Master's Thesis – Master Innovation Sciences

All at Sea

Accelerating the Sustainable Transition of International Shipping

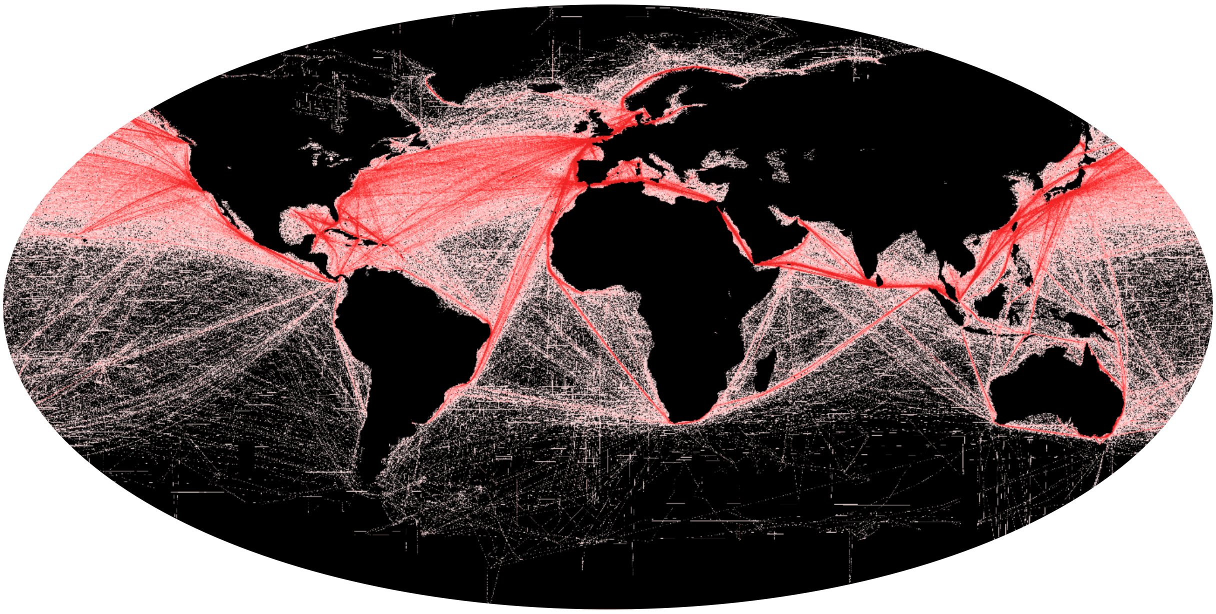

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Image: "Shipping density (commercial). A Global Map of Human Impacts to Marine Ecosystems, showing relative density (in color) against a black background." (Groll et al., 2012) Free to use under Wikimedia Commons license.

Abstract

Introduction

This thesis assesses the sustainable transition of international shipping and how it can be accelerated. Shipping is a hard-to-abate industry which is run unsustainably on a very polluting fossil fuel and accounts for as much CO_2-emissions as aviation.

Theory

The study draws on socio-technical transition theory, using Kivimaa & Kern's creation/destruction functions framework (based on the multi-level perspective and technological innovation systems) as well as the recent strand of literature on hard-to-abate industries, to ascertain which functions need to be fulfilled to accelerate the transition and how these functions are inhibited by 8 sector-specific barriers.

Methods

A mixed-method approach is used to generate insights into the case study of international shipping, with three methods used: 1) Literature analysis of academic and grey literature, including various reports on shipping (qualitative); 2) 12 semi-structured interviews with shipping stakeholders and experts (qualitative); 3) A historic event analysis of 1.460 relevant events identified in shipping news in the period since the IMO's initial GHG strategy (quantitative).

Results

The shipping regime is so stable because of its complex industry structure involving many different stakeholders, a strong fossil fuel lock-in that developed in symbiosis with globalisation, and the way it is governed through the slow-moving International Maritime Organisation. The 8 barriers for hard-to-abate industries also apply for shipping. Alternative technologies are available, but have not yet been implemented on a large scale. The dominant alternative options for a long time were LNG (i.e. another fossil fuel) and efficiency increases (i.e. incremental innovations), but recently the focus has shifted towards more radically different alternative fuels such as hydrogen and ammonia. Electric propulsion has an important role in specific market segments, while biofuel, wind propulsion and methanol are adopted to a lesser extent across all segments. Barriers influence different technologies differently and therefore a coexistence or combination of various alternatives is likely to be the future of shipping. Hard-to-abate-sector-specific solutions can accelerate the shipping transition, including carbon pricing, regional governance, cooperation on R&D and the creation of new coalitions.

Conclusion/discussion

Incorporating sector-specific factors into transition frameworks allows for a more accurate assessment of regime types, resulting in better advice. Hard-to-abate transitions can be achieved, but they are unlikely to arise from niches without substantial policy action to destabilise and put pressure on the regime. Pathways where the regime is transformed from within are more probable than those where the regime and its actors are substituted.

Preface

In the early phases of the thesis process, after having broadly settled on the topic of sustainable shipping, the magnitude of the issue and the amount of possible angles to take on it was quite intimidating. It seemed almost futile to try to grasp this literally world-spanning transport system with all its stakeholders and complexities. However, the attempt to navigate the ocean of available information paid off increasingly with the time spent studying it. The biggest motivation turned out to be the realisation of how shipping is not just some industry that is "out there", but how intricately linked it is to all of our daily lives. The notebook this was written on, the clothes I wear and the breakfast I had this morning most probably all have components that have been transported on the gigantic container ships that make their ways across the seas endlessly. At the same time, it was a bit puzzling how much the climate effects of road transport, electricity generation and aviation are publicly and privately discussed and how little attention is paid to a sector which emits roughly as much greenhouse gases as aviation does. There is so much talk about the detrimental effects of flying that with "flight shame" even a term was coined to describe the embarrassment that people feel when stepping on a plane (and deservedly so), but "shipping shame" is unheard off. This might stem from the fact that for most of the population, international shipping is completely out of view.

Two months of the work on this thesis were conducted on the island of Curaçao, where I went (despite my flight shame) to accompany my girlfriend on her fieldwork she conducted on Venezuelan migration and to escape the hard Covid-19-lockdown imposed on the Netherlands and Germany in early 2021. There, it became clear that another reason for this differential treatment is that flying is perceived as a luxury, whereas shipping is a lifeline to the many parts of the world that are completely dependent on food imports and where all manufactured goods arrive by ship. Buying Dutch-grown vegetables in the supermarkets on a Caribbean island was at first a surreal experience, but then a reminder that this also forms part of globalisation. Moreover, sitting in a café in Willemstad, reading up on shipping, while massive ships emitting clouds of dark smoke passed by in front of me, made the thesis topic a lot more palpable.

Overall, the most interesting part of the research were definitely the interviews conducted with the very different stakeholders, which immediately provided two valuable insights: Firstly, the issue of sustainable shipping was seen as increasingly important in the shipping sector, which confirmed the relevance of my topic choice. Secondly, whereas participants working for entrepreneurial companies focused on a specific technological alternative naturally saw their technology as the best solution, all other interviewees and especially the incumbent actors unanimously emphasised the uncertainty with regards to what will be the shipping of the future. In other words, the shipping industry seems to be "all at sea" when it comes to sustainability.

Contents

1. Introduction

1.1. Background

On the 23rd of March 2021, the Ever Given, a huge ship loaded with 18.300 containers, got stuck sideways in the Suez canal, blocking for six days a route where roughly 12% of world trade passes through and thereby disrupting logistic chains all over the world (BBC News, 2021; Martin, 2021). The ship perfectly illustrates the global nature of international shipping: it was part of a Taiwanese fleet, owned by a Japanese company, manned with an Indian crew, guided by two Egyptian Suez Canal Authority pilots, sailing under the flag of Panama and loaded full of goods destined for European markets (BBC News, 2021; Vesselfinder, 2021). The incident briefly brought the world's attention to the often overlooked undercurrent of the global economy: the shipping industry.

Ever Given, stuck in the canal (Markuse, 2021)

The international shipping industry is inherently linked to economic globalisation like no other industry. As the World Shipping Council (WSC), the largest liner shipping trade association, put it succinctly, it is the "lifeblood of global economic vitality" (WSC, 2021a). Without shipping, the globalised trade networks of today could not exist. One fundamental reason for the predominance of this mode of transport is its relative energy efficiency, as cargo transported on ever larger container ships requires far less fuel than it does on road transport, railways or air travel. Due to this fact, actors from the shipping industry never tire to emphasise that it is the "most carbon-efficient mode of transportation", which is correct when measured in grams of CO_2 produced per ton of freight (WSC, 2021b). However, there are some problematic caveats that make the industry, as it is run today, unsustainable on the long term: Whereas currently, shipping is responsible for an estimated 2.6% of global human-made CO_2 emissions, this share is projected by the International Maritime Organisation (IMO) to rise up to 17% by 2050, if no action is taken (SSI, 2020). Moreover, while other modes of transport have promising venues to full electrification (ETC, 2018a), ships run almost exclusively on the dirtiest of fossil fuels: heavy fuel oil (HFO), a cheap leftover product of the refining process (Wijnolst & Wergeland, 2009). As such, serious efforts are required for a transition of shipping to a more sustainable mode of operation.

1.2. Previous studies

How such sustainability transitions work has been one of the central questions in the field of transition studies, an interdisciplinary area of research which has contributed substantially over the last decades to the understanding of socio-technical transitions. A major framework herein is the multi-level perspective (MLP), which conceptualises transitions as an interplay of landscape, regime and niche level, where change happens when innovations rise from the niche and transform the regime (Geels, 2002). Innovation literature has thus been a focus for illuminating these niche-regime interactions. Herein the concept of technological innovation systems (TIS) is influential in describing the conditions that niche technologies need to transform the regime (Hekkert et al., 2007). The TIS framework has been deemed useful for giving concrete policy advice to facilitate the development of sustainable innovations from niche to regime level (Markard & Truffer, 2008). Due to this complementarity, attempts have been made to integrate the MLP and TIS frameworks (Markard & Truffer, 2008). Kivimaa & Kern (2016) have done so with their creation & destruction functions, including the creation of niche technologies through TIS as well as the destruction of the regime needed for a transition in the MLP. However, some scholars have criticised that case studies of both MLP and TIS tend to have a (sub-)national focus and thus suffer from "implicit methodological nationalism", which does not pay sufficient attention to the increasingly global nature of many incumbent industries as well as innovation networks (Fuenfschilling & Binz, 2018, p. 737). Accordingly, they have suggested the frameworks of global socio-technical regimes (Fuenfschilling & Binz, 2018) and global innovation systems (GIS) (Binz & Truffer, 2017), with an explicit transnational global focus. Another very recent contribution to innovation systems literature with a different scope are mission-oriented innovation systems (MIS), which aim to provide concrete policy advice by defining the system around missions to solve wicked societal problems, instead of national borders or specific technologies (Hekkert et al., 2020).

A related upcoming topic in transition studies are hard-to-abate sectors, industries with specific properties that make their transition relatively difficult to achieve (Åhman, 2020) and hence "wicked" in terms of MIS literature. In comparison to electricity generation and personal road transport, where low-carbon alternatives have become competitive enough to reach the market, these sectors are characterised by a lack of established radical innovations, making their emissions harder to abate and their transition neglected, since policy-makers focus on the "lower-hanging fruit" of easier-to-abate sectors (ETC, 2018a). Originally, hard-to-abate industries have been narrowly defined as energy-intensive processing industries (EPIs) such as steel, aluminium, cement and other basic commodity production, as well as the chemical industry (Bataille et al., 2018; Wesseling et al., 2017). Some analyses of these sectors have applied the TIS framework (Wesseling & Van der Vooren, 2017) or combinations of TIS and MLP (Wesseling et al., 2017). Other authors make reference to the MLP, but admit to taking a rather techno-economic perspective themselves (Bataille et al., 2018). Further work has studied the carbon lock-in of (Janipour et al., 2020) and the global socio-technical regime (Bauer & Fuenfschilling, 2019) surrounding the chemical industry, as well as the transition of hard-to-abate industries from an earth systems governance perspective (Oberthür et al., 2020). Studies have also been strongly influenced by sectoral approaches to transitions (Baron et al., 2007) and sectoral innovation systems literature (Malerba, 2005), which both focus on specificities of certain industries with regards to their dynamics of change. A reoccurring conclusion of these studies is that the transition of the analysed sectors face barriers which are specific to those industries and thus require specific solutions (Wesseling et al., 2017).

Recently, the Mission Possible report by the Energy Transitions Commission has added heavy-duty transport, i.e. heavy road transport, aviation and shipping to their definition of hard-to-abate industries (ETC, 2018a). What unites these sectors with EPIs is that 1) their operations tend to be on a very large scale, resulting in the need for lots of infrastructure and typically domination by big corporations due to the high entry barriers and strong economies of scale and 2) they serve globalised markets with generic products & services traded to other businesses, leading to competition mainly by price and little consumer pressure. All of these factors lead to a lack of product differentiation and radical innovations, resulting in difficulties for sustainable technologies to succeed. Apart from those characteristics that apply to all hard-to-abate industries, shipping also possesses the particularity that it is largely situated outside of individual states' jurisdiction and is mainly governed through an international body, the IMO, making its regulation and governance even more difficult (van Leeuwen, 2015).

There are some notable previous studies on transitions in the shipping industry: The first to come to mind is the inaugural case study of the MLP on the transition from wind propulsion to steam power in the 19th century and thus ironically from a carbon-free to a polluting technology (Geels, 2002). More recent literature on sustainability transitions has often focused on specific technologies, such as a TIS analysis of modern wind propulsion technologies (Rojon & Dieperink, 2014) or MLP studies on wind propulsion and slow steaming (Mander, 2017) and efficiency increases (Pettit et al., 2018). These studies all come to similar conclusions, namely that a transformation of the shipping regime through these innovations is unlikely, either because the technologies will not make it to the market without further support (in the case of wind propulsion) or that they are not radical enough to have sufficient impact (in the case of efficiency increases).[1] Pettit et al. (2018) go so far to suggest that a landscape change in shifting consumption and production patterns reducing shipping demand is more likely than a successful regime change through the implementation of new technology. However, this thesis argues that two major factors give reason for a reassessment of the shipping industry through the lenses of transition theory: Firstly, landscape pressures on the regime have substantially increased in recent years, as evident in the IMO's initial strategy on GHG emissions, which set concrete targets for CO_2 reduction for the first time (Joung et al., 2020). Secondly, renewed interest in low-carbon technologies have led to the creation and further development of an array of viable alternatives.

1.3. Literature gap

Previous studies on shipping have focused on a few selected technologies and either applied the MLP or the TIS framework. This thesis takes a different approach, using Kivimaa & Kern's creative destruction functions framework, which combines insights from TIS and MLP. Hereby, the regime and all the relevant competing niche technologies can be assessed simultaneously, allowing for a more comprehensive look at the transition of shipping. On a more general note, while there is an abundance of transition literature on regime change and there exists a typology of transitions (Geels & Schot, 2007), there is no sufficient distinction between different regime types. Regimes are seemingly treated as uniform structures and regime characteristics remain abstract. However, as the emerging literature on hard-to-abate industries shows, these industries have a very specific type of regime which requires further examination. Understanding the specific lock-in mechanisms at play has crucial implications for regime change. That makes the transition of hard-to-abate-industries a major puzzle to be solved, since by definition there are no examples of such transitions. This thesis thus represents a first step towards solving this puzzle, by focusing more on regime stability than previous MLP studies.

1.4. Research question

This leads to the following research question: *What are the dynamics of the transition to sustainable international shipping and how can this transition be accelerated?* To answer the research question, it first needs to be established what exactly it is that makes the shipping

[1] It can also be argued that despite their radical appearance in the form of Flettner rotors, fixed sails or AI-controlled kites, wind propulsion solutions are not truly radical innovations in this context, since they are conceived as auxiliary propulsion on ships that still run on fuel oil, thus having the same effect as energy efficiency measures, merely reducing fossil fuel use instead of replacing it.

industry so slow to transition to sustainability. Then, drawing on relevant transition theories and taking into account the available technological alternatives, advice can be given on how the transition might be accelerated. Accordingly, the research question will be divided into two sub-questions: *SQ1: Why is international shipping such a hard-to-abate industry?* and *SQ2: How can the shipping transition be accelerated?*

This research is relevant for transition studies in several ways. Firstly, its contributions to the emerging literature on hard-to-abate sectors and their transition are threefold: It gives detailed insights into specific lock-in mechanisms, it shows how hard-to-abate sectors are slowly reorienting towards transition and it provides first insights into how to accelerate these transitions. Secondly, it extends on dynamics of innovation systems and socio-technical regimes on a global level, as paying attention to the transition of a truly global industry can build upon existing globalised variations of transition study concepts and give valuable insights into how dynamics play out trans- and internationally. Thirdly, it reveals more about the geography of socio-technical transitions, specifically how the global and local interact in such a fully globalised sector as shipping. Fourthly, as the MLP has been criticised for its methodology (Genus & Coles, 2008) and even its proponents have acknowledged that it would benefit from methods such as event sequence analysis (Geels, 2011), the application of a historic event analysis to provide a backdrop for qualitative interview data constitutes a novel approach to the study of niche-regime interactions.

Furthermore, this research is also relevant for society at large. It gives specific advice for policy-makers on different levels (local, national and global) on how to govern the transition of the shipping sector, which can aid in achieving deep emission reductions from this area. Moreover, it might help entrepreneurs developing alternative technologies to understand how they can bring their innovations to the market and advise incumbent actors on how to adapt to technological changes. Lastly, the accomplishment of these feats would allow global trade routes to keep functioning without jeopardising the world through contributing to global warming.

1.5. Outline

The thesis is structured as follows: First, the theory section presents the relevant transition theories and explains which sector-specific barriers hard-to-abate industries literature suggests and how they are expected to affect transition dynamics. Then, the methods section clarifies how literature analysis, interviews and historic event analysis have been applied to shipping, which type of data has been used and how it has been collected and analysed. Next, two analytical chapters present the results: Section 4 answers *SQ1* and focuses on understanding lock-in and stability: it explains the shipping regime and which factors make it so resistant to change, taking into account the specific barriers for hard-to-abate industries. Section 5 answers *SQ2* and is centred on understanding the dynamics of change: it presents alternative technologies, demonstrates regime-niche interactions over the time periods identified in the event analysis and relates the results to barriers as well as solutions from hard-to-abate literature. Finally, the conclusion and discussion sums up the findings, illuminates the implications for theory and practice, provides policy advice and suggests future directions for research.

2. Theory

2.1. Socio-technical and innovation system perspectives

As mentioned in the introduction, this study will make use of socio-technical transition theory, or what Wesseling et al. (2017) call socio-technical and innovation systems perspectives. These include the MLP as well as technological innovation systems literature. One of the key insights of these strands of literature is that a dominant technology does not simply exist by itself, but is surrounded by a complex system of actors and institutions that work in interplay with the physical manifestations of the technology and its required infrastructure. On the one hand, this system (which often has developed over a long period of time) makes the functioning of a technology a lot more efficient. On the other hand, however, it limits the possibilities of change to what is possible within said system, at least if one does not want to go through the huge effort of dismantling it. In terms of the MLP, this system is a socio-technical regime, consisting of the dimensions of technology, markets and user practices, sectoral policy, techno-scientific knowledge, industrial networks, culture and symbolic meaning, and infrastructure (Geels, 2002).

This has major implications for transitions to radically different technologies. In these kinds of systems, revolutionary innovations often do not simply arise and overthrow the *ancien* socio-technical *régime*; instead, a transition is a gradual, slow and difficult process where innovations that depart from "the way of doing things" face strong resistance. According to the MLP, this process successfully comes about when (radical) niche-innovations build up sufficient momentum, while the regime, under pressure from landscape developments, is destabilised and either incorporates or is swept away by the new technology (Geels, 2020). Having been criticised for niche bias, the MLP was further developed and next to this "classical" *technological substitution* pathway, the pathways of *transformation* (technological change from within the regime), *de-alignment and re-alignment* (regime collapse before niche technologies are ready) and *reconfiguration* (change from within the regime including a change in the regime's basic architecture) were added (Geels & Schot, 2007). In all of these pathways, a precondition for transition is that sufficient landscape pressure is felt by the regime. However, the actors within the regime do not easily succumb to this pressure, as incumbent firms tend to disapprove of radical innovations and are often characterised by institutional inertia (Chandy & Tellis, 2000). Instead, they might even proactively apply a myriad of strategies to resist change by slowing it down (Smink et al., 2015), for example by lobbying for favourable regulation and further securing the own market position (Light & Lexchin, 2012). Hence, a transition is far from guaranteed, even when alternatives exist and landscape pressure is present.

This is where TIS literature provides a useful addition: Whereas the MLP gives a good overview of transitions on a wider societal level, it has been criticised for not explaining sufficiently how new technologies arise from niche to regime and what the role of actors is in this development, something the TIS pays more attention to (Markard & Truffer, 2008). In this strand of innovation systems thinking, the system is defined around a specific technology and everyone that contributes to its success by fulfilling certain functions. If TIS form around radical niche innovations, its actors create a system that can match the power of the regime by fulfilling seven functions, namely *entrepreneurial activities*, *knowledge development* and *diffusion*, *guidance of the search*, *niche market formation*, *mobilisation of financial and other resources*, as well as *support from advocacy coalitions* that create legitimacy and counteract the incumbent industries' resistance (Hekkert et al., 2007).

Nevertheless, a well-functioning TIS does not guarantee a transition either. TIS analyses can give a good indication of how far the system around a specific technology has developed, but their focus does not lie on the incumbent regime. On the contrary, the MLP and associated approaches, such as strategic niche management (SNM) and transition management (TM) have put an emphasis on how the regime has to be destabilised to allow for windows of opportunity for niche technologies to break through (Kivimaa & Kern, 2016). Kivimaa & Kern (2016) have thus argued that for policy to drive a transition, policy mixes have to attend to both niche development and regime destabilisation. Combining insights from TIS literature, as well as SNM and TM, they have proposed a new framework inspired by Joseph Schumpeter's seminal concept of creative destruction, a process that "continuously revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one" (Schumpeter, 1942/1994, pp. 82–83). Accordingly, Kivimaa & Kern suggest to add to the 7 TIS-based creation functions (*C1: knowledge creation, development & 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*) a set of destruction functions.

These destruction functions are as follows. Firstly, *D1: control policies* have the main aim of internalising the external environmental costs of regime technology, by the means of taxes, carbon pricing or other market-based measures (MBMs), or outright technology bans. Secondly, *D2: significant changes in regime rules* entail a modification of the regime's deep structure, i.e. a reconfiguration of institutional rules favourable to the status quo. Thirdly, *D3: reduced support for dominant regime technologies* involve a discontinuation of policies and actions that are upholding regime technology advantage, such as cutting of subsidies or R&D funding. Fourthly, *D4: changes in social networks, replacement of key actors* includes replacement of incumbents, "breaking up of established actor-network structures" and "developing different fora to bypass traditional policy networks" (Kivimaa & Kern, 2016, p. 209). Hence, the two sets of functions are complementary and both necessary for a transition, the former fostering niche-innovations, the latter destabilising the regime to create windows of opportunity. In their accompanying case studies, Kivimaa & Kern found that there is often a lack of policies that fulfil the task of regime destabilisation.

Despite not being inherently territorially limited and the TIS even being explicitly conceived as stretching over several national innovation systems (Hekkert et al., 2007), the applications of MLP and TIS have often been limited to a national or subnational scale. The same goes for Kivimaa & Kern's creative destruction functions, which have been applied to two national case studies of Finland and the UK (Kivimaa & Kern, 2016). This has been criticised by some scholars, who devised the GIS and global regime concepts (Binz & Truffer, 2017; Fuenfschilling & Binz, 2018). The GIS focuses on the globalisation of innovation and argues that resources are generated in multi-location subsystems, connected by structural couplings, i.e. actor networks or institutions which overlap for these systems (Binz & Truffer, 2017). It therefore emphasises the importance of system builders and intermediaries. Global socio-technical regimes are defined 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" (Fuenfschilling & Binz, 2018, p. 739). Regimes are thus seen as mostly stretching far beyond national borders, implying that case studies within national borders are often unable to capture the full picture (Bauer & Fuenfschilling, 2019).

In the context of sustainability transitions, climate change can thus be described as putting landscape pressure on the regime to change its technologies and behaviours. Often, this pressure is initially resisted by incumbents and, when it becomes strong enough to require proper action, responded to with minimal change and incremental innovations (Penna & Geels, 2015). Unfortunately, a serious attempt at mitigating climate change requires more in most cases, namely a drastic reduction of CO_2 emissions using radically different technologies: a deep decarbonisation. This paradigm shift is always difficult due to the economic, technical and institutional path-dependencies that a socio-technical regime entails, but some sectors, such as electricity and mobility, do already show significant change, seen in the increasing adoption of renewable energy sources and battery-powered vehicles.

However, the transition is much more cumbersome in the case of the hard-to-abate sectors, including heavy industry, aviation and shipping, which face additional issues (ETC, 2018a). These issues are related to technology, industry structure and, particularly in the case of shipping, the global nature of business operations as well as governance. It is therefore worthwhile to give an overview of those barriers that hard-to-abate industries face according to the literature. It should be noted that these studies mostly focused on cases of narrowly defined hard-to-abate sectors, i.e. heavy industry, chemical industry and basic commodity production (e.g. concrete, wood pulp, etc.). Still, the challenge for the shipping transition seems similar enough that insights from these studies can be valuable for shipping (ETC, 2018a), which will become more clear in the analytical chapters.

2.2. Specific barriers in hard-to-abate industries literature

Conceptualising hard-to-abate industries as peculiar types of regimes requires some clarification as to what makes their lock-in so strong and their transitions so difficult. A thorough review of the literature on hard-to-abate sectors (Åhman, 2020; Baron et al., 2007; C. Bataille et al., 2018; C. G. F. Bataille, 2020; Bauer & Fuenfschilling, 2019; Janipour et al., 2020; Oberthür et al., 2020; Wesseling et al., 2017; Wesseling & Van der Vooren, 2017) allowed for the identification of eight barriers, encapsulating the main problems that these sectors' transitions face according to the authors. Table 1 lists these barriers to sustainable transitions and how they affect creation & destruction functions.

Table 1: Barriers to transition & solutions identified in literature on hard-to-abate industries
(Åhman, 2020; Baron et al., 2007; Bataille et al., 2018; Bauer & Fuenfschilling, 2019; Janipour et al., 2020; Oberthür et al., 2020; Wesseling et al., 2017; Wesseling & Van der Vooren, 2017)

Barrier	***Explanation***	***Mentioned in***	***Effect on functions***
B1: Long-lived installations	Installations have a long lifetime, making the pace of technological change slow and creating a preference for retrofit solutions.	Wesseling & Van der Vooren, 2017; Wesseling et al., 2017; Bataille et al., 2018	*no specific effect*
B2: Infrastructure lock-in	The necessary large scale energy and feedstock infrastructure is locked-in into fossil fuels. Often, facilities are integrated into systems related to production and storage of fossil fuels.	Wesseling et al., 2017; Bataille et al., 2018; Åhman, 2020; Janipour et al. 2020	*no specific effect*
B3: High entry barriers	Capital intensity of investments, concentrated market and economies of scale lead to high entry barriers and therefore a lack	Wesseling & Van der Vooren, 2017; Wesseling et al., 2017; Bauer &	-C4 -D4

	of new entries with radically different technology.	Fuenfschilling 2019; Åhman, 2020	
B4: Lack of demand for sustainable alternatives	Due to the business-to-business nature of the industry, operations are far away from consumer pressure and competition takes place mainly by price. Therefore, there is no differentiation for cleaner products and no willingness to pay more for sustainable operations.	Wesseling & Van der Vooren, 2017; Wesseling et al., 2017; Bataille et al., 2018; Bauer & Fuenfschilling, 2019	-C1 -C2 -C6 -C7
B5: Lack of supply of sustainable alternatives	Most low emission alternative technologies are still at an early stage and not sufficiently developed to be deployed.	Åhman, 2020; Oberthür et al., 2020	-C3 -C4
B6: Vested interests favour efficiency improvements to deep decarbonisation	Powerful and well-organized industries prefer incremental changes and tend to select clean solutions which are more along these lines. These efficiency improvements lead to further lock-in since they make the technology cheaper and deep decarbonisation more unlikely.	Wesseling & Van der Vooren, 2017; Bauer & Fuenfschilling 2019; Janipour et al., 2020	-C6 -C7 -D4
B7: Global markets	Global trade exposure and the resulting intense competition lead to low profit margins, lack of willingness to invest in R&D and a perceived high risk of innovation.	Baron et al., 2007; Wesseling & Van der Vooren, 2017; Janipour et al., 2020; Oberthür et al., 2020	-C2 -C5
B8: Limited national policy efforts	National level measures are not taken due to fear of destroying domestic industry or have limited effect due to carbon leakage. Moreover, there is a general lack of prioritisation of these industries.	Åhman, 2020; Janipour et al. 2020; Oberthür et al., 2020	-C5 -C7 -D1 -D2 -D3

Some of these barriers are more of an economic nature (B3, B4, B7), others rather technical (B1, B2, B5) and some revolve around politics and governance (B6, B8). However, these categorisations are not always clear-cut. The barriers hinder the transition process in different ways.

The way hard-to-abate industries work affects the different MLP transition pathways: The long lifetime of installations (B1) generally slows down the pace of technological change, which means that new innovations take longer to be implemented if they cannot be retrofitted. The necessary large scale infrastructure (B2) for energy supply, feedstock, or – in the case of shipping – fuel supply is built for fossil fuels and often cannot be easily used with other fuels. High entry barriers (B3) make it very unlikely that new entrepreneurial entrants bring about a radical change, limiting the possibility of the *technological substitution* pathway. The lack of demand for sustainable alternatives (B4), due to the business-to-business nature of the industries, make the establishment of a sustainable niche market as well as up-scaling from niche to regime very difficult. Moreover, being far away from the end consumer limits the amount of landscape pressure in the form of public pressure, which is a crucial force in the *transformation* pathway. The lack of sufficiently developed alternative technologies (B5) is problematic for the *technological substitution* and *reconfiguration* pathways, since both require ready-to-use niche technologies. Vested industry interests favouring efficiency improvements instead of alternative technologies (B6) stabilise the regime further and strengthen the lock-in, leading to reproduction of the regime, making the collapse of the regime necessary for the *de-alignment and re-alignment* pathway very unlikely. Global markets and trade exposure (B7) result in less R&D and associated innovation, again slowing down any technological change. Lastly, a lack of national policy efforts (B8) result in less landscape pressure perceived by regime actors. In summary, B1, B2 and B7 curb the pace of change by limiting innovation and adoption, B3, B4, B5 and B6 restrict the opportunities for niche technologies to rise to the regime, and B4 & B8 limit the amount of landscape pressure perceived by regime actors.

The barriers also constitute a problem for Kivimaa & Kern's creation functions, partly congruent with Wesseling & Van der Vooren's (2017) analysis of their effects on the TIS: B3 limits *entrepreneurial experimentation (C4)* by blocking new entrants. B4 results in no market incentive to develop knowledge about sustainable alternatives *(C1: knowledge creation, development & diffusion)*, less business efforts to guide innovations towards sustainability *(C7: influence on the direction of search)* and a lack of differentiation into sustainability *(C2: niche market formation)* and little *support from powerful groups/legitimation (C6)*. B5 means there is little availability of alternatives and thus a lack of *entrepreneurial experimentation (C4)* as well as further development leading to *price-performance improvements (C3)*. B6 results in industry forces *influencing the direction of search (C7)* towards more incremental and less radical innovations as well as strong lobbying in favour of the industry *(C6: support from powerful groups/legitimation)*. B7 is problematic for both *niche market formation (C2)* and *resource mobilisation (C5)*, since there is a perceived high risk and low benefit of sustainable innovation. Lastly, B8 results in a lack of national efforts to guide sustainable innovation and a lack of national policy attention *(C7: influence on the direction of search)*, also being problematic for *resource mobilisation (C5)*. Hence, the barriers strongly inhibit the fulfilment of the creation functions, thus limiting the development of sustainable technologies.

Also the destruction functions by Kivimaa & Kern are inhibited by the barriers: B4 prevents the *replacement of key actors (D4)* in the incumbent regime. Similarly, powerful and well-connected vested interests (B6) make it hard to achieve *changes in social networks (D4)*, since it is difficult to break up these established actor-network structures. Most importantly though, B8 hinders the pursuit of the difficult task of regime destabilisation through *control policies (D1), significant changes in regime rules (D2)* and *reduced support for dominant regime technologies (D3).*

Some barriers do not directly affect the creation & destruction functions, since they are quite specific to hard-to-abate industries: B1 and B2 are rather technical factors that slow down any transition and make the lock-in stronger. This global nature plays out differently in the different sectors, with heavy industries it has a lot to do with trade exposure of basic materials having a high potential for carbon leakage, whereas with shipping and aviation it stems from those forms of transports largely taking place outside of national jurisdiction and thus being governed primarily by global institutions, i.e. the IMO in the case of shipping (Sainlos, 2011).

Thus, the theoretical framework of this thesis can be summed up as follows. Destruction functions destabilise the regime and create windows of opportunity, while creation functions support alternative technologies in breaking through to regime level. Hard-to-abate-sector-specific barriers slow down technological change and inhibit destruction and creation functions in different ways.

2.3. Contribution to theory

This study thus draws on both general socio-technical and innovation systems perspectives and sector-specific hard-to-abate industries literature, aiming to synthesise their findings and apply them to the complex case of the shipping industry. It constitutes a contribution to both strands of transition scholarship, applying and extending their concepts where needed. Hereby a special interest lies on the Kivimaa & Kern's destruction functions, how they are already performed and how they can be elaborated. Furthermore, the global nature of shipping provides a connection to the global socio-technical regime and GIS concepts (Binz & Truffer, 2017; Fuenfschilling & Binz, 2018), this study thus contributes to an answer to the question of how such a global regime can be governed. Moreover, to transform a global regime, a properly functioning GIS around radical innovations might be necessary. Lastly, a contribution to the MLP framework consists in the application of a historic event analysis, a systematic method taken from TIS analyses, which allows to examine niche-regime interactions thoroughly. This method and other methods used for this research are explained in detail in the following section.

3. Methods

3.1. Research design

The research design of this study is an in-depth case study of the shipping sector, using mixed methods. A case study is an appropriate research design for this research, as it allows for a holistic view of a phenomenon and is particularly useful in more exploratory types of inquiry (Mohd Noor, 2008). Mixed methods are useful since they allow for triangulation of results and have the advantage of combining the systematic nature of quantitative analysis, which helps in the detection of patterns, with the in-depth insights into subjective perspectives and actor motivations resulting from qualitative methods (Bryman, 2015). The study draws from three different types of analysis, namely literature analysis, interviews and historic event analysis. The literature analysis has been used to provide background information on the shipping industry and alternative technologies, the interviews have allowed for deep insights into various stakeholders' view on problems and solutions, and the historic event analysis enables a comprehensive overview of landscape pressures on the regime and niche developments. A combination of these three components enables a rich description of the incumbent shipping regime, as well as the evolution of the various alternative technologies (Reichardt et al., 2016). The analysis can hereby answer both *SQ1* about why shipping is such a hard-to-abate sector, by describing the lock-in of the regime and *SQ2* about how the transition can be achieved, by identifying promising alternatives and where they need policy support.

3.2. Data collection & analysis

For the literature analysis, academic literature as well as grey literature have been used to sketch an overview of the shipping industry. For the former, the main sources have been journal articles and academic books on the matter, some with a focus on sustainability issues, others providing more general information on the sector. The latter comprises reports by the ETC on hard-to-abate sectors (ETC, 2018a, 2018b), MAN and ITF/OECD on the decarbonisation of shipping (Dönitz et al., 2020; Kirstein et al., 2018), UNCTAD's reviews on maritime transport (Asariotis et al., 2009, 2019, 2020) and the EEA on shipping and aviation (EEA, 2018), thus again using both sources explicitly addressing sustainability themes and sources reporting on the industry in general.

For the interviews, five types of actors were identified as highly relevant: 1) innovative enterprises which are developing or applying radical innovations in ship propulsion and operation which have a promise of deep reduction in CO_2 emissions, thus representing niche actors; 2) incumbent companies which are potential adopters of these technologies, i.e. engine manufacturers, shipyards and big shipping corporations, where a particular interest lied in the innovation and sustainability departments, thus representing established regime actors; 3) governance actors, who are creating and implementing regulation on different levels, such as national governments and port authorities; 4) NGOs involved in making the shipping sector more sustainable; and 5) academic experts on sustainable shipping. Since interviewees were selected not at random but due to their position in specific organisations, the sampling took the form of purposive sampling. Due to some limitations in the scope of the research and the effects of the ongoing Covid-19 pandemic, it resembled in some ways convenience sampling, a practical strategy where those respondents are selected that can be accessed (Bryman, 2015).

Consequently, a large variety of companies and organisations have been contacted via phone, e-mail, online contact forms and the professional networking website LinkedIn. This has resulted in 12 semi-structured interviews with 13 participants, as one of the interviews included two participants (see table 2). All interviewees provided their informed consent in writing before participation, the informed consent form can be found in appendix 3. For privacy reasons, all participants' and some organisations' names have been anonymised. In the text, they are referred to with abbreviations relating to their actor type, namely innovative enterprise (*IE*), established actor (*EA*), governance actors in the form of port authorities (*PA*) and policy-makers (*PM*), NGOs (*NGO*) and academic experts (*EX*). Interview guides were created for each different actor type and questions adapted based on online research on the specific actor. All interviews were conducted online via videocall on MS Teams, lasting 48 minutes on average, with the shortest taking 24 minutes and the longest 70 minutes. Two interviews were conducted in German (for the translation of quotes used in the text see appendix 2), the other 10 in English. The interviews were recorded, transcribed manually and coded in Nvivo using open coding (Bryman, 2015).

Table 2: Interview Participants Overview

Actor type	***Organisation***	***Participant position***	***Abbreviation***
Innovative enterprise	Major fertiliser company - customer for shipping and ammonia producer	VP Ammonia Energy and Shipping Fuel	*IE1*
	Ship design company – developer of commercial wind propelled ships	Project Manager for fully wind-propelled ship	*IE2*
	Producer of biofuels for shipping applications	Innovation Manager	*IE3*
Established actor	Shipbuilding conglomerate	1. Programme Manager Sustainability 2. Development Manager	*EA1a* *EA1b*
	Container shipping company	Head of Sustainability	*EA2*
	National industry association for shipbuilding and marine technology	Director	*EA3*
Governance actor	Hamburg Port Authority	Senior Consultant Sustainability	*PA1*
	Port of Rotterdam	CSR Manager	*PA2*
	Port Authority of Valencia	Head of Environmental Policies	*PA3*
	Dutch Ministry of Infrastructure and Water Management	Senior Advisor Knowledge and Innovation in Shipping	*PM*
NGO	Sustainable Shipping Initiative	Head of Programme Management and Fundraising	*NGO*
Academic expert	Erasmus University	Professor in the Governance of Sustainable Mobility	*EX*

To ground interview insights in a broader empirical basis, a historic event analysis of the development of the shipping regime as well as the innovation systems surrounding alternative technologies has been conducted. Historic event analysis is a method pioneered by Negro et al. (2007), which maps functional patterns over time to draw a picture of the development of a TIS and gain insights into how its functions interact. To achieve this, a database of relevant events is created based on industry journals, newspapers and websites (Negro et al., 2007). These events are then coded according to their positive or negative contribution to a system function. Based on arising patterns, different periods and crucial events are identified, resulting in a storyline of system development and hence an overview of TIS evolution (Hekkert et al., 2007; Reichardt et al., 2016).

Accordingly, a database was created in Excel, compiling news items from SAFETY4SEA (SAFETY4SEA, 2021a), a shipping and maritime news website which has also been used as a source for other publications on shipping, such as the UNCTAD's yearly reviews on maritime transport and can thus be considered a reliable source (Asariotis et al., 2020). This particular website was chosen from the variety of shipping news sources available online, since it has an archive going back to 2011, is easily accessible and has a "green" category, which allows for easier filtering of those articles which are relevant for sustainable shipping. A brief comparison of recent new items with those of similar websites showed that the events mentioned were largely congruent, thus justifying the use of just one website for practical reasons. The time period chosen for analysis starts April 13th 2018, the date when the Initial IMO GHG strategy was adopted (constituting the first time that the IMO took action on climate change) and ends June 29th 2021, when the database was compiled. Hence, it entails events over a period of a little less than 39 months. Within the "green" category of SAFETY4SEA, only those items were selected which were deemed relevant for reduction of carbon emissions from ship propulsion. This resulted in a list of 1460 events, which were classified according to the technology affected. One event could be related to multiple technologies. The different technological categories were *LNG, hydrogen, efficiency, electric, ammonia, biofuel, methanol, wind, ex post, LPG* and *nuclear* (here sorted by number of mentions). What exactly these categories included is explained in detail in the chapter on alternative technologies. An additional category of *general* was created to classify events which did not refer to any specific technology but were still about carbon emission reduction in shipping.

After compiling this database, each event was coded by assessing its (positive or negative) contribution to the creation and destruction functions developed by Kivimaa & Kern (2016). Events classified as relating to specific alternative technologies could contribute to the creation functions, thus representing fulfilment of the TIS functions of that technology, whereas events not referring to such a specific technology (pertaining to the *general* category) could be coded for creation and destruction functions, as they might either affect all alternative technologies' TIS or the destabilisation of the regime. Table 3 shows the indicators used for coding.

Table 3: Indicators for measuring system functions

Function	***Indicator***	***Coding***
C1 - knowledge creation, development & diffusion	R&D projects, R&D investments, feasibility studies, workshops/conferences, innovation platforms, …	+1
C2 - establishing market niches/market formation	Tax exemptions, public procurement, deployment subsidies, new niche markets, new environmental standards Expressed lack of the above, taxes on technology	+1 -1
C3 - price-performance improvements	Tools to increase performance, lower relative fuel price Expressed too high price of technology, higher relative fuel price	+1 -1
C4 - entrepreneurial experimentation	Diversification of existing firms, incubators, accelerators, pilots, business adoption of alternative technologies Projects stopped, expressed lack of infrastructure	+1 -1
C5 - resource mobilisation	Loans, funds set up for long-term R&D programmes, venture capital Expressed lack of funding	+1 -1
C6 - support from powerful groups/legitimation	Social acceptance, labelling to create legitimacy, compliance with relevant institutions, development of technological standards, rise and growth of interest groups and their lobby actions	+1

	Expressed lack of support by powerful groups, resistance by public	-1
C7 - influence on the direction of search	Framing in strategies, expectations about a technology – focus on problems or advantages, long-term goals set by governance actors and/or industry (e.g. reduction by certain %, getting zero-emission vehicles in by a certain time) Negative framing, focus on problems	+1 -1
D1 - control policies	Internalisation of costs through taxes, carbon pricing or other market-based measures, technology bans Expressed lack of control policies, opposition to control policies	+1 -1
D2 - significant changes in regime rules	Changes in deep structure of the regime, reconfiguration in institutional rules favourable to status quo (e.g. structured & radical reforms in legislation, new overarching laws) Expressed lack of changes, retraction of legislation	+1 -1
D3 - reduced support for dominant regime technologies	Cuts in subsidies, R&D funding for regime technologies, statements against regime technologies	+1
D4 - changes in social networks, replacement of key actors	Replacement of incumbents, breaking up of established actor-network structures, developing different for a to bypass traditional policy networks, inclusion of niche actors, formation of new organisations/networks to take	+1

Then, separate tables were created for the *general* category as well as the various technology categories. To gain an overview of the density of events, events were counted per month for each function fulfilment (positive or negative), resulting in a heat map giving an indication of which function was strengthened or weakened in which month, for each technology separately and for all technologies together. These heatmaps can be found in the Appendix. Using this technique allowed for identification of differing periods. Then, looking at overall patterns in event occurrence, the descriptions of events and using interviews for triangulation, general trends and key events could be identified, providing the basis for the event sequence description in section 5.2.

The following chapters present the results that the analysis using the different methods yielded. Section 4 focuses on the shipping regime, while section 5 presents alternative technologies, illuminates regime-niche interactions over the time periods identified in the event analysis and relates the results to the barriers & solutions from hard-to-abate literature. Section 4 is based on literature analysis and interviews, whereas the section 5 is mainly based on the historic event analysis, but also includes insights from interviews and, to a lesser extent, literature.

4. The shipping regime

This chapter presents the dominant regime in the shipping industry, elaborating on how it arose and where its stability stems from. First, an overview of the shipping industry is given in 4.1, also addressing issues of agency, ownership, control, responsibility and power relations. Then, the development of its fossil fuel lock-in is explained in 4.2, including infrastructure and technological characteristics. Lastly, the way that shipping and its environmental problems are governed is elucidated in 4.3, thus entailing the most important institutions for shipping governance. At the end of each subsection, the results are related to relevant hard-to-abate barriers.

4.1. Shipping industry structure

The shipping industry is a dispersed sector and "there is not *the* maritime sector", so several distinctions are useful when examining it (*EX*). A first distinction can be made by the distances travelled: Inland shipping refers to traffic on waterways which are not part of the sea, such as rivers, canals and lakes (Eurostat, 2019a). Short sea shipping, sometimes historically called coastal shipping, refers to ship traffic along coasts and within the same continent, i.e. without traversing an ocean (Eurostat, 2019b; Mulligan & Lombardo, 2006). Deep sea shipping refers to traffic across oceans, taking place on the high seas and often between different continents (Eurostat, 2015). This distinction has implications for the viability of different technologies as well as the regulatory regime, since inland and short sea shipping generally have stricter rules and can fall under national jurisdictions, whereas deep sea shipping is mainly regulated under IMO rules (*PM*; *EX*). The IMO is a UN specialised agency with the mandate to develop globally applicable rules for shipping and (with 174 members) has near universal membership (IMO, 2019h; Sainlos, 2011). International shipping, i.e. short sea and deep sea shipping, are estimated to account for 87% of CO_2 emissions from shipping, inland shipping for 8% and fishing for 5% (Olmer et al., 2017).

A second distinction can be made by the type of ship. The world fleet can be divided into cargo, non-cargo and military vessels. In 2002, cargo vessels represented 66% of ship energy demand, whereas non-cargo, which entails passenger transport (including cruises and ferries), fishing, tugboats and other, represented 20% and military vessels accounted for the remaining 14% (Corbett & Winebrake, 2008). The merchant fleet can be further divided by the type of cargo the ships carry, which determines ship design. Tankers transport liquids, which is mainly crude oil transported to refineries, but also other liquid cargos such as chemicals or liquefied gases. Bulk carriers carry dry bulk cargo, such as coal, iron ore or other raw materials; container ships carry standardised containers, which tend to contain various types of manufactured and consumer goods. By tonnage, ship trade in 2019 consisted to 42% out of containers, minor bulk and general cargo, 29% main bulk and 29% tanker trade (Asariotis et al., 2020). These proportions have changed considerably within the last decades: In 1970, the majority was still tanker trade with 55%, followed by containers, minor bulk and general cargo with 28% and main bulk with 17%. 2013-2015, container ships accounted for 23% of shipping's CO_2 emissions, bulk carriers for 19% and oil tankers for 13% (Olmer et al., 2017).

The "mammoth task" for the shipping transition and the main focus of this thesis are thus international cargo ships, which represent the bulk of emissions. However, inland shipping (and to a lesser extent short sea shipping), non-cargo vessels and military ships all can provide protected niche markets where different regulatory regimes and market conditions allow for the growth of radical innovations, as occurred in the 19^{th} century transition from wind to steam propulsion (*EX*; Geels, 2002). Inland shipping and harbour craft can be subject to far stricter environmental regulation by national governments and ports (*EX*; *EA1a*; *EA1b*). Furthermore, the distance of a shipping service to the consumer plays a crucial role in how much landscape pressure is felt and to what extent a higher price for a sustainable service can be asked (*IE2; EA3*). Ferries, cruises and other passenger ships directly service end consumers and have the highest visibility, making them tendentially early adopters for sustainable innovations (*EA1a*; *EA3*). Having less visibility, container shipping works in a business-to-business environment, but its customers are often producers of consumer goods which care about their environmental image and try to distinguish themselves with low-carbon transport and decarbonisation of their value chain, examples being IKEA, Heineken, Nike and BMW, all corporations interested in sustainable shipping services and major clients for the shipping industry (*NGO*; *IE1*; *IE3*; *EA2*). The furthest away from this direct and indirect consumer pressure are tankers and bulk ships, which do not ship consumer goods, but raw materials and commodities for businesses and thus have far less incentives for changing (*EA3*).

Another way of looking at shipping is in terms of logistic chains (*EX*). Here, shipping lines present a network connecting countries all over the world (see title page image), with ports serving as nodes and points where goods change from one mode of transport to another, i.e. from sea shipping to hinterland transport by truck, railway or inland shipping (*EX*; *PA3*). Hereby, shipping forms an integral part of the value chain of many if not most products. Taking this logistic chain perspective provides another view on the issue, since shipping emissions can be seen as transport emissions that are part of companies' or a product's total emissions. As with the different types of shipping, transitions can be expected to begin "closer" to the final product and move towards more distant parts of the value chain (*EX*; *PM*). As an interviewee working for a major fertiliser company explained, when looking to reduce carbon emissions around their product, transport generally comes last (*IE1*).

A further complicating issue is that shipping generally involves multiple stakeholders from various different countries, as illustrated by the example of the Ever Given from the introduction. This begins with the construction and purchase of a ship. Shipping is a highly capital intensive industry, with ships costing tens or even hundreds of millions of Euros, so shipowners are dependent on banks and other investors for finance (*PA1*; *PM*; *EA2*). These investment pay off on the long term, since ships often last 20-30 years and more. Most ships are built in East Asia, with Chinese, South Korean and Japanese shipbuilders having constructed 93% of ships in 2019 (Asariotis et al., 2020). The engines, however, are made both in Asia and Europe, with three manufacturers dominating the market for the large two-stroke engines used in the biggest ships: MAN from Germany, Wärtsilä from Finland and Mitsubishi Heavy Industries from Japan (MC01, 2018). The major shipowner countries are Greece, Japan and China, with 18%, 11% and 11% of tonnage, respectively, but most ships sail under a flag of convenience, such as Panama, Liberia or the Marshall Islands, together representing 42% of worldwide carrying capacity (Asariotis et al., 2020). This means that only the national regulations of those flag states apply, which tend to be very lenient.

As soon as the ship is being used, there are often also various actors in play. In the container and bulk sector (representing the majority of international shipping), 60-70% of ships are chartered (Kirstein et al., 2018). Here, shipowners provide the vessels, whereas the fuel costs are paid by the charterers using the ship, meaning that shipowners have no direct incentive to make their ships more fuel efficient and shippers are not able to change ship technology easily (Kirstein et al., 2018). This is referred to as the problem of split incentives in shipping (ETC, 2018b; Kirstein et al., 2018). Another crucial role is played by classification societies, who determine whether a ship fulfils necessary standards and is eligible to be insured (*IE3*; EMSA, 2021) and, as technical advisors to the IMO, often write its standards and regulations (*EA3*; IMO, 2019d). This complexity, division of tasks and organisational as well as geographical dispersion leads to a situation where any fundamental change in technology requires the cooperation and coordination of various actors (*EA1a*; *EA1b*). In the words of a participant from a shipbuilding company, "we not only have to prepare ourselves for technology change but also business process and business capability change" (*EA1a*).

Correlating industry structure issues with hard-to-abate barriers, B1, B3, B4 and B7 are the most relevant. The long lifetime of ships matches the long-lived installations (B1) in other hard-to-abate sectors, slowing down change and meaning that, in the words of an interviewee, "2030, 2040 […] for the shipping industry that is sort of tomorrow", since ships constructed today might sail up to 2050 (*EA1b*). The capital intensity of international shipping, combined with the complex relation between various stakeholders, creates high entry barriers (B3), which is especially the case for those segments that emit most emissions. However, due to shipping's dispersion, not all of it is dominated by a few major companies, but also involves small and medium sized ones as well as other actors (e.g. governments) (*NGO*; *IE2*), allowing for lower entry barriers in some segments. Lack of demand for sustainable alternatives (B4) is a crucial barrier in shipping, where much of competition takes place by price and the bulk of activities are of a business-to-business nature. Still, demand for alternatives varies strongly with the subsector and the "distance" to the end consumer, with those parts of the industry that are closer to consumers being more exposed to societal landscape pressure, and potentially serving as the early adopter markets that sustainable alternatives need to thrive. Here, taking a logistics chain perspective on shipping might be helpful, as companies decarbonising their full supply chains would create a substantial demand for sustainable alternatives and this pressure by cargo owners seems to already take a hold in some parts of container shipping (*NGO*; *IE3*; *EA2*). Nevertheless, it should be noted that voluntary commitments to carbon reduction are limited and most actors are not interested in sustainability by itself, but only if it becomes a requirement to operate (*EA1b*). Finally, highly competitive global markets (B7) are evidently one major factor in shipping that keeps profit margins thin (*IE3*; *EA1a*), R&D expenditure low (*PM*) and risk aversion high (*PM*; *IE2*).

4.2. Development of the fossil fuel lock-in

The development of the shipping fossil fuel lock-in began with the shipping industry's gradual transition from wind propulsion to coal-fired steam power in the 19th century, proceeding from niche applications such as inland shipping (1800s), tugs (1810s), coastal shipping (1820s), military ships (1820s), mail transport (1830s) and passenger transport (1840s) towards the main regime of deep sea cargo shipping in the 1860s (Geels, 2002). Between the late 19th century and the early 20th century, the growing exploitation of petroleum resources led to the replacement of coal-fired with petroleum-fired steam engines in commercial ships (Uhler et al., 2016). Then, beginning with the first diesel-powered ocean-going ship in 1912, the more efficient diesel engine began to outcompete the steam engine (Motorship, 2003). By 1959, the majority of vessels were motor-powered and by 1970, 85% of ships ran on diesel engines (Corbett & Winebrake, 2008). In the early decades of petroleum-powered shipping, high-quality distillates were still the rule, but with the advent of cars running on gasoline, both steam engines and diesel engines were developed further to enable them to burn the cheaper residual fuels that remained after the refining process, which came to be known as HFOs (Uhler et al., 2016). Incentivised by the oil crises in the 1970s, refineries further refined their processes to retain more valuable petroleum products, making the resulting leftover HFOs more viscous and containing more sulphur, metals and other residues, while at the same time marine diesel engines were further improved to be able to burn these fuels (Uhler et al., 2016). At the end of these developments stands the current dominant technology in the shipping industry, which mainly runs on the waste products of the petrochemical industry (*IE1*), with ships basically acting as giant incinerators (*EX*).

However, the fossil fuel lock-in goes further than fuel choice: Not only does shipping almost exclusively run on fossil fuels, but coal and oil have been and still are a considerable portion of the cargo that is shipped. In 1970, the majority of shipping by weight was tanker trade and despite this share having decreased since, in 2015 still 30% of international trade consisted of gas and oil and another 11% of coal (Asariotis et al., 2020; Kirstein et al., 2018). A large part of shipping is thus dependent on the fossil fuel industry, although there are some reasonable expectations that a decrease in fossil fuel transport could coincide with an increase in low-carbon fuel transport (Kirstein et al., 2018). Another factor is the simple geographical proximity of shipping and the oil industry: as shipping is both customer and service provider to refineries, some of the largest ports in the world also house major petrochemical clusters, prominent examples being Singapore, Rotterdam and Houston (*EX*).

The combination of shipping and fossil fuels thus came to work as a well-oiled machine, running so efficiently that the low cost of cargo transport, combined with the innovation of the shipping container, allowed for processes of globalisation and outsourcing of production (Corbett & Winebrake, 2008). Since the 1980s, containerised trade has had an annual average growth rate of around 8% and bulk trade increased substantially, as the growing manufactures and raw materials trade embodied an "international division of labour" (Asariotis et al., 2019, p. 4). Shipping and globalisation thus have a symbiotic relationship, "whereby globalization has increased the demand for maritime shipping while maritime shipping […] has more fully enabled globalization" (Corbett & Winebrake, 2008, p. 4). With higher demand for shipping and global competition, economies of scale became the most important trend in ship innovation as well as in shipping industry structure (Notteboom, 2004; Wijnolst & Wergeland, 2009). In a way, the only limits to ship size increases are literal landscape factors such as the width of canals and the depth of harbours (Wijnolst & Wergeland, 2009). In turn, these trends made shipping cheaper again and further stimulated globalisation processes (Corbett & Winebrake, 2008). Hence, globalisation is deeply entangled with the shipping industry and the way it is currently operated. The global economy is dependent on shipping and shipping is dependent on fossil fuels.

As an old industry with such a deeply entrenched mode of operation, shipping is often characterised as a very conservative sector (*PA1*; *EX*; *EA2*). In the words of an interviewee, it is "still a real oldschool sector, that does not yet feel pressure to rethink its way of doing things" (*PA2*). Traditionally, spending on R&D has also been relatively low, especially if compared to other sectors such as the car industry (*PM*). The relevant hard-to-abate barriers for the fossil fuel lock-in are thus B2 and B6. The infrastructure lock-in (B2) not only relates to fuel bunkering infrastructure, but also to fuel supply, where petrochemical clusters and ports are often identical. Moreover, vested interests (B6) in shipping are closely related to fossil fuel corporations, since shipping is both a crucial customer and a transport service provider to the fossil fuel industry.

4.3. Governance of shipping

Much of the shipping industry's activities take place outside of the jurisdiction of national governments, in international waters. Nevertheless, it is a misconception that the high seas are a lawless place. Maybe precisely because they have always been a natural space for interactions between different nations and systems of law, they can be seen as the birthplace of international law: Hugo Grotius, widely seen as the founding father of international law, started his work writing on the law of the seas (Butler, 1992; Haggenmacher, 2012). Also the first recognised international crimes that could be universally prosecuted were committed on the sea: piracy, going back to antiquity, and, since the 19th century, the slave trade (Bederman, 2012). In modern history, the regulation of the high seas was formalised and extended, with the development of new institutions and rules on international shipping often coming as a response to major catastrophes (Sainlos, 2011). The "founding myth" (*EA3*) of the IMO is the famous Titanic disaster, which led to the adoption of the Convention for the Safety of Life at Sea (SOLAS) in 1914, setting minimum safety standards, such as prescribing radio communication equipment, life boats and life jackets on ships (IMO, 2019i). Later, in 1948, the IMO was founded by the UN as a permanent regulatory body with the mandate to improve SOLAS and develop globally applicable rules for maritime safety as well as marine pollution (IMO, 2019b; Sainlos, 2011) and in 1958 it assumed its work (van Leeuwen, 2015).

While maritime safety remains one of its core tasks, the IMO has slowly shifted its focus towards the issue of environmental pollution (*EA3*; IMO, 2019e). It became the custodian of the 1954 International Convention for the Prevention of Pollution of the Sea by Oil (OILPOL), which was later subsumed into the 1973 International Convention for the Prevention of Pollution from Ships (MARPOL), covering many different types of pollution instead of the original focus on oil spills (IMO, 2019f). Crucial events for the development of MARPOL were the 1967 Torrey Canyon supertanker disaster right off the coast of England, which motivated its conception (SAFETY4SEA, 2019d) and the even bigger 1978 Amoco Cadiz oil spill, which occurred a mere 190 km away, close to the French coast, and, among other tanker accidents in the late 1970s, led to the adoption of the more stringent 1978 protocol (IMO, 2019g; SAFETY4SEA, 2019e). In 1989 the infamous Exxon Valdez spill caused the US government to unilaterally make double hulls mandatory for tankers calling at US ports, driving the IMO to amend MARPOL to require double hulls globally in 1992 (Sainlos, 2011; van Leeuwen, 2015). In 1997 Annex VI on the Prevention of Air Pollution from Ships was added to MARPOL, for the first time directly addressing the issue of ship emissions, focusing on NOx, SOx, ozone depleting substances and volatile organic compounds (IMO, 2019a). Within the IMO, the Marine Environment Protection Committee (MEPC) is the body addressing prevention and control of pollution from ships (IMO, 2019j; Vogler & Sattler, 2016).

Despite climate change becoming a more pressing topic, both the 1997 Kyoto Protocol and 2016 Paris Agreement excluded shipping, declaring its emissions not attributable to specific countries, but instead called on the IMO and shipping to act voluntarily to reduce GHG emissions (IMO, 2019a; Joung et al., 2020). In 2011 the IMO adopted the first legally binding climate change treaty since the Kyoto Protocol in the form of an amendment to MARPOL Annex VI and made energy efficiency measures mandatory (IMO, 2019c). Specifically, it created the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP), concerning technical efficiency for newly built ships and operational efficiency for all ships, respectively (IMO, 2019c). They prescribe a reduction of carbon intensity over time, with different requirements for different ship types and a goal of 30% decrease by 2025

(IMO, 2019c). However, these measures have been criticised for being far too weak, being easily achievable by optimising existing technology or through simple operational measures such as speed reduction, thus only having a marginal impact on emissions (Kirstein et al., 2018; Polakis et al., 2019). Finally, in April 2018, the IMO adopted their initial strategy on GHG emissions, setting two targets: 1) the reduction of carbon intensity of international shipping by 40% by 2030, aiming towards 70% by 2050 and 2) the reduction of total annual GHG emissions from international shipping by 2050 by 50% compared to 2008 (IMO, 2019e).

Since then, follow-up action has been rather slow. In general, the IMO is characterised by most interviewees as a slow-moving and rather non-transparent organisation (*NGO*; *IE1*; *IE3*; *PA1*; *PA2*; *EA1a*; *EA1b*; *EA3*). Its voting procedures are based on tacit acceptance, meaning that an amendment automatically enters into force if there is not a certain number of members that reject it (Sainlos, 2011). However, in practice that means that one third of members is enough to block any decision, making the organisation reliant on compromises (*EA3*). Moreover, the shipping industry is well-organised and has powerful industry associations (*EX*; *EA3*; *PA1*), the most prominent ones being the WSC, the International Chamber of Shipping (ICS) and the Baltic and International Maritime Council (BIMCO) (BIMCO, n.d.; ICS, n.d.; WSC, n.d.). Within the IMO, ambitious proposals by the EU and others tend to be blocked or watered down by developing countries that lack capability for sustainability and countries with strong shipping industry interests (*EA2*; *EA3*).

Apart from governance processes at the global level in the IMO, it is important to note that there also have been regional and national approaches. Van Leeuwen (2015) has found that since the 1980s there has been a move from a centralised IMO-focused approach to polycentric governance, driven by the EU's and other actors' dissatisfaction with the watered-down ambition level at the IMO as well as enforcement when it comes to environmental protection. In some cases, individual states pressing ahead with regulation such as the aforementioned US action on double-hull tankers has led to the IMO following suit. In other cases, regions have adopted stricter measures, either within, or outside of the IMO structure: IMO rules allow regional actors to designate areas as Special Areas or Emission Protection Areas, which happened in for the Baltic Sea, North Sea and North America with regards to SOx emissions (Sainlos, 2011). Operating outside of the IMO, European states created an enforcement system in the 1982 with the Paris Memorandum of Understanding on Port State Control, allowing port states to ensure compliance with IMO standards, which was later integrated into an EU directive (van Leeuwen, 2015). Hence, governance of international shipping can also succeed on a non-IMO level. Still, most participants agree that global rules are preferable (*NGO*; *PA2*; *IE1*; *IE2*; *IE3*; *EA1a*; *EA1b*) and some argue that regional (*EA1b*) or national (*EA3*) solutions might be ineffective or even counterproductive.

Governance on the smallest scale takes place in ports. Ports have a role as service providers for shipping, related mainly to loading/unloading of ships and fuel bunkering (Zis, 2019). On the one hand, they are run as for-profit businesses, but on the other hand, they are often owned and managed by public authorities, the port authorities (*EA1b*; *PA3*). These port authorities are a connection point between international shipping and national or local governments and can have their own specific regulations (*EX*). Regulations can take the form of environmental restrictions within the port area or positive incentives to encourage the uptake of sustainable technologies (*PA2*). However, even among port authorities there is disagreement as to how effectively these regulations can actually influence shipping (*PA1*; *PA2; PA3*). There is also considerable competition between ports, particularly if they lie close to another, limiting to some extent the willingness to adopt stricter rules (*EX*; *PA2*). Interestingly, ports are also organised on the regional level, such as in the European Seaport Organisation (ESPO), as well as the global level, in the International Association of Ports and Harbours (IAPH), where they can coordinate their actions (*PA1*; *PA3*). A harmonisation of policies on these levels can reduce damaging competition and increase the effectiveness of port regulations (*EX*). The topic of more sustainable ports has also received increasing scholarly attention recently (Zis, 2019). Ports thus seem to receive more attention as important actors.

The governance of shipping relates to hard-to-abate barrier B8, namely limited national policy efforts. However, this plays out differently than in the case of other hard-to-abate sectors such as heavy industry, where B8 has a lot to do with trade exposure of basic materials resulting in high potential for carbon leakage, which is less of an issue for shipping, since shippers cannot simply move all operations away from an area with critical markets (*EA3*). With shipping, as with aviation, B8 relates to those forms of transports largely taking place outside of national jurisdiction and thus being governed primarily by global institutions, i.e. the IMO in the case of shipping (Sainlos, 2011). Since shipping takes place in various different jurisdictions, national governments have varying effects on different shipping sectors, with inland shipping clearly being under national jurisdiction (*NGO*), short sea shipping less so and deep sea shipping rather being outside of national governments' reach.

In summary, the shipping regime is a very complex example of a hard-to-abate sector. The industry structure, involving different segments and various stakeholders, makes technological change difficult to implement, due to long-lived installations (B1), high entry barriers (B3), lack of demand for sustainable alternatives (B4) and global markets (B7). Moreover, it has developed in symbiosis with globalisation and shows a strong fossil fuel lock-in, particularly with regards to infrastructure (B2) and vested interests that are closely related to the fossil fuel industry (B6). Lastly, governance is complicated by its levels, from the slow-moving global IMO via regional organisations down to national, local and port-level jurisdictions, where national and lower level policy efforts are limited (B8). Having presented the currently dominant shipping regime, the question becomes what sustainable options are available and in how far they are ready to be applied (B5). Hence, the following chapter explains which technological alternatives are considered for the industry and how dynamics have been evolving between them and the regime.

5. Dynamics of change

This chapter explores the dynamics of change that can be seen as the initial move towards a sustainable transition of shipping. In section 5.1, the different types of alternative technologies are presented. Then, section 5.2 assesses the interaction between alternative options and the regime on the basis of the historic event analysis and interviews. Finally, section 5.3 draws lessons for the shipping transition, taking into account hard-to-abate industry literature.

5.1. Alternative technologies

There is a variety of low-carbon technologies that are considered options for the sustainable transition of shipping. This section explains how they work, how they have been categorised for the purposes of this study and what are their advantages and disadvantages. Some of these categorisations are not that clear cut and demand some clarification. LNG, methanol and ammonia can also be produced from biogenic sources, i.e. they could also be produced as biofuels. However, in the majority of cases LNG is understood as coming from fossil sources and methanol/ammonia are thought of as e-fuels instead of biofuels. Moreover, hydrogen is considered for shipping both running in fuel cells or in combustion engines. Still, most hydrogen-related projects aim to use it in fuel cells, therefore hydrogen and fuel cell projects were treated as pertaining to the same category. Also, as noted in the introduction, wind assistance could be seen as an efficiency measure since it is often applied as an additional measure reducing fuel use. Nevertheless, this usage should still be considered as an alternative propulsion technology since it is rather a case of hybrid propulsion than efficiency improvement and wind assistance is categorised like this in other publications as well (Kirstein et al., 2018).

5.1.1. Efficiency measures: operational & technical

Efficiency measures can be defined as those innovations which do not change the form of propulsion, but improve its operation in a way that reduces fuel consumption and thereby also emissions. In a way they are thus incremental innovations that can be accommodated within the dominant regime. Efficiency measures can be roughly divided further into operational and technical efficiency (Kirstein et al., 2018).

Operational efficiency measures are those that are related to ship handling. The most prominent example is slow steaming, which refers to the simple practice of sailing ships at lower speed to reduce fuel consumption, based on the fact that friction increases exponentially with speed increases (de Kat & Mouawad, 2019). This method has been proposed repeatedly for short term emission reductions in the form of speed limits, but there have also been doubts about its overall effectiveness and some safety concerns. Another, more complex measure is the use of AI or just-in-time arrivals for ships to make routes more efficient and reduce waiting times at ports or canals (Fjortoft & Berge, 2019). For the shipping company of one participant, implementation of operational efficiency measures have already led to emission reductions of 10-15% (*EA2*).

Technical efficiency measures incorporate technological solutions. Often they are related to reductions of water resistance, for instance through changing the shape of ship hulls (e.g. bulbous bows) or using techniques to reduce friction (e.g. air lubrication) (de Kat & Mouawad, 2019). Cold ironing – i.e. plugging in ships to on-shore power supply while in ports – is also considered a technical efficiency measure in this study, since it reduces fuel use and emissions without changing the form of propulsion (Zis, 2019). Technical energy efficiency measures can reduce overall emissions by 20-30% and cold ironing enables local CO_2 emission reductions by up to 70% (*EA3*; Zis, 2019). However, cold ironing is also seen critically by some who argue that it could prolong the eventually inevitable exit from fossil fuel propulsion and criticise that its infrastructure is sometimes built at ports with public money and ends up not being used because HFO is still cheaper (*PA1*; *PA3*).

5.1.2. Alternative fuels: LNG, LPG, biofuel, ammonia & methanol

Alternative fuels are fuels which are not produced from crude oil and have a promise of significant emission reduction, but they are still used in internal combustion engines. Some of them are drop-in fuels, i.e. they can be used in current ship engines, but most require modified or new engines.

LNG stands for liquefied natural gas, which consists mainly of methane (CH_4) and to a lesser extent of ethane (C_2H_6), cooled down to -162 °C to a liquid state (Psaraftis & Zachariadis, 2019). LNG technology was invented in 19th century Germany and originally used from the early 20th century on as a way to store natural gas, since in liquid state it only has 1/600th of its gaseous volume (Chiu, 2008). Natural gas is a common by-product of oil production and tends to be flared, i.e. burned, if no pipeline connection is available (Gould et al., 2020). However, by the 1960s, LNG arose as an alternative way of transporting natural gas in ships, leading to the development of an international LNG market, independent from pipelines (Adriatic LNG, n.d.). These LNG tankers were also the first ships to use LNG as a fuel, but recently the technology has increasingly been adopted by other ships as well (DNV, 2021). LNG is relatively cheap, with a price comparable to HFO (Sames et al., 2011). It can be used in specially-built dual fuel engines, able to run on both HFO and LNG. It offers a clear advantage with regards to pollutants such as SOx and NOx, which it reduces by up to 100% and 80%, respectively (DNV, 2021). However, its contribution to GHG emission reduction is highly disputed. Some sources claim it can reduce GHG emissions by 23% (DNV, 2021), but others worry that these reductions are far outweighed by a phenomenon called methane slip: imperfect combustion leads to methane leaking into the atmosphere and since it is a powerful GHG itself, the overall effect on climate change might even be worse than HFO according to some calculations (Psaraftis & Zachariadis, 2019). Apart from this issue, LNG still remains a fossil fuel and is thus not sustainable on the long term. Nevertheless, LNG technology could also be used with biomethane, which is generated from biomass (*PA3*).

Opinions on LNG are strongly divided. Its proponents see it as one of the only viable short-term solutions to emission reduction, if not for GHG emissions, then at least for SOx and NOx (*EA2*; *EX*; *PA3*). It is a mature technology with a growing bunkering infrastructure and the most widely adopted alternative fuel (*PA2*). Moreover, there is no agreement on how problematic methane slip is in practice, since it also depends on the type of the engine (*EA3*), so it could still offer significant GHG emission reductions (*PA3*). More critical views on LNG see it as a failure "that cost some companies quite a lot of money and the engine makers a lot of investment […] and now they are selling almost no LNG engines any more" (*IE3*). They say that this made shipping actors more cautious about potential solutions, since companies invested heavily and "they're a little unhappy that, well, they were given hope that this would be regarded as a good solution for sustainability" but it turned out not to be (*PM*). In the end, LNG is still used by many actors, but others, the most prominent among them container giant Maersk, decided to stop supporting LNG (*IE1*; *PA1*). LNG has one of the most active advocacy coalitions of all alternative technologies, namely SEA-LNG (SEA-LNG, 2020), which came up a total of 22 times in the dataset.

LPG, or liquefied petroleum gas, consists of propane (C_3H_8) and butane (C_4H_{10}), which have boiling points -42°C and -10°C, respectively, thus being easier to cool down to liquid form than LNG. These heavier hydrocarbon gases come as a by-product of natural gas exploitation and oil refining and are thus relatively limited in supply (Psaraftis & Zachariadis, 2019). LPG has a 15% CO_2 emission reduction potential but also faces the issue of LPG slip (Psaraftis & Zachariadis, 2019). It plays a relatively minor role in shipping due to its limited availability.

Biofuels are fuels made from organic materials (Psaraftis & Zachariadis, 2019). They are commonly distinguished into three generations, where 1st generation biofuels are made from food crops such as corn or potato, 2nd generation biofuels are produced using wood, straw or grasses, and 3rd generation biofuels are made mainly from algae or food waste (Nanda et al., 2018). For shipping, they come in a variety of forms, of which some are of higher quality and can also be used in cars, such as biodiesel, and others are more comparable to HFO, such as biocrude (*NGO*; *IE3*). Biofuels generally have the advantage of being very similar in properties to fossil fuels, thus making them so-called drop-in fuels, as they can use the same engines and the same infrastructure as HFO (*IE3*; *EA1a*). When looking at their whole lifecycle, biofuels have a 100% CO_2 emission reduction potential, since in theory all carbon that is released when they are burned has been taken from the atmosphere by the organisms the fuels are made from.

However, there are some concerns with biofuels that make it a controversial alternative fuel. Firstly, despite them being carbon neutral, they can still emit unhealthy air pollutants locally (Psaraftis & Zachariadis, 2019). Secondly, increasing biofuel production might lead to competition with food crops or destroy natural environments which serve as carbon sinks, thus having problematic implications for social and environmental sustainability (*IE1*; *EA2*), although this is mainly an issue for 1st generation biofuels, less so for 2nd generation fuels and no issue for 3rd generation fuels (*IE3*; *PA1*). Thirdly, it might simply not be possible to produce enough biofuels to supply shipping and other sectors which require them, such as aviation (*IE1*). These concerns have led to biofuels facing considerable criticism (*NGO*; *EA3*). Nevertheless, they are arguably the only carbon neutral technology for shipping that is already applied commercially and despite their problems, some shipping biofuel might in any case be necessary in the future, since many other alternative fuels require a pilot fuel for combustion (*NGO*; *IE1*; *IE3*). Moreover, similarly to LNG it is seen as a viable short-term solution, especially because it does not require different engines and thus evades the problem of long ship lifetime (*IE3*).

Ammonia (NH_4) is a chemical that has been used for fertiliser production for more than a century, since the invention of the Haber-Bosch synthesis, which arguably laid the foundation for modern agriculture (*IE1*; Paull, 2009). Since very recently it is also considered as a zero-carbon fuel, as it contains no carbon atoms and thus cannot emit any CO_2 (*IE3*; *EA3*). In a way it can be seen as a hydrogen carrier that has a higher energy density and – being liquid below negative 34°C – can be stored far easier than pure H_2 (PA3; Psaraftis & Zachariadis, 2019). Major ship engine builders are working on developing an ammonia-powered engine, but so far no ship is running on the fuel (*IE1*). It would require a different bunkering infrastructure, but since it has been produced, stored and transported widely, a considerable ammonia infrastructure already exists (*IE1*). Due to these factors, ammonia is increasingly named as the preferable solution in reports on the shipping transition (*NGO*; *IE3*; *EA1a*; *EA2*; ETC, 2018b). Nevertheless, there are some problems surrounding this fuel. First of all, there are serious safety concerns (*NGO*; *EA3*). Ammonia is highly toxic to humans and to ocean life (*PA1*; DoH, 2004) and has a very unpleasant smell, what one interviewee calls "a very unfortunate mix of different properties" that "sounds more like a horror cabinet" (*EA3*). Moreover, currently most ammonia is produced using natural gas or coal and it would only become a fully sustainable fuel if produced exclusively with renewable energy (Psaraftis & Zachariadis, 2019). Hence, a rapid expansion of renewable energy production and ammonia infrastructure would be needed to fully transition the shipping sector to this fuel, making it rather a long-term solution (*IE3*).

Methanol or methyl alcohol (CH_3OH) is a substance infamous for leading to blindness or death in consumers of badly made moonshine (Ahmad, 2000). It is also a widely used chemical needed for the production of plastics and other everyday products and a promising low-carbon fuel, with lifecycle emission reductions between 70% and 95% (DNV GL, 2016; Methanol Institute, 2021b). Methanol is liquid at room temperature, only requires relatively small modifications on engines and infrastructure to be used and is fully biodegradable (Methanex, 2020). Similar to ammonia, as a widely used chemical, methanol already has a significant existing infrastructure around ports. However, it is only a sustainable fuel if it is made from captured CO_2 using renewable energy or from biomass (*IE1*; *IE3*; *EA3*). Currently, most of it is still produced using fossil fuels, resulting in lifecycle CO_2 emissions worse than HFO when burned in ship engines (DNV GL, 2016). Due to its technological readiness and some positive properties, it is seen as a good short to mid-term solution (*IE1*; *EA1b*; *EA3*). Methanol has an active lobby group called the Methanol Institute (Methanol Institute, 2021a), which appeared 16 times in the dataset.

Together, ammonia, methanol and hydrogen are also sometimes referred to as e-fuels for shipping, since they can be produced using electricity (Van Kranenburg et al., 2020). Another connection between the three is that both ammonia and methanol can be seen as hydrogen carriers (*PA3*).

5.1.3. Alternative propulsion technologies: hydrogen, wind, nuclear & electric

Hydrogen is a gas and the most common fuel for fuel cells, which convert chemical energy into electricity without combustion. Fuel cells are thus a novel way of generating energy and can also be run on ammonia, methanol or LNG (Psaraftis & Zachariadis, 2019). If pure hydrogen is used, the only exhaust is water and the engine itself runs completely emission-free. It is also possible to burn hydrogen in combustion engines, either pure or mixed with other fuels (*EX*). Theoretically, hydrogen-powered shipping would be the ideal long-term solution, but there are several current limitations. Firstly, fuel cell technology is not mature enough to be used for main propulsion on big cargo ships (*EA3*; *PA2*). Secondly, as the lightest element, hydrogen has a very large volume and low energy density, storing it in pressurised tanks or cooling it down to liquid state (at -253°C) thus requires huge efforts (*IE3*; *PM*; *EA3*). Thirdly, as with the other e-fuels, currently most hydrogen is generated using fossil fuels and shifting the full supply to sustainable sources would require far greater amounts of renewable electricity generation than currently available (*EA3*; *PA1*; *PA2*). Fourthly, the necessary novel hydrogen infrastructure still does not exist and would take time to develop (Vogler & Sattler, 2016). Still, hydrogen's promising properties have led to many actors investing in it and it is increasingly named as a favoured solution (*EA3*; *PM*). So far its applications are limited to some pilot projects and niche applications in inland shipping, ferries, harbour craft and military use in submarines (*EA1a*; *EA1b*; Vogler & Sattler, 2016).

Wind is by far the oldest form of marine propulsion. Sailing ships have dominated shipping for millennia, up until the gradual introduction of steam-powered shipping in the 19^{th} century (Geels, 2002). Wind-propelled shipping is one of the oldest forms of transportation at all, even predating the use of horses and wheels by centuries (InpaperMagazine, 2011; Tallis, 2012).

Largely absent from commercial transport in the 20th century, wind propulsion technologies are recently making a comeback (de Kat & Mouawad, 2019). Combined with modern technology, sails can take the form of extendable rigid wing sails, AI-controlled kites or Flettner rotors, large rotating cylinders harnessing the same physical effect that makes a football with spin change direction mid-air (Rojon & Dieperink, 2014). In most cases these technologies are conceived as wind assistance, thus not propelling ships by themselves, but instead helping to reduce fuel consumption 10-20% by providing additional propulsion under the right weather conditions (*PM*; *EA3*). However, there are also projects to create almost fully wind-propelled cargo ships (*IE2*; Oceanbird, n.d.). The obvious downside to wind propulsion is its dependence on weather conditions (*EA2*), but it could provide considerable emission and cost reductions without requiring a new fuel (*EA3*; de Kat & Mouawad, 2019). Wind propulsion has a very active advocacy group in the International Windship Association (NGO; IWSA, 2021), which came up 21 times in the dataset, but despite this is not mentioned very frequently as a key solution (*NGO*; *PM*; *EA3*). This might have to do with its appearance as a very radical departure from current propulsion systems, which seems a bigger step than a fuel switch (*IE2*).

Nuclear power has a 65-year history in ship propulsion, mainly in military applications, where reactors have powered submarines, aircraft carriers and other navy ships since the early years of the Cold War (Hore-Lacy, 2007). There have been some pilots for nuclear-powered cargo ships in the 1970s, but they were all discontinued due to high costs and safety concerns. The only economically viable civil application to date are icebreakers in the Russian arctic, where the exceptional power is needed to break up to 3 m thick ice shields (Hore-Lacy, 2007). Despite its potential to be virtually carbon-free, nuclear power has been largely absent from most discussions on sustainable shipping, due to some substantial problems related to massive safety concerns, high upfront costs, the unresolved question of nuclear waste disposal and a widespread lack of societal legitimacy (*PA3*; *PM*; de Kat & Mouawad, 2019). In the words of an interviewee, the nuclear option "is blacklisted and nobody wants to hear about it" (*PA3*). Nonetheless, research projects are still being done and some interviewees did not want to exclude the possibility that nuclear power could be used in future shipping (*EX*; *PA3*; *PM*).

Electric motors have been used for almost two centuries and are some of the most efficient engines existing (*IE1*; *PA1*). If renewable electricity is used, electric propulsion can be virtually emission-free. The main problem is limited battery storage, which limits applications to shorter distances and makes battery-powered electric propulsion for deep sea shipping currently nonviable (*NGO*; *PA1*; *PA2*). Nevertheless, electric and hybrid propulsion is increasingly considered and used for niche applications, such as ferries, inland navigation, harbour craft and even short sea shipping (*NGO*; *PA1*; *PA2*; *PM*; de Kat & Mouawad, 2019). Moreover, there is the idea to begin building more ships with electric propulsion that can be connected to various electricity generation devices that could potentially run on any fuel (de Kat & Mouawad, 2019). This would allow for the construction of more modular and upgradable ships, solving the issue of long ship life slowing down technological change, as new innovations could be easily retrofitted in such an arrangement (*PM*; *EA1a*; de Kat & Mouawad, 2019). In some very rare cases, solar power on ships is considered to supply electricity, but the lack space on ships and the sensitive nature of photovoltaics makes this rather impractical (de Kat & Mouawad, 2019).

5.1.4. Ex post emission reduction measures: CCS & offset

Apart from the previous solutions which try to prevent CO_2 emissions by reducing their creation, there are also measures which attempt to cancel them out after they have been emitted.

These measures are referred to in this study as **ex post** measures. One is carbon capture & storage (CCS), which mostly describes techniques of removing carbon emissions directly from the engine exhaust. There are some projects trying to implement such CCS system on ships, such as decarbonICE (SAFETY4SEA, 2019g). The other method are carbon offsets, which are diverse ranges of projects somehow reducing emissions in other places or absorbing CO_2 from the atmosphere, e.g. through reforestation (Carbon Offset Guide, n.d.). Offsets are currently used by shipping companies to offer carbon neutral shipments to customers, but they are also criticised (*EA2*). As an interviewee whose company also uses offsets put it drastically: "It's nice, it's good, it's important, but it's not real. It's not a real solution." (*EA2*).

In summary, there is a variety of alternative technologies that promise emission reductions in shipping. They have advantages and disadvantages and vary in readiness, "radicalness", availability and in their diffusion. Due to this large amount of imperfect options and the uncertainty as to which one might prevail on the long term, it is helpful to have a detailed look at how these technologies compete not only against the dominant regime technology, but also amongst each other. Consequently, the following section presents the results of the historic event analysis to illuminate these dynamics.

5.2. Event sequence

This section combines the results from the historic event analysis based on the event database with insights from interviews, to create a storyline of the development of the TIS surrounding alternative technologies through creation function fulfilment and the destabilisation of the regime through destruction function fulfilment. It begins with an overview (5.2.1), then dives into the analysis of the distinctive periods (5.2.2-5.2.6) and concludes with a section on the relations between functions and general trends encountered in the historic event analysis (5.2.7).

5.2.1. Overview

Figure 1 shows how often the various technology categories were mentioned overall in the event dataset. LPG and nuclear had such few mentions that they were excluded from the further detailed analysis. LNG had the most events, followed by hydrogen, electric and efficiency. However, as figure 2 illustrates, the dominance of LNG has recently come under pressure, as its growth slowed down and "the curve flattened", while hydrogen and ammonia showed exponential increases, putting hydrogen in second place before electric and efficiency and ammonia on par with biofuel. Methanol also has a slight "bend to the left" in the last months, hinting to a general increase in event growth rate for all three e-fuels.

Figure 3 shows the division of events into the different creation functions. It becomes clear that there is fulfilment for all functions, but price-performance improvements (C3) seem to be largely lacking. This is probably some indication that this function is indeed not being fulfilled, but it might also be due to this type of event not being mentioned on shipping news websites in general. Hence, it might have been better to measure this function performance in a different way. It can also be seen that entrepreneurial experimentation (C4) accounts for by far the largest chunk of creation events, influence on the direction of search (C7) and knowledge creation, development & diffusion (C1) for about a quarter and a fifth of total events, respectively, and market creation (C2), resource mobilisation (C5) and support from powerful groups/legitimation (C6) for a relatively small part.

Figure 1: overall share of events per technology

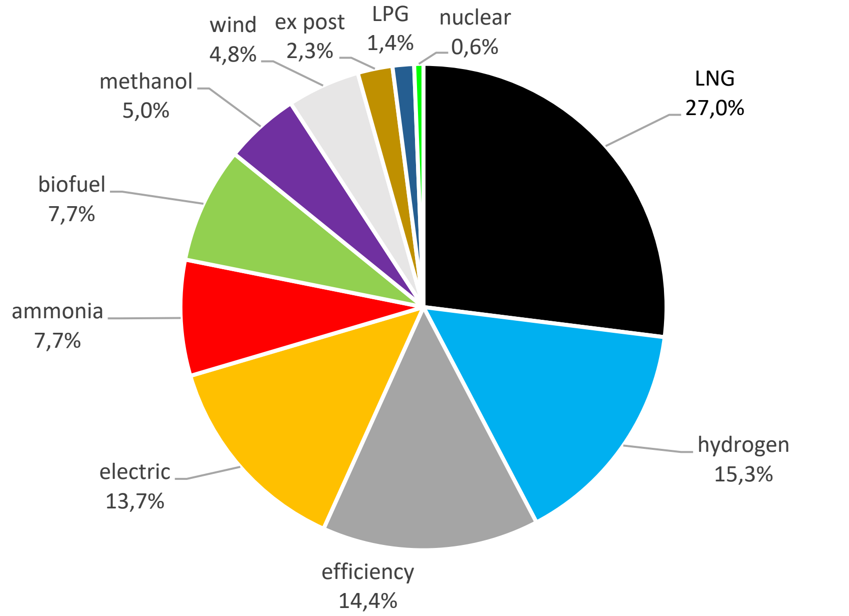


Figure 2: cumulative events per technology over time

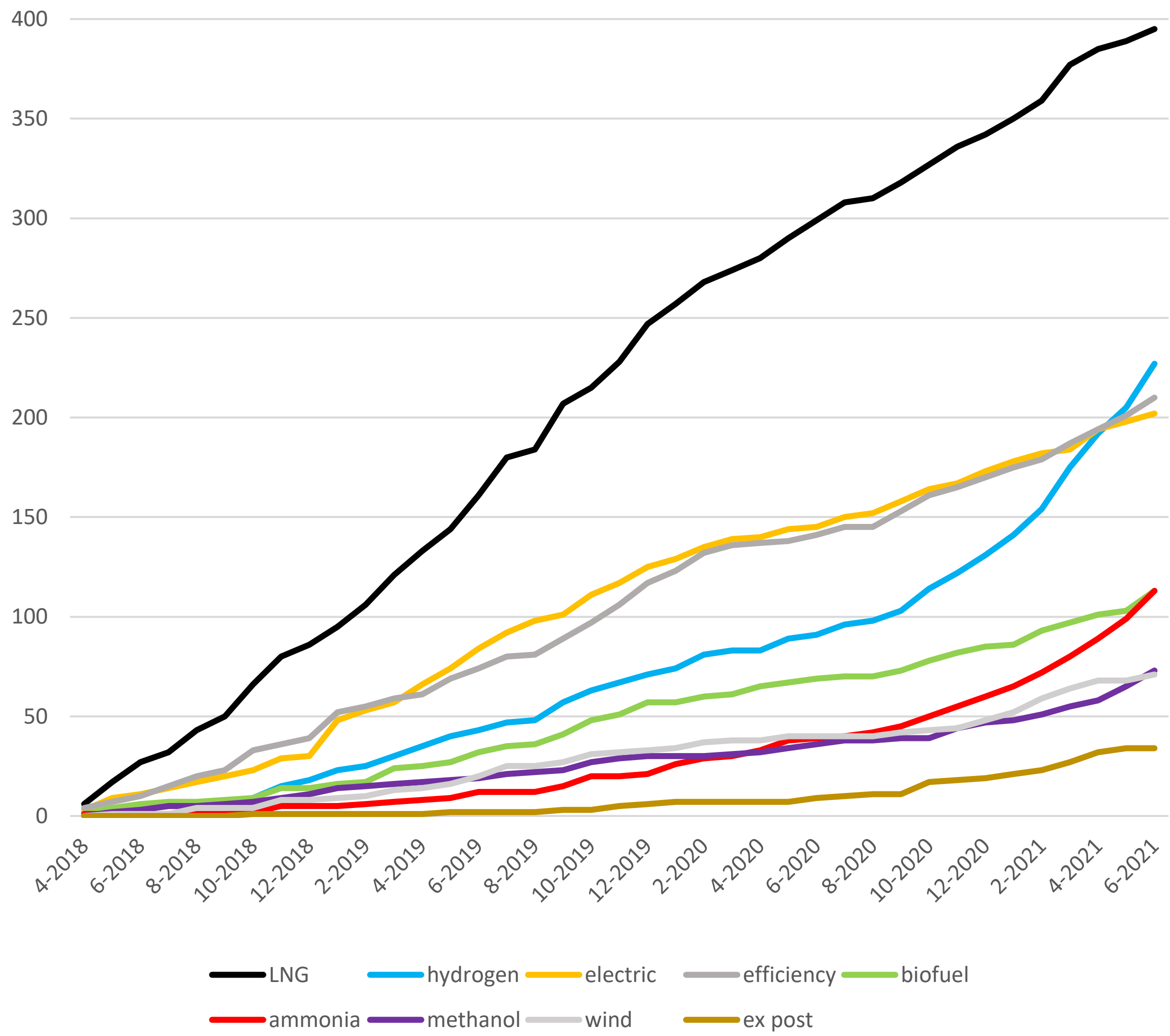
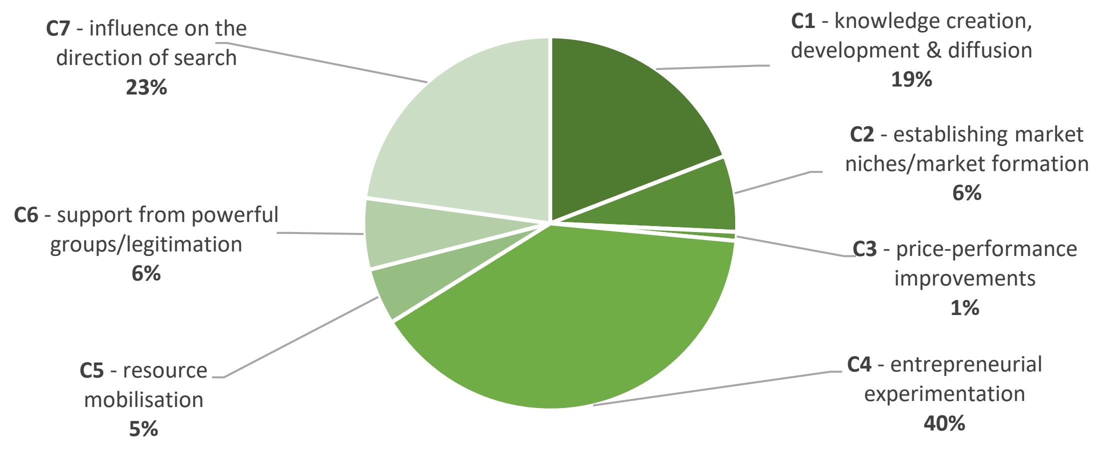
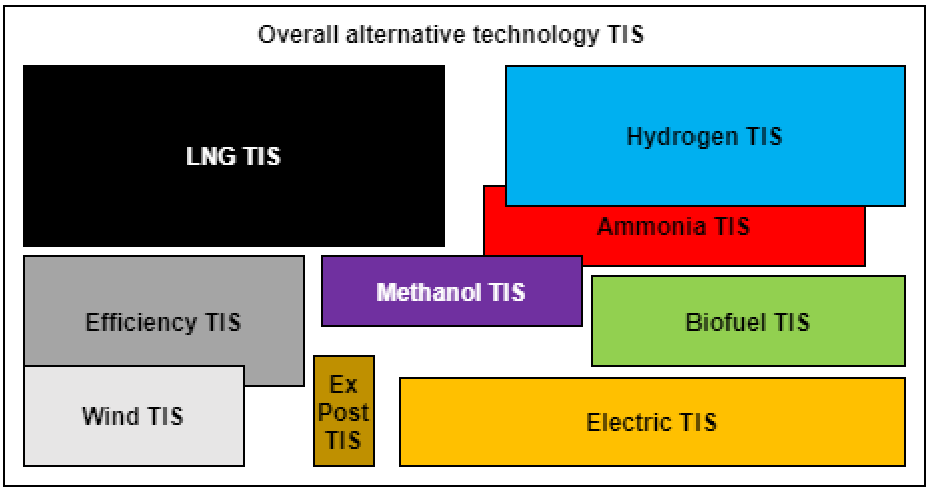


Figure 3: overall share of creation functions



Since the different technologies' TIS all have different dynamics and phases, the sequence analysis was structured according to the overall alternative technology TIS dynamics, i.e. phases were construed from event trends taken from the combination of all creation function events and the destruction functions. This led to a broad division of the observed timeframe into 5 periods that are further elaborated in the next subsections. Accordingly, for each period the general dynamics and key events will be described first, looking at both overall creation and destruction functions. Then, activities and trends will be broken up into the different technologies that were relevant in the respective period, hereby exploring the competition between alternative technologies and the performance of their respective TIS. Figure 4 visualises the relations between the different TIS, where the overall alternative technology TIS includes all the TIS of the specific technologies, which are of different sizes and sometimes overlap. The white space represents general (non-technology-specific) creation function fulfilment.

Figure 4: Overall TIS vs. specific TIS



During the process of coding events for destruction functions, a reoccurring type of destabilisation event was found that did not fit in the existing four destruction categories. Thus, a fifth destruction function *D5: monitoring & prediction of emissions* was added, since it became clear that this "fact-finding" activity seemed an important part of regime destabilisation. The extent of the societal problem that a regime constitutes through its emissions and where exactly these emissions arise, appeared to be a crucial precondition for the justification of other destruction functions. Therefore, establishing clear measures to monitor emissions and reliable calculations to predict emission growth, should be considered a part of regime destabilisation. Table 4 shows the indicator used for measuring this additional destruction function.

Table 4: Indicator for measuring added destruction function		
Function	***Indicator***	***Coding***
D5 - monitoring & prediction of emissions	Data collection, fact-finding, trying to establish clear measures and guidelines to monitor emissions as a necessary first step to reduce them, predictions for emission growth	+1

5.2.2. Period I: setting sail (April 2018 to September 2018)

This first period was characterised by the initial IMO strategy and a first burst of activity. In April 2018, the IMO's MEPC adopted the initial GHG strategy during its 72nd session in London, with the aim of "reducing GHG emissions from international shipping" and to "phase them out as soon as possible in this century" (IMO, 2018). Moreover, it set out a clear level of ambition with regards to emission reduction targets, thus being an example of guidance of the search (C7). This was followed by diverse industry actors' affirmation that they plan to reduce their emissions (C7). These statements were followed by a burst of entrepreneurial activity (C4) in May and June. Over the next three months until September, this entrepreneurial activity (C4) decreased a bit, but there was some more knowledge creation (C1) and market formation (C2) happening. Destruction functions remained largely neglected, with the only notable activity being a legal study published in June, finding that the IMO did indeed have the authority to implement globally binding climate measures through amending Annex VI of MARPOL (SAFETY4SEA, 2018a), thus providing a basis for potential control policies (D1).

The dominating alternative technology in this period was clearly LNG, having the highest amount of events for all creation functions except legitimation (C6). Particularly the area of entrepreneurial experimentation consisted to roughly a half out of LNG projects. What is interesting about this is that at the same time LNG was also controversially discussed: Many referred to LNG as promising venue of decarbonisation, while at the same time some noted that by itself it will not be able to achieve the targets. Illustrating this, one manager at Lloyd's Register stated that she expected the future to include a "diverse range of zero-carbon technologies/fuels deployed across the world's fleet", such as electric, hydrogen, ammonia, biofuels and wind (Palmer, 2018). Thus, the same amount of guidance of the search (C7) activities focused on LNG's advantages as did on its problems.

Apart from LNG, only efficiency and electric had a significant number of events in period I. Both were mentioned repeatedly in guidance of the search (C7) activities and registered some entrepreneurial experimentation (C4). Methanol was also mentioned as an option and received some institutional legitimation through its implementation into new fuel standards (C6), but showed no other function fulfilment. Lastly, there was a very small amount of events relating to hydrogen, wind and biofuel, respectively.

5.2.3. Period II: the wind is picking up (October 2018 to June 2019)

This second period showed renewed attention and growth. The topic of sustainable shipping received new attention in October 2018, related to three significant events: Seven major ports in North America and Europe launched the World Ports Climate Action Program to accelerate the development of low-carbon fuels and cold ironing infrastructure (SAFETY4SEA, 2018b), 34 industry leaders signed a call for action on decarbonisation at the Global Maritime Forum (SAFETY4SEA, 2018c) and the 73rd session of the MEPC took place, discussing follow-up actions on the initial strategy (SAFETY4SEA, 2018d). This was followed by more commitments to emission reduction by various industry actors as well as some governments, such as those of South Korea and Finland. As in period I, these guidance of the search (C7) activities were followed by strong increases of entrepreneurial experimentation (C4), in October and November. November also showed a strengthening of knowledge creation, development and diffusion (C1). In January and February 2019 there was renewed influence on the direction of search (C7), with several reports published emphasising the importance of new technologies to achieve the 2050 goal of halving emissions, as well as country commitments: the Netherlands stated that it wanted to decarbonise inland shipping and Sweden set the goal to decarbonise its whole shipping sector by 2045. Furthermore, the IMO called for emission reduction, particularly emphasising ports' role and Maersk, the world's biggest container company, announced that it wanted to become fully carbon neutral by 2050. Again, a strong increase in entrepreneurial activities (C4) followed, but this time this increased activity did not drop again and remained on a high level. At the same time, in March, there was an increase in knowledge creation (C1). In May, MEPC 74 proceeded in London and strengthened some emission targets under the EEDI, a move which was criticised as too low in ambition by environmental groups (SAFETY4SEA, 2019b). In June, many guidance of the search (C7) events followed, with Norway's government, the ICS and the Greek shipping industry calling for action on carbon emission reduction. Overall, this period showed a higher density of creation events than the first period did and had twice the amount of average monthly events in entrepreneurial experimentation (C4), guidance of the search (C7) and knowledge creation (C1), with also a notable increase in resource mobilisation (C5).

With regards to destabilisation of the regime through fulfilment of destruction functions, there was also an increase in period II. Some events could be linked to changes in old networks and creation of new networks linked to system change (D4), such as the growth of a global industry alliance for low carbon shipping, and the decision of Shell to leave a major fuel & petrochemical interest group due to climate policy disagreements (SAFETY4SEA, 2019a). There was also some reduction in support for regime technologies (D3), in the form of reports that noted that ship investors will link their finance to stronger sustainability compliance. Lastly, there was some activity on the monitoring & prediction of emissions (D5), with the EU commission planning to revise their shipping emissions monitoring system and BIMCO criticising the way that the IMO predicts future emission growth.

Looking at the alternative technologies, LNG still led the pack, but its advantage towards other alternative melted away a bit. It still had by far the largest share of events and was especially prominent in entrepreneurial experimentation (C4). However, it was not the most frequently mentioned positively in influence on the direction of search (C7) activities and was subject to quite some criticism. An example of this were various reports published by the NGO Transport & Environment (T&E) and other actors, which concluded that LNG is not a solution and might even be counterproductive for emission reduction due to methane slip (SAFETY4SEA, 2018e).

Similarly, Maersk stated that it does not see LNG as a solution for climate issues. These problems were also noted by interviewees, with some seeing LNG as a failed approach which made the shipping industry even more cautious about alternative technologies (*IE3*; *PM*).

Electric came in second by numbers, mostly due to its extreme growth in entrepreneurial experimentation (C4) as it was increasingly implemented in ferries, but it also had solid guidance of the search (C7) support. It was closely followed by efficiency, which had a considerable increase in entrepreneurial activity (C4) and the most support from guidance of the search (C7) events among all alternative technologies, despite also receiving a little criticism. The gains for electric are mirrored in the opinions of interviewees, who agreed across the board that electric propulsion is the most efficient of all technologies and that shipping "should electrify whatever can be electrified" (*IE1*), but also noted that the role of electric will be limited to harbour craft, inland and short sea shipping (*NGO*; *IE1*; *IE3*; *PA1*; *PA2*; *PM*).

The newcomer of this period was definitely hydrogen, with the fourth highest overall event count, the most knowledge (C1) activities, good support from guidance of the search (C7) actions and for the first time a high amount of entrepreneurial experimentation (C4).

Biofuel also showed considerable growth, largely in the form of entrepreneurial experimentation (C4), but also some knowledge (C1) activities and guidance of the search (C7). However, in the latter it had roughly the same amount of positive and negative mentions and was subject to heavy criticism, exemplified by T&E referring to it as "biggest pitfall" on the path to shipping decarbonisation (SAFETY4SEA, 2018f). Also among interviewees opinions on biofuel were highly polarised, with some seeing it as an immediate, promising and workable solution (*NGO*; *IE3*; *PA1*; *PA2*) and others discarding it as environmentally damaging or seeing only a very limited role for it (*IE1*; *EA2*; *EA3*).

Furthermore, there were more events related to wind, methanol and ammonia in this period. Activity around wind mainly consisted of entrepreneurial experimentation (C4) and to a smaller extent knowledge (C1), methanol showed events for almost all creation functions but particularly related to knowledge (C1) and ammonia only came up as a promising solution in guidance of the search activities (C7).

On a last note, there were for the first time some activities related to ex post measures, with a few instances of entrepreneurial activity (C4).

5.2.4. Period III: the flagship EU sails ahead (July 2019 to February 2020)

In July 2019, a new dynamic shook up the shipping industry, when it became increasingly clear that the EU was not satisfied with progress at the IMO and wanted to press ahead with its own, more stringent climate targets: the new Commission president Ursula von der Leyen proposed a new climate policy with carbon neutrality by 2050 and called for a future inclusion of the shipping sector in the EU ETS (SAFETY4SEA, 2019c). In this month, entrepreneurial experimentation (C4), guidance of the search (C7) and knowledge (C1) activities were all at high levels. After all activities took a dive in August for unclear reasons, September came back strong with two major industry-supported initiatives: the Getting to Zero Coalition was announced by Maersk and the Port of Antwerp and supported by the IAPH, to drive forward the development of zero-emission ships by 2030; and the WSC proposed to the IMO the creation of an International Maritime Research Board (IMRB) as a global R&D entity under IMO supervision. At the same time, knowledge (C1) and entrepreneurial activities (C4) reached new peaks. In October, the Getting to Zero Coalition was launched at the Global Maritime

Forum in Singapore with the support of 70 major corporations and was seen as "leading the way", next to the Poseidon Principles, a new ruleset for banks to link funds to sustainability criteria and hereby redirect resources from polluting to greener shipping technologies (SAFETY4SEA, 2019f). Guidance of the search (C7) events reached a new peak that month. In December 2019 the European Green Deal was officially announced by the EU, setting the goal of becoming the first climate neutral continent by 2050, again pointing to an eventual inclusion of shipping in the ETS. By February 2020, the Getting to Zero Coalition had grown to 100 members who gathered for the first time in Copenhagen to map out the ways to achieve their goal. Overall, period III showed very similar event counts for each creation function as period II did, with the only exception of legitimation and support by advocacy groups (C6), which almost tripled.

Whereas creation functions remained on similar levels, the picture was very different for destruction functions, which had a considerable increase in period III. All of the five destruction functions had corresponding events occurring. The EU's intention to include shipping in its ETS as well as the French government's call to create an EU-wide bunker fuel tax were major steps towards the establishment of control policies (D1). The announcement of the European Green Deal constituted a significant change in regime rules (D2), as this ambitious plan amounted to a long-term overarching change in policy. The continued efforts to redirect financial streams away from fossil fuels and towards more sustainable shipping and thereby reducing support for dominant regime technologies (D3) found expression in the Poseidon Principles for banks, the European Green Deal Investment Plan and Maersk receiving a new sustainability linked credit. Changes in social networks through the formation of new organisations (D4) were evident in the creation of the Getting to Zero Coalition, the Coalition for Maritime Environmental and Energy Transition and the proposed creation of the IMRB. Finally, monitoring of emissions (D5) could be seen in the EU publishing extensive data on ship emissions and the Korean Register's launch of an emission reporting & management system. Thus, the creation functions appeared to be increasingly accompanied by complementary destruction functions.

The EU pressing ahead was also a reoccurring topic in interviews, where participants noted that this might be a way to pressure the IMO and industry actors to implement stricter measures, as they want to avoid a worldwide patchwork of varying regulations (*NGO*; *EX*; *IE1*; *PA3*). All agreed that global IMO regulation would be preferable (*NGO*; *IE1*; *IE2*; *IE3*; *EA1b*; *PA2*), but opinions were divided on whether a regional approach was the next best thing (*IE1*; *EA3*; *PA2*), or rather ineffective (*EA1b*; *EA2*). Moreover, particularly the European Green Deal was named repeatedly as putting political pressure on the shipping sector (*IE1*; *PA1*; *EA1a*).

With regards to the different technologies, there was no fundamental difference to period II at first sight. LNG was still the most prominent technology, with most functions staying at a similar level, a slight increase in entrepreneurial experimentation (C4), a doubling of legitimation/advocacy group support (C6), mostly due to the activity of SEA-LNG, and far less focus on its problems in guidance of the search events (C7).

Efficiency took over electric as the second place and showed increases in entrepreneurial activity (C4), knowledge creation, development and diffusion (C1) and guidance of the search (C7), however with both more focus on its advantages and its problems, mirroring a controversial discussion of efficiency measures. This controversy also came up in interviews: where some stated that any efficiency gain should be exploited (*EA2*; *EA3*), but others noted that too much focus on efficiency "actually prolongs and legitimates the continuation of fossil fuel use" (*PA1*).

Events related to electric decreased overall and there was less fulfilment of entrepreneurial experimentation (C4) and guidance of the search (C7) functions. Despite the overall worse performance, there was quite an increase in knowledge (C1) activities, market creation (C2) and legitimation (C6).

The TIS around hydrogen in shipping grew, with this technology coming in fourth overall and for the first time showing events for all seven functions, something which had occurred so far only for LNG. There were slightly increased knowledge (C1) and guidance of the search activities (C7) and an especially strong growth in legitimation and support by advocacy groups (C6). However, entrepreneurial experimentation (C4) actually decreased a bit in this period.

Biofuel showed growth as well, with entrepreneurial activity (C4) picking up considerably and some legitimation (C6) as well as guidance of the search (C7) in favour of this technology. Interestingly, as opposed to period II, there seems to have been less of a discussion about biofuel, since there were no negative mentions in guidance of the search activities.

Ammonia and wind had the same amount of associated events in period III. Ammonia again showed strong guidance of the search (C7), but also had an increase in knowledge activities (C1) and entrepreneurial experimentation (C4), leading to an overall solid growth. Similarly to period II, wind was strong in entrepreneurial activity (C4) and had some knowledge creation, development and diffusion (C1). However, this period also showed a considerable increase in legitimation (C6) for wind, linked to the activities of the IWSA.

Methanol was the only technology that showed an overall decrease in period III, despite some more entrepreneurial experimentation (C4) and legitimation (C6).

Lastly, ex post measures showed some more activity, with some knowledge (C1), legitimation (C6) and guidance of the search (C7) events occurring next to entrepreneurial experimentation (C4). Still, compared to other technologies events belonging to this category remained miniscule.

5.2.5. Period IV: stuck in the pandemic doldrums (March 2020 to August 2020)

On 11 March 2020, the World Health Organisation declared the novel Covid-19 outbreak a worldwide pandemic (WHO, 2020). This global health crisis triggered a worldwide economic crisis which had wide-ranging impacts on the shipping industry: global GDP went down by 4.2%, seaborn trade contracted by 9.5% in 2020 (Gladen, 2021) and shipping suffered a serious disruption due to continuous uncertainty (Asariotis et al., 2020). These landscape factors were also clearly reflected in sustainable shipping events. Particularly in March and April, there was far fewer overall activity and all creation functions showed a stark reduction, with the notable exception of knowledge creation, development and diffusion (C1), which remained relatively stable. Historically low oil prices due to the Saudi-Russian price war, exacerbated by the pandemic and even becoming negative in the US in April, were another disadvantageous landscape factor for alternative technologies, since this worsened the already significant price gap to HFO (Blessing, 2021; SAFETY4SEA, 2020a). However, after the initial shock, there was some renewed attention in the form of substantial guidance of the search (C7) activities in May, including commitments to 2050 carbon neutrality by the UK, Norwegian shipowners, CMA CGM, and Alfa Laval. This was followed by some signs of recovery in June and July, with entrepreneurial experimentation (C4), knowledge (C1) activities, resource mobilisation (C5) and legitimation (C6) increasing. Overall, the number of monthly creation events was halved compared to period III, demonstrating a significant drop due to the Covid-19 pandemic.

Looking at the destruction functions, period IV also showed a clear overall reduction compared to period III. Nonetheless, there was still some activity: Whereas a report highlighted that shipping still lacked control policies, the EU took further steps towards an inclusion of the sector into its ETS (D1), including a meeting of its transport ministers in March and its Environment Committee deciding on further details. Reduced support for dominant regime technologies (D3) became clear through redirection of finance towards more sustainable shipping: the Poseidon Principles grew further and the UN Secretary General emphasised that shipping bailouts needed to be in line with climate commitments and should not support fossil fuels (SAFETY4SEA, 2020b). Finally, July saw the founding of two new industry coalitions to advance the transition of shipping, an example of the formation of new networks (D4).

With regards to the competing alternative technologies, the pandemic shook up the dynamics a bit. LNG remained at the top despite suffering strong reductions in all seven functions, mostly due to it still having the main share of entrepreneurial activities (C4).

Electric came back to the second place, with solid knowledge (C1) activities and some entrepreneurial experimentation (C4) and guidance of the search (C7).

However, it shared this position with hydrogen, which stood out through its increased mentions in guidance of the search (C7) activities. Many reports increasingly referred to hydrogen as a preferred solution.

Efficiency measures fell behind, were not mentioned at all in guidance of the search (C7) activities and only had a reduced number of events for knowledge creation, development and diffusion (C1) and entrepreneurial experimentation (C4).

Ammonia was the only technology which had more events in period IV than in the previous one, due to a doubling of knowledge-related (C1) and almost no reduction in entrepreneurial (C4) and guidance of the search (C7) activities. Hence, ammonia and hydrogen made strong relative gains compared to the previously predominant alternative technologies of LNG, electric and efficiency, foreshadowing a development which became evident in period V.

Methanol stayed at a similar level as it had in period III, largely thanks to a strong increase in knowledge creation, development and diffusion (C1).

Lastly, wind showed almost no activity in period IV.

5.2.6. Period V: gathering speed (September 2020 to June 2021)

Beginning around September 2020, sustainable shipping developments began to gather speed, more than they ever had before. Various commitments to 2050 carbon neutrality were made by industry actors while the IEA, as well as BP and Shell were among the major energy actors that expressed their belief that alternative fuels were the future of shipping. The US withdrawal from the Paris Agreement in November could be seen as a setback, but at the same time the European Parliament settled on increased emission targets and MEPC 75 took place, with the IMO approving additional measures such as an energy efficiency index for existing ships. Together these events constituted a significant burst of guidance of the search (C7) activities. Moreover, October saw the highest number of knowledge-related (C1) events in a month to date, while function fulfilment for entrepreneurial experimentation (C4), market creation (C2), resource mobilisation (C5) and legitimation (C6) all picked up around this time and continued to increase towards the end of the period. In early 2021, the US rejoined the Paris Agreement under its newly elected president and the EU Commission launched a new major initiative to require ships sailing into EU ports to operate on low-carbon fuels. Entrepreneurial activity (C4) reached a new peak in March and knowledge creation, development and diffusion (C1) as well as guidance of the search (C7) strongly increased up to and around MEPC 76 in June 2021, bringing the observed period to a close. MEPC's 76th session itself was seen by many actors as disappointing and insufficient, making future unilateral action by the EU (and the US) more likely (EA3). As one interviewee who participated as an observer stated coming right from the conference, when asked whether enough is happening at the IMO: "Well, there is virtually nothing happening [laughter]" (EA3). Nevertheless, overall, period V was the best one for sustainable technologies so far, with the fulfilment of every single creation function strongly increasing and the number of monthly events being more than double that of period IV, while also clearly outperforming the previous periods.

Whilst creation function activity strongly increased, the growth of destruction events was even more extreme: period V saw more activity related to regime destabilisation than all the previous observed periods combined. Destruction function fulfilment increased across the board, with the exception of changes in social networks (D4). The function that showed by far the strongest increase was control policies (D1). This began with the EU parliament greenlighting the ETS inclusion in September, reaffirming EU willingness to follow through with its vanguard strategy. Similarly, the UK and China voiced plans to include shipping in their own carbon markets. This looming prospect of regional or national emission trading systems divided actors in the shipping industry, with some seeing this as a viable way to proceed and others, such as BIMCO, the Liberian registry, Lloyd's Register, several Asian countries and EU shipowners heavily criticising regional approaches and instead attempting to pressure the IMO to adopt global market-based measures to pre-empt a patchwork of smaller-scale systems. Moreover, a debate flared up about who should be held responsible for shipping emissions in the EU, with Greece as the major shipowner nation trying to shift the responsibility towards fuel suppliers and engine manufacturers instead. In the end, the IMO could not settle on global MBMs despite all efforts and the EU took this as a confirmation that it needed to act regionally. In the words of a member of the EU's IMO-delegation: Brussels "gave the IMO all the opportunity and it was not taken. […] It is time for us to move forward" (SAFETY4SEA, 2021b). Similarly, US climate envoy John Kerry called for 2050 carbon neutrality, far stricter than the IMO 50% emission reduction target. This perceived failure to act at IMO level might increasingly lead to the creation of alternative fora (D4) that simply circumvent the IMO and press ahead with more stringent measure, as evident in the first meeting of the so-called M7, consisting of the maritime bodies of the G7 plus Australia, India, South Africa, South Korea as well as ICS, BIMCO and ECSA representatives. Other instances of new network formation (D4) were the Mission Possible partnership, founded in the context of the World Economic Forum in Davos to accelerate the decarbonisation of hard-to-abate sectors and the Sea Cargo Charter, a framework to tackle the sustainability transition in the bulk sector. Significant changes in regime rules (D2) were hoped by some to occur around the latest MEPC sessions and due to the US completely changing course again and putting climate policy at the forefront, but in the end many actors still expressed a perceived lack of fundamental change (registered as negative D2). Reduced support for regime technologies (D3) could be seen in the continuous growth of the Poseidon Principles and the EU repeatedly urging its members to stop subsidising fossil fuels, resulting in some binding commitments. Lastly, there were several activities with regards to emission monitoring (D5), including the new Carbon Intensity Indicator introduced by the IMO and a database on ship emissions by the IAPH. Overall, there was a strong increase in destruction function fulfilment, but statements on the lack of destabilising measures were still plenty to be found, demonstrating that there was still much room for improvement.

When looking at the development of the competing alternative technologies, a very different picture emerges compared to the previous periods. Events for every single technology category increased in period V compared to period IV, but a possibly more insightful comparison can be made to period III, before the impact of the Covid-19 pandemic: here, all three previously dominant technologies, i.e. LNG, efficiency and electric, actually showed a decrease in monthly events. Of them, only LNG stayed in the top three, and the rise of hydrogen and ammonia to the position of most mentioned technologies which had already showed itself in period IV, materialised itself. Hence, hydrogen had the most events, mostly due to an extremely high amount of knowledge (C1) activities, but also the highest number of positive guidance of the search (C7) mentions, much entrepreneurial experimentation (C4) and the highest amount of resource mobilisation (C5) events for any technology so far. This clearly shows that the TIS surrounding hydrogen grew considerably.

Nevertheless, LNG still remained in the second spot and had the highest number of entrepreneurial (C4) activities. However, this number was less than half of the amount of entrepreneurial experimentation it had had in period III and especially towards the end of period V those events became fewer. It also became clear that it remained a controversial technology, with a relatively large amount of negative mentions in guidance of the search (C7) activities. Together, these tendencies showed that LNG was increasingly replaced as the dominant alternative technology.

Ammonia climbed up to become the third most mentioned technology. It was often mentioned together with hydrogen in reports, surveys and other guidance of the search (C7) activities. Moreover, it showed a strong increase in entrepreneurial experimentation (C4) and knowledge creation, development and diffusion (C1). Thus ammonia seems to have turned from a rarely considered technology in period I into a likely candidate for shipping decarbonisation in period V.

Efficiency measures remained popular, particularly with regards to knowledge-related (C1) and entrepreneurial (C4) activity. However it had been mentioned far more frequently in guidance of the search (C7) activities in periods II and III. These changes reflect the fact that efficiency measures, while being a crucial building block in decarbonisation, are not able to achieve the transition by themselves, thus making a shift in focus towards true zero-carbon technologies reasonable.

A similar conclusion can be made about electric, which has a promising role in niche applications such as ferries, harbour craft, inland shipping and in the form of hybrid propulsion that can be used by ocean-going ships when in port. This showed in continued good numbers for entrepreneurial activities (C4) related to electric, but overall it is taken over by other technologies, since it has very limited potential for deep sea shipping decarbonisation.

Biofuel was in an interesting position, as it had a pretty high amount of entrepreneurial experimentation (C4) on the one hand, but was the most disputed technology on the other hand, with nearly as many negative mentions as positive mentions in guidance of the search (C7) activities. It was often named together with LNG as a problematic technology, which should have no or only a very limited role in the shipping transition.

Methanol had good growth in entrepreneurial activities (C4), resource mobilisation (C5) and guidance of the search mentions (C7). However, it was also portrayed negatively in some reports and did not get as much traction as ammonia did, which it was often compared to as both are e-fuels and hydrogen derivatives.

After two periods of slight decline, wind demonstrated some growth again, with a good number of entrepreneurial activities (C4) and solid knowledge activity (C1) as well as legitimation and support by advocacy groups (C6). Still, it seemed to remain a relatively overlooked technology, with the fewest mentions in guidance of the search (C7) activities. This is consistent with participants' opinions that wind can have a helpful role in the transition, but in most cases does not have a 100% reduction potential and is therefore not featured prominently in discussions (*NGO*; *EA2*; *EA3*).

Lastly, ex post measures appeared to have received some new attention, with quite some entrepreneurial experimentation (C4) as well as knowledge creation, development and diffusion (C1) and some mentions in guidance of the search (C7) activities. However, it was still the least mentioned technology overall. As an interviewee noted, offsets in particular remain one of the only options to offer fully carbon neutral shopping services, but at the same time their use should be taken with caution, as their actual efficacy is questionable (*EA2*).

5.2.7. Relations between functions & overall trends

Looking at relations between functions and overall trends in the event analysis reveals some further insights. In general it seemed as if guidance of the search (C7) activity often predated or coincided with increases in other functions, mostly entrepreneurial experimentation (C4) and knowledge creation (C1), but also mobilisation of resources (C5). This finding is consistent with interviewees' statements emphasising the importance of government guidance to encourage the uptake of sustainable technologies (*IE1*; *IE3*; *EA1a*) and it also amounts to a translation of societal landscape pressure into actual activity in the industry. However, negative guidance of the search (C7) not necessarily led to decreases in other functions. This could be interpreted to the effect that rather than causality flowing from a focus on problems of a technology to less adoption in the form of reduced entrepreneurial activity (C4), more use of a technology simply led to increased scrutiny and a consequent discussion of its downsides. Moreover, the creation of R&D funds and other resource mobilisation was often named explicitly in events as a follow-up action on reduction goal setting in event descriptions. Unsurprisingly, resource mobilisation (C5) also seemed to foster entrepreneurial experimentation (C4).

The analysis could also shed some light on the relations between creation & destruction functions. Resource mobilisation (C5) and reduced support for dominant regime technologies (D3) were often related, which makes sense, since a reduction of funds and other resources for the polluting regime technology frees these resources to be redirected towards sustainable alternatives. Another way for alternatives to mobilise resources was the proposed idea of creating a global maritime research board, funded by introducing a carbon levy on shipping, so control policies (D1) can also go hand in hand with resource mobilisation (C5). The actual introduction of control policies (D1) would also automatically lead to market creation (C2) and/or price-performance improvements (C3) in case some sort of carbon pricing is applied.

Interestingly, the declaration in events that a certain technology might be the solution (C7) was often combined with a call for carbon pricing (D1) to enable the further adoption of this solution.

Overall, the event analysis clearly showed that there was a substantial overall increase in activity related to sustainable shipping technologies, despite the "Covid-dip". This is consistent with interviewee perception. In the past, sustainable shipping was seen as an unattainable "utopia" (*PA2*) and sustainability was "not a topic" for a long time (*EA3*), but this seems to have changed in the past years (*PA2*) and shipping actors are increasingly interested in decarbonisation (*NGO*; *PM*). This increased interest is driven by several factors. First of all, actions by the IMO, EU and national governments constitute a regulation-push factor, with not only current regulations, but also the expectations of future stricter regulation in an industry where investments have to be used for a long time to prevent sunken costs making action necessary (*PM*; *EA1a*). Still, some say that not much is happening, particularly with regards to stricter and strictly enforced regulation at the IMO level (*EX*; *PA1*). Therefore, a second and maybe more important factor is coming from industry stakeholders. There is a demand-pull from cargo owners and others who want to decarbonise their supply chains or operations (*EA1b*) and there are investors and financers who demand sustainability so their investments are safe on the long term (*EA1a*; *EA2; EX*). A third issue is that some frontrunner companies and countries see sustainable shipping as a business opportunity and are seeking first mover advantage (*NGO*; *IE1*; *IE3*; *PA2*).

Moreover, the amount of events for all the different technologies show that there are plenty of technological options that are being developed further. On the one hand, this provides more potential solutions, but on the other hand, this diversity of options leads to a fear of betting on the wrong horse (*IE3*; *EA1a*; *EA1b*; *EA3*). Hence, companies prepare for different options but are hesitant to commit to any one of them (*EA1b*). This fear was reinforced by ups and downs for technologies, such as the boom around LNG in period II and III and its subsequent decline due to aforementioned problems (*IE3*; *PM*). The variety of options, the different requirements for different market segments and the general issue of scalability of the solutions leads to a likely scenario where different technologies coexist or are implemented in hybrid solutions, if not on the long term then at least for the short and mid-term (*NGO*; *IE1*; *IE2*; *EA1a*; *EA1b*; *EA2*; *PA3*). This was coined "horses for courses" by one interviewee (*EA1a*), meaning that different technological solutions are required for different market segments (*IE2*; *EA1a*; *EA3*; *PA2*).

The increasing demand for and enaction of destruction functions next to creation functions fits with what participants perceived as the necessary role of governance actors. Governments and ports need to use the "carrot and the stick", i.e. positive incentives to motivate early movers as well as punishing and prohibiting the continued use of polluting regime technologies by laggards (*IE1*; *EA1a*).

Looking at the dominant alternative technologies, it becomes clear that while slightly declining, LNG and biofuel are still the only options that are widely applied, despite their disadvantages and might thus be the only short term options. Hydrogen and ammonia, on the other hand, have recently come up as the most likely long term solutions, but they are still not ready to be deployed and their support comes mostly in the form of positive expectations and R&D. Generally, the more incremental innovations such as LNG and efficiency measures were favoured strongly in the beginning, but this seems to be changing towards a focus on more radical options such as hydrogen and ammonia. Methanol is a likely short- and midterm option that also becomes increasingly relevant. Lastly, it is not fully understandable that despite its advantages, wind is a comparatively overlooked solution. This might have something to do with its radical appearance departing more from the traditional way of doing things, where a switch to a different fuel is more within the standard procedures, or it is simply that HFO is still too cheap for companies to consider wind assistance or fully wind propelled ships (*IE1*; *IE2*).

5.3. Lessons for the shipping transition

Looking back at the barriers that were identified in hard-to-abate industry literature, for some of them (B1, B2, B3, B5, B6, B8) the way that they influence the transition of shipping becomes more clear when combining insights from event analysis and interviews.

B1: The extent of the problem of ship longevity depends on the alternative technology. By definition it is not an issue for drop-in fuels such as biofuels and less of a problem for retrofit solutions such as some forms of wind assistance (*IE2*; *IE3*). On the contrary, it is a major issue for those alternative fuels which require a completely different engine, such as ammonia (*IE1*). Hence, this barrier has implications for the timeline of solutions: on the short term, drop-in fuels and retrofits are the only viable solution, whereas on the long term alternative fuels or propulsion methods could be implemented (*IE3*). Hence, achieving 2030 or 2050 goals might require quite different technologies (*EA1b*). An innovative solution to this problem might be the introduction of electric drivetrains which could be connected to generators running on different fuels and/or batteries or other ways of building modular ships (*EA1a*; *EA1b*; *PM*).

B2: Similarