owner	Offshore supply	Generic	2018	1 – CEO	60
48	Ship yard	Offshore supply, coastal ferry	Generic	2018	2 – Deputy Managing Director, Naval Architect	70
49	Tech.-specific interest group	Generic (BE)	BE	2018	1 – Managing Director	25

50	Ship design/yard	Generic	Generic	2018	2 – VP Conceptual Design, VP Technical	70
51	Ship yard	Generic/coastal ferry	Generic	2018	2 – CEO, CTO	100
52	Technology supplier	Generic	BE	2018	2 – Sales manager, Business development manager	90
53	Public authority	Generic	Generic	2018	3 – Senior advisor, Technical Manager, Head of division	120
54*	Ship owner	Fishing	Generic	2018	1 – CEO	75
55	Ship owner	Offshore supply	Generic	2018	1 – Head of Operations	20
56*	Public authority	Coastal ferry	Generic	2018	1 – Senior advisor	80
57	Ship yard	Fishing, aquaculture	Generic/ BE	2018	1 – Managing Director	45
58	Ship owner	Fishing	Generic/ BE	2019	1 – CEO	60
59	Industry association	Generic	Generic	2019	1 – Director Environment	60
60	Tech.-specific interest group	Generic	H2	2019	1 – General secretary	65
61*	Industry association	Generic	LNG/bio/ H2	2019	1 – General Manager	55
62	Other	Generic	Generic	2019	1 – General Manager	30
63*	Fuel producer/ distributor	Generic	LNG/bio/ H2	2019	2 – Head of Business Development Clean Energy, Sales Manager	60
64*	Fuel producer	Generic	H2	2019	1 – Senior Advisor	50
65*	R&D	Generic	Biofuels	2019	1 – Research scientist	50
66	Tech.-specific interest group	Generic	BE	2018	1 – Project manager	70
67	Industry association	Generic	Generic	2018	2 – Policy advisor, Special advisor	65
68	Technology supplier	Generic	BE	2018	1 – VP Business development	60
69	Ship owner	Coastal ferry	Generic	2018	1 – CTO	55
70	Public authority	Coastal ferry	Generic	2018	1 – Senior advisor	80
71	Technology supplier	Generic	BE	2018	1 - GVP Sales & Marketing	90
72	Technology supplier	Generic	BE	2018	1 - Chairman & Co-Founder	80
73	R&D	Generic	Generic	2020	1 – Research Manager	90
74*	Technology supplier	Generic	Generic	2020	1 R&D – Senior Technical Officer	60

Exemplary interview guide

Purpose of interview

Short presentation round, project info and interview background

Clarification recording, anonymity, quote.

Short intro (informant)

Background: informant and business

What role in the business does the informant have, background?

Business brief: location, size, turnover, products / services, market.

Status of activities within the TIS

Search processes, motivation / incentive

Motivation for entering the field/domain/activity?

External factors, e.g.,

- Politically driven?
- External expectations?
- Customer demand?

Internal factors, e.g.,

- Advantages (competences)
- Economically motivated (winning tenders, savings etc)
- "Green" motives

How did you get into X?

- Via R&D, demo / pilot, or 'straight to' procurement?
- With others?
- When did you start considering the new technology, and when seriously?

Technology and knowledge

How do you assess which technologies / solutions you are investing in?

- Long term?
- Short term?

What knowledge is required for this?

Who do you work/collaborate with?

- If what, how / in what way?

How quickly does technology X develop in terms of price and performance?

What knowledge is needed to implement / apply new technology?

- How to develop /access knowledge/skills that are lacking?

What are your expectations for further technology development?

Low- and zero-emission technologies

How do you see the competition between different zero-/ low-emission solutions?

- Pros / cons of the different technologies?

Are they in competition or can they be complementary (incl. with conventional technology)?

Do you envision different solutions / technologies for different segments (within shipping)?

Have you used or tried to access support instruments for low- or zero-emission technology?
- Which?
- What / how do these contribute?

What is good / less good about instruments?
- What is missing and why?
- Do you have an overview of relevant support instruments?

What new products and services do you see emerging within this (technological) area?

In what areas do you see the potential for introducing new business models?

Legitimation

What laws / regulations affect the area?
- Are these adapted to uses, needs, requirements?
- Is the development/uptake hindered by legislation /regulations in any way?

Are there standards for the technology/ies, products?
- Are standards needed?

Do you do anything active to influence legislation / regulation / instruments and the like?

Do you attend workshops, seminars and the like?
- Any benefits?

Market formation

Who are your customers?

Do you have different customers in different segments?
- What are their buying incentives?
- Competition?

Who are your suppliers?
- Several?

What kinds of relationships do you have with your customers and suppliers?
- Cooperation? In what ways?

Describe the buying process

- Tender?
- Long processes?
- Complexity?

Use of new energy technology / fuel – does that change…

- Supplier Relationships?
- Business model?

What expectations do you have for future market developments?

Resource mobilization

How is development / implementation of new energy solutions financed?

- Challenges related to financing?

What infrastructure is needed for you to use new energy solutions (e.g., battery electric, hydrogen, biofuels)

- Demonstration or pilot plant?
- Production plants?
- Logistics system for distribution and filling / making available?

Is there anything that hinders infrastructure development?

- What drives / prevents it from being built?

New energy solutions - does it require new skills / knowledge, for example by hiring new employees with specialized expertise?

- Is this available?

Success criteria and barriers

What are the critical criteria for success?

- Technology, resources, policy support, market

Circumstances that make you consider abandoning X?

How about the sector /TIS as a whole?

What are the biggest uncertainties?

- Why and what are these?
- How do you handle these uncertainties?
- Technology, market, other?

Final questions (wrapping up)

How do you view the long-term development of shipping and what role will you have?

- What will be the role of technology X?

Norwegian maritime industry has ambition for significant emission cuts in the years to come - What do you think it will take to make this happen?

If you were to advise those who develop and implement regulations and legislation and (in part) can directly influence the framework conditions - what would your main message(s) be?

Is there something we haven't touched upon that you think is important for the success of green transformation in maritime transport?

Is it ok if we contact you later for a follow-up interview, workshop etc.?

Code book

Category 1 – Technology type

Here we would expect most codes to be quite long pieces of text – in some cases entire interviews.

- Biogas
- Biodiesel
- Bioethanol
- Electric
- Hydrogen
- LNG
- Conventional
- Other

In using these codes, we do not distinguish between single technology and hybrids. The only exemption from this is that we only code "conventional" when it is not a hybrid

This has the following implications:

- Text on battery electric / conventional hybrid = "battery electric"
- Text on battery electric / hydrogen hybrid = "battery electric" + "hydrogen"
- Text on conventional single technology = "conventional"

Category 2 – TIS structural components

This category might result in many, many coding stripes, if we code every actor mentioned, every relation between actors etc. One suggestion could be to only code when a structural component is – according to the interviewee – of considerable importance to the TIS, but as noted by Anna, if we want a complete structural map, all should probably be coded. So, perhaps we code everything in the first interviews and see if it is manageable?

ACTORS

- Ship-owners
- Yards
- Technology suppliers (for ships and vessels)
- Technology suppliers (for infrastructure)
- Ship/maritime designers
- System integrators (e.g., Siemens which is also a technology supplier for both ships/vessels and infrastructure)
- R&D
- Public support agencies (e.g., Enova, Innovasjon Norge, NO_x-fondet)
- Public authorities (e.g Kystverket, Sjøfartsdirektoratet, Statens Vegvesen, Direktoratet for samfunnsikkerhet og beredskap, Samferdselsdepartementet)
- NGOs (e.g. Bellona, ZERO)
- Local and regional government
- Logistic operators
- Ports/harbours

NETWORKS BETWEEN ACTORS

- Cluster organisations (e.g., NCE Maritime Cleantech, GCE Maritime Cleantech)
- Research, innovation and demonstration projects (e.g., Pilot-e projects)
- Industry associations or coalitions (e.g., Norsk Industri maritime bransjeforening, Maritimt forum (Trøndelag, Nordvest etc.))
- Other partnership programs (e.g., Grønt Kystfartsprogram)

RULES, REGULATIONS AND OTHER FORMAL INSTITUTIONS

- The interviewee mentions particular formal institutions that impact a TIS, e.g., safety regulations for batteries on ships

NORMS, VALUES AND OTHER INFORMAL INSTITUTIONS

- The interviewee mentions particular informal institutions that impact a TIS, e.g., new technology that doesn't fit with institutionalised practice

Category 3 – TIS functions

Below, so-called rules for inclusion are provided for each of the codes to ensure a joint understanding of what the code signifies.

- Knowledge development and diffusion
    - The interviewee talks about development of knowledge of importance for the TIS or diffusion of knowledge in the TIS.

Knowledge can be of different types, including scientific knowledge, market knowledge, and knowledge about production, natural resources or logistics

- Direction of search
    - The interviewee talks about how drivers and incentives influence the development of the TIS. Examples of drivers and incentives are interest of key (potential) customers, interest of key (potential) suppliers of technologies, components and services, interest of key policymakers, and the suitability of current policy instruments. It is particularly important to capture reasons for actors to deploy their resources in a particular direction, as we are covering several competing/complementary technologies. What are the arguments for focusing on a given technology?
    - Note that direction of search refers to both directions to enter the TIS, but also direction within the TIS
- Entrepreneurial experimentation
    - The interviewee talks about experimenting with different solutions to practical challenges, or the sources of uncertainty that these experiments are meant to reduce. This may for example be concerned with testing new technologies, applications, or business models
- Market formation
    - The interviewee talks about aspects related to market development. Examples of such aspects are market size, pricing systems, primary demand vs derived demand, articulation of demand (including customer preferences), and other drivers of market formation such as standards and procurement practices
- Legitimation
    - The interviewee talks about social acceptance and alignment of the TIS/industry with formal (e.g., certifications, rules and regulations) and informal (e.g., reputation, norms and values) institutions.
    - The interviewee talks about acceptability of the technology itself, for instance in relation to performance assessments, actual or perceived problems with the technology etc.
- Resource mobilization
    - The interviewee talks about mobilisation of financial capital, human capital (including training, education etc.) or infrastructure (e.g., demonstration facilities) of importance for development of the TIS
- Development of positive externalities
    - The interviewee talks about the development of positive external economies in the TIS in the form of e.g., specialised suppliers, intermediaries, complementary technologies (e.g. infrastructure) or

a pool of shared labour. In other words, freeriding is possible – actors may benefit without investing

Category 4 – Magnitude codes

Magnitude coding is a coding technique where the codes *"can consist of words or numbers that suggest evaluative content"* (Saldaña, 2009, p. 59). In this project, the suggestion is to use magnitude codes in relation to at least the TIS functions codes (category 3) and the TIS context codes (category 6) in order to facilitate the analysis. Consequently, when a piece of text is coded with a TIS function or TIS context code, it should also be coded with a magnitude code.

- Positive
  - The interviewee talks about a strength of a TIS function (in relation to Category 3) or a positive contextual interaction (in relation to Category 6), e.g., beneficial sectoral regulations/institutions, ("lead") users, diversifying companies or supporting industry associations
- Negative
  - The interviewee talks about a weakness of a TIS function (in relation to Category 3) or a negative contextual interaction (in relation to Category 6), e.g., barriers and resistance to change, including actors that are not part of the TIS, e.g. ship companies who are not engaged in any of the TIS
- Neutral
  - The interviewee talks about a TIS function (in relation to Category 3) or a contextual interaction (in relation to Category 6) in a neutral manner
- Mixed
  - The interviewee talks about a strength and a weakness of a TIS function (in relation to Category 3) or a mixed contextual interaction (in relation to Category 6) at the same time

Category 5 – Market segments

- Passenger market segment:
  - Near shore (domestic market) passenger market segment: ferries (bil- og passasjerferger), high-speed ferry (hurtigbåt), coastal express (hurtigruta). Specify if case vessels operate in the tourist market segment (e.g., Vision of the Fjords, Hurtigruta Expedition ships)
  - International passenger market segment: ferries between e.g. Norway and Denmark, Sweden, cruise ships
- Offshore supply segment: vessels serving offshore oil and gas or wind operations

- Aquaculture market segment: e.g., work boats, live-haul boats (brønnbåt, for transporting fish from pens to processing site)
- Fishing market segment: ranges from small fishing boats that operate nearshore to large seagoing 'fish factories'. Should distinguish between sub-market segments
- Freight market segment: vessels transporting bulk, dry and liquid goods
- Other

Category 6 – TIS context

Here we are interested in inducement and blocking mechanisms in the context of the TIS, and how they contribute to the TIS functions. We use magnitude codes (category 4) to indicate the type of interaction between TIS and context, and contribution to TIS functions. Context dimensions include:

- TIS-TIS interaction
    - The interviewee talks about interaction between the focal TIS (e.g., hydrogen) and other TIS (e.g., battery-electric)
        - Biogas
        - Biodiesel
        - Bioethanol
        - Electric
        - Hydrogen
        - LNG
        - Conventional
- TIS-sector interaction
    - The interviewee talks about interaction between the TIS (in the scope of maritime transport) and key sectors
        - Maritime shipping
        - Onshore transport
        - Power sector
        - Agriculture/forestry
        - Oil & gas
- TIS and geographical scale:
    - The interviewee talks about geographical scale:
        - Local
        - Regional
        - National
        - International
- TIS interaction with political context:
    - The interviewee talks about political processes and attempts/actions (lobbying) to influence policymaking or regulations

Survey data used in Paper III

LNG		Implemented	<10 years	<20 years	>20 years	Never
Reduction of CO_2	Not a priority	0	0	0	0	18
	Low/medium priority	1	23	9	14	56
	High/very high priority	17	32	7	6	41
Reduction of PM	Not a priority	1	1	1	2	19
	Low/medium priority	5	19	7	13	64
	High/very high priority	12	31	8	4	33

Appendix B: Supplementary materials for Study 2

List of attendance at conferences and webinars

* Events that were used for triangulation and validation of findings from document analysis and interviews conducted for Paper I

Date	Event: title	Organiser
2020		
May 29th - June 1st	Industry conference: The Future of Ocean Energy and Shipping	Blue Forum, industry association
June 17th	Webinar: The role of biofuels in maritime operations	NCE Maritime CleanTech, industry association
June 19th	Webinar: Wärtsila Zero Emissions webinar	Wärtsila, technology supplier
June 23rd	Webinar: First results from the Swedish Transport Administration's industry research program 'Sustainable Shipping'	Lighthouse – Swedish Maritime Competence Centre, research institute
June 23rd	Webinar: Ensuring efficiency in electric vessels	NCE Maritime CleanTech, industry association
August 31st	Webinar - Blue Growth's shipping policy webinar – how do we create a sustainable restart?	Swedish Shipowners' Association
October 6th	Webinar: New results from the Swedish Transport Administration's industry research program 'Sustainable Shipping'	Lighthouse – Swedish Maritime Competence Centre, research institute
October 13th	Webinar: Fairway Forward Sustainability webinar	Swedish Shipowners' Association & Finnish Shipowners' Association
October 28th	*Webinar: Where does shipping's decarbonisation agenda sit in a post-Covid-19 world?	International Chamber of Shipping, Shipowners' Association
October 28th	*Industry conference: Danish Maritime Day 2020 – The maritime climate agenda post Covid-19	Danish Shipowners' Association
November 5th	Webinar: LTH Methanol webinar day	Lund University, research institute
November 6th	Webinar: What are the plans for the shipping sector?	Swedish Shipowners' Association
November 18th	Webinar: Focus area shipping, maritime technology & marine energy	Swedish Institute for the Marine Environment, research institute
November 19th	*Webinar: Swedish Shipowners' Association's autumn meeting 2020 – Shipping's role in a green restart	Swedish Shipowners' Association
November 26th	*Webinar: Insights from MEPC 75	DNV, classification society
December 15th	*Industry conference: Decarbonising Shipping – Virtual Forum	ALJ Group, interest organisation
2021		
January 15th	Webinar - Blue Growth's shipping policy webinar – Which financial policy measures are needed for a sustainable restart?	Swedish Shipowners' Association
January 20th	*Webinar: EEXI – what do you need to know?	DNV, classification society
January 27th	Webinar: EU ETS	European Community Shipowners' Association

February 9th	Webinar: Managing Shipping 1 – creating sustainability through management	Gothenburg Research Institute
February 11th	*Webinar: The Swedish Transport Agency's Maritime Shipping Seminar	The Swedish Transport Agency
March 2-3rd	*Industry conference: 3rd Greentech in Shipping Virtual Forum	ALJ Group, interest organisation
March 10th	*Webinar: Legal, stakeholder and commercial forces of change – lessons for the maritime sector	International Chamber of Shipping, Shipowners' Association
March 17th	Webinar: New results from the Swedish Transport Administration's industry research program 'Sustainable Shipping'	Lighthouse – Swedish Maritime Competence Centre, research institute
April 6th	Webinar: Managing Shipping 2 - Research at sea – challenges and possibilities	Gothenburg Research Institute
April 14th	Webinar: NRIA Shipping 2021 – presentation of the national maritime shipping agenda	Lighthouse – Swedish Maritime Competence Centre, research institute
April 27-28th	*Industry conference: 2nd Decarbonizing Shipping - Virtual Forum	ALJ Group, interest organisation
May 4th	Webinar: Managing Shipping 3 - Reasons for why we should target big shipping firms for climate change mitigation	Gothenburg Research Institute
May 11th	*Webinar: LNG as a ship fuel – where are we and what comes next?	DNV, classification society
May 12th	*Webinar: How to decarbonise shipping	Lloyd's Register, classification society
May 18th	Webinar: A green maritime shift - Lessons from the electrification of ferries in Norway	Team Society, Norwegian University of Science and Technology
May 21st	Webinar: The Swedish Shipowners' Associations webinar series on the green transition 1: The EU taxonomy and its impact on shipping	Swedish Shipowners' Association
May 26th	Webinar: Maritime shipping in the EU ETS	Lighthouse – Swedish Maritime Competence Centre, research institute
May 27th	*Webinar: Danish Shipowners' Association's annual meeting: First Movers on Climate - Perspectives and demands from customers	Danish Shipowners' Association
May 28th	*Webinar: The Swedish Shipowners' Associations webinar series on the green transition 2: What is happening with development of future ship fuels at the global level?	Swedish Shipowners' Association
June 1st	Webinar: Managing Shipping 4 - Refrigerated goods at sea	Gothenburg Research Institute
June 4th	Webinar: The Swedish Shipowners' Associations webinar series on the green transition 3: Climate, environment and politics	Swedish Shipowners' Association
June 8th	Webinar: Finance, Innovation, Transition 1 – Finance in focus	European Community Shipowners' Association
June 11th	Webinar: The Swedish Shipowners' Associations webinar series on the green transition 4: Green financial support	Swedish Shipowners' Association
June 15th	Webinar: Finance, Innovation, Transition 2 – Innovation in focus	European Community Shipowners' Association
June 23rd	*Webinar: MEPC76 in focus – CO_2 emissions regulations adopted	DNV, classification society

July 6th	*Webinar: How to decarbonise shipping by 2050?	The European Federation for Transport and Environment, NGO
July 7th	*Webinar: EEXI and CII calculations – DNV's way forward	DNV, classification society
September 7th-8th	Webinar: Ship.Energy Summit 2021	Ship.Energy, maritime industry journal
September 9th	Webinar: Finance, Innovation, Transition 3 – Transition in focus	European Community Shipowners' Association
September 16th	*Webinar: Carbon Intensity Indicator (CII) – a closer look	DNV, classification society
September 16th	Webinar: Freight at sea – current affairs	The Swedish Transport Administration
October 13th	*Webinar: How to decarbonise international shipping and aviation	The European Federation for Transport and Environment, NGO
October 13th	Webinar: Decarbonising maritime transport	One Ocean Summit, interest organisation
October 19th	*4th Greentech in Shipping – Virtual Forum	ALJ Group, interest organisation
October 19th	*Webinar: The 4th Propulsion Revolution – Commitment and Challenge	International Chamber of Shipping, Shipowners' Association
November 18th	Webinar: The Swedish Shipowners' Association's autumn meeting seminar – Regulation and financing of the green transition	Swedish Shipowners' Association
November 18th	*Webinar: COP26 – take aways and a feasible pathway to net zero	DNV, classification society
December 14th	Webinar: Methanol powered pilot boat launch event	FASTWATER Research project, Lund University
December 17th	Webinar: Sustainable ship fuels – current debates	Lighthouse – Swedish Maritime Competence Centre, research institute
2022		
January 11th	Industry conference: The fuel of the future	DNV, classification society
January 13th	Webinar: Hydrogen: Green or greenwashing?	The European Federation for Transport and Environment, NGO
March 1st	Webinar: Acting now for the zero-emission planes and ships of tomorrow	The European Federation for Transport and Environment, NGO
March 15th	Webinar: Insights after COP26	DNV, classification society
March 17th	*Webinar: Green shipping – Nordic actions to foster European and global zero emission	The European Federation for Transport and Environment, NGO
April 6th	*Webinar: CII Shipping Efficiency Game 2023-2030	Lloyd's Register, classification society
April 6th	Webinar: LBG at land and at sea	Biogas West, interest organisation
April 26-28th	Industry conference: World Maritime Technology Conference 2022 – Help set the green agenda for the years to come (Copenhagen)	World Maritime Technology Congress & Maritime Development Centre, interest organisations
June 16th	*Webinar: MEPC 78 in focus	DNV, classification society
November 22nd	*Webinar: How will COP27 shape MEPC79 for shipping and beyond?	Lloyd's Register, classification society

December 20th	Webinar: MEPC 79 in focus	DNV, classification society

List of data sources for document analysis of the policy strategy

Type of Document	Year
Strategic Plan for the Organization for the Six Year Period XX	2000-2006
	2006-2011
	2012-2017
	2018-2023
High-Level Action Plan of the Organization and Priorities for the XX Biennium *(published every two years)*	2004-2005
	2006-2007
	2008-2009
	2010-2011
	2012-2013
	2014-2015
	2016-2017[7]
List of Outputs for the years XX-YY Biennium *(published every two years)*	2018-2019
	2020-2021
Resolution A.963(23) IMO Policies and Practice Related to the Reduction of Greenhouse Gas Emissions from Ships	2004
Initial IMO Strategy on Reduction of Greenhouse Gas Emissions from Ships	2018
MEPC73/19 Annex 9 Programme of Follow-up Actions of the Initial IMO Strategy on Reduction of GHG Emissions from Ships up to 2023	2019

Materials provided to respondents before interviews

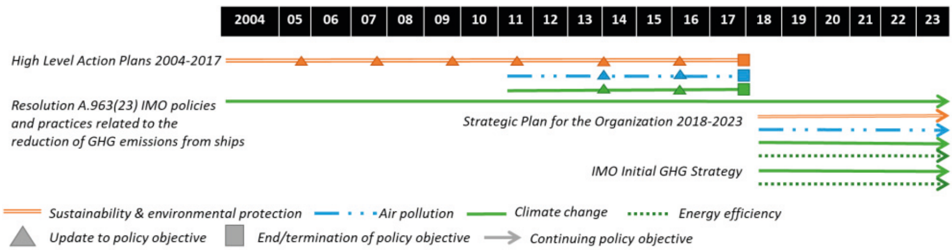
”Dear interview respondent,

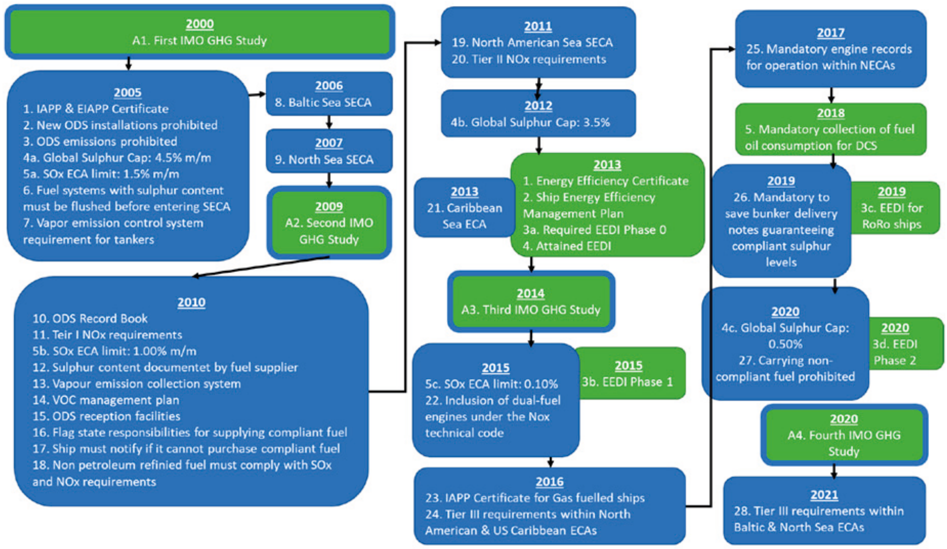
In preparation for our interview, we kindly ask you to take a look at the two figures in this document. Part of our project is based on a content analysis of IMO strategies and policy instruments, to map the global level policies for international shipping, and we would very much appreciate your input on if we have identified all relevant instruments or if there is something missing. These figures will also provide a starting point for some other questions during the interview.

The first figure represents a timeline of the thematic focus of the High Level Action Plans for 2004-2017, the Strategic Plan for the Organization 2018-2023, and the IMO GHG strategy. The second figure is a detailed timeline of the identified policy measures collected from MARPOL Annex VI (and the IMO GHG studies) since its implementation in 2005 until today.

Thank you in advance!”

[7] In 2018 the High-Level Action Plans was replaced by the “List of Outputs for the XX Biennial”.





Interview guide

Introduction

Introduction of research project and setting for the interview

What are your responsibilities within your division?

Development of regulation over time

Can you tell us a little bit about the background of the implementation of MARPOL Annex VI?

How do you interpret that IMO regulation for air emissions have developed over time (since the implementation of MARPOL Annex VI in 2005)?

How do you perceive the balance between regulation aimed at air pollution vs. GHG has developed over time since the implementation of MARPOL Annex VI?

Connections between implemented measures

We sent you a timeline over identified measures that has been implemented within Annex VI:

- Do you see any particular turning points in the development of regulation?
- Is there any regulation that is not included in the timeline?
- When looking at the timeline, were you surprised by the division between air polluters and GHG?

How extensive do you think the current measures within Annex VI are when it comes to covering all types of air emissions from ships?

Do you see it as possible for a certain ship to comply with all regulation simultaneously?

- Do you see any particular differences regarding the ability to comply with regulation between different segments?
- Do you see that the possibility to comply with all regulation simultaneously has changed over time? More difficult? Why?
- Are there any potential trade-offs associated with complying with the complete regulation?
- Do you see any contradictions between individual policy measures?
- Can you identify any policies that in combination with each other clarify what the regulation is aiming to achieve? For example, when it comes to what technology choices to make in order to comply with the rules?
- (Can you give examples of instruments reinforcing or contradicting each other?)

We have also looked at the strategic directions of IMO in the past 20 years (show timeline over strategies), and have identified themes within the High Level Action Plans, Strategic Plans of the Organisation and also the IMO GHG study.

- Do you agree or disagree with the development of thematic focus that is showed in this figure?
- Do you have any additional insights in the development of strategic focus for IMO?
- What do you think about the relation between the thematic focus of the IMO strategies, and the division between policy measures focusing on air pollution vs. GHG?

Effects from current regulation

The industry continuously asks for a levelled playing field, do you think it is possible to achieve that?

In relation to the overarching targets within the Strategic Plan for the Organisation (give example) – do you see that the current policy instruments are sufficient to reach these targets?

- Do you think the current global regulation regarding air emissions from ships is sufficient to reach the targets stated in the IMO GHG Strategy? If not, what is missing?

IMO regulation aims to be technology neutral, do you agree that it is in fact technology neutral?

As the IMO regulation is designed today, do you see any propulsion technology or fuel being favoured?

What do you think are the major challenges ship-owners face regarding technology choices for new builds?

- How are these challenges related to that the global order book is currently at a record low?

Do you see a risk for technological lock-in on a certain propulsion technology based on how regulation looks like today?

Future regulation and policy processes

What is your impression of the policy development processes within IMO?

- What do you think are the advantages and disadvantages with the routines of the IMO negotiations?
- Do you think the process allow for implementation of coherent policy instruments?

What do you think are the biggest challenges for stricter global regulation of GHG?

What do you think about the recent MEPC76 negotiations? Were they successful in your opinion?

How do you perceive the current speed of developments of IMO regulation, specifically in relation to the GHG strategy?

- Compared to previous years?

How do you see the relationship between global and regional regulation?

- Positive or negative with stricter regulations on regional/national level than IMO regulation?
- Do you see regional measures as a potential driver or hinder for development of global regulation?

Currently, all global regulation from the IMO is aimed at restrictions, stating what ships are allowed and not allowed to do – but there is no global policy to promote sustainable propulsion. Do you know anything about the reasons for IMO regulation only being restrictive and not proactive?

- What do you think about that? Is it problematic?
- What type of policy to promote sustainable technologies would you like to see?
- What do you think would speed up implementation of alternative solutions the most?

- Are there any types of policy measures you see would be ineffective for the shipping sector?

How is the discussion around regulation of methane emissions proceeding?

- The implementation of LNG ships has increased drastically in the last decade, and especially in the last years – and the latest GHG study showed that the methane emissions from shipping has increased with around 150 % since the last study.
- The industry claims that the methane slip from LNG engines will decrease with technology improvement, do you think this technology improvements will happen without regulation of methane emissions/slip?

Do you have any recommendations of others that we should talk to as well?

Code book

- Policy element
  - Policy Instrument – Instrument mix
  - Policy Objective – Policy Strategy
- Policy Topic
  - Air Pollution
    - NMVOCs
    - NO_x
    - Ozone Depleting Substances
    - PM
    - SO_x
    - VOC
  - Climate Change
    - BC
    - CO
    - CO_2
    - Energy Efficiency
    - GHG
    - HFCs
    - Methane
    - N_2O
    - PECs
    - SF6
  - Sustainability and environment
  - Fuel oil quality
  - Marine environment
- Synergies with other instruments or objectives
- Trade-offs with other instruments or objectives
- Timeline

  - Coming
  - Discontinued
  - Addition
  - Replacement
  - Year
    - 2000
    - 2003
    - 2005
    - 2006
    - 2007
    - 2008
    - 2009
    - 2010
    - 2011
    - 2012
    - 2013
    - 2014
    - 2015
    - 2016
    - 2017
    - 2018
    - 2019
    - 2020
    - 2021
    - 2023
- Type of policy instrument
  - Economic
  - Regulatory
  - Soft
  - Instrument targeting creative processes
    - C1 – Knowledge creation, development and diffusion
    - C2 – Establishing market niches/Market formation
    - C3 – Price performance improvements
    - C4 – Entrepreneurial experimentation
    - C5 – Resource mobilisation
    - C6 – Support from powerful groups/legitimation
    - C7 – Influence on the direction of search
  - Instrument targeting destructive processes
    - D1 – Control policies
    - D2 – Significant changes in regime rules
    - D3 – Reduced support for dominant regime technologies
    - D4 – Changes in social networks, replacement of key actors

Appendix C: Supplementary materials for Study 3

Exemplary interview questions

Interviews with sail cargo initiatives

DRIVERS

What do you see as the main drivers for sail cargo operations?

Where does the demand for sail cargo come from? Would you say that it is costumer driven, or driven by you that are operating the sail cargo ships?

HINDERS

What are the main hinders for doing sail cargo operations? Daily operations/costs/access to trained crew/port infrastructure?

What challenges have you encountered since starting your company?

What do you think are the main hinders for someone who wants to start a sail cargo company?

BUSINESS MODEL

What does your business model look like? Has it changed since the company started?

How dependent are you on paying guests who sail along to make the business model viable?

Would you be willing to share your cargo rates? How much more expensive is it to ship cargo with you compared to conventional shipping? Have you increased prices after the pandemic, war in Ukraine, current economic state?

Cargo going westerly over the Atlantic?

COOPERATION

Who are your partners? Cargo owners, ship agents, brokers? How did/do you find cargo to be shipped by your ship(s)?

When we met in August you said that there is no cooperation between your company and other sail cargo initiatives, but I saw that you now have taken some cargo for Fairtransport? How did that collaboration come about?

Do you think the sail cargo community would benefit from working more together? In what way?

How would you like to see collaborations happen in the future?

FUTURE

Do you want to add additional ships to your fleet?

What do you see as the potential for sail cargo in the future? Should it be upscaled?

What do you think is needed to upscale sail cargo?

SKILLS

How difficult is it to find crew for all journeys? How often does crew come back?

Do you have any intentional plan for training new crew?

Do you think there is enough competence and human resources available for you to continue doing this? To upscale sail cargo?

REGULATION

Are you anticipating that sail cargo ships will be subject to increasing regulation? What do you think about that? Do you think that would be beneficial or a hinder for scaling up sail cargo operations?

RELATION TO CONVENTIONAL SHIPPING

How do you see sail cargo's relation to conventional shipping?

Do you feel like sail cargo is making a difference in the shift to sustainable shipping? Are there other (better) ways to make an impact?

Relation between traditional designs and modern wind-assisted ships?

Interviews with cargo owners

INTRODUCTION

Can you tell me a bit about your company, what was the motivation for starting it and how does it look like today?

(What does your business model look like? Has it changed since the company started?)

MOTIVATION

How did you first come in contact with Fairtransport? Can you tell me about the decision to start transporting cacao with sail cargo ships?

What motivates you to work with sail cargo? Has this motivation changed over the years?

IMPORTING WITH SAIL CARGO SHIP

How much of your cacao is imported by sail ship?

How much more does it cost? What makes the price worth it? How do you make it work?

How does the costumers react to the sail cargo wrapping? Has there been an increased interest in the chocolate bars produced from sail shipped cacao?

Are you looking to increase the volumes shipped by sail? Why/why not? Are you transporting cacao with other sail cargo companies? Are looking to transport cargo with additional sail cargo companies?

Is there anything that would make you stop importing cacao with sail cargo?

Would you recommend someone else looking to transport their cargo in a sustainable way to make use of sail cargo ships?

Would you be interested in a Fair trade lable for the transport part?

FUTURE

How do you see the future of sail cargo? In 5 years? In 50 years?

Do you think sail cargo should be upscaled?

How do you see your role as a costumer or cargo owner in the future/upscaling of sail cargo?

What role do you see sail cargo playing in the overall transition to a sustainable society?

Outside of your company, what hinders do you see for sail cargo?

Code book

Coding structure: enabler/hinder + factor for development + stage of development + scale

Enabler: Coded for development factors mentioned as drivers or enabling sail cargo operations. Includes factors that could be enabling if implemented.

Hinder: Coded for development factors mentioned as challenges or hinders for sail cargo operations. Includes factors that could be hinders if implemented.

Factors for development

Institutions

- Classification society
- Education institute
- Flag state
- Insurance company

- Port authority
- Regulatory institution

Markets

- Demand
- Supply

Networks

- Cargo costumers
- Cargo producers
- Crew
- Education
- Intermediaries
- Investors
- Formal networks
- Informal networks

Resources

- Financial
- Human
- Infrastructure

Stage of development

- All stages
- Initiation
- Operations
- Upscaling or diversification

Scale

- Global
- EU
- National
- Home locality or region
- Host locality or region

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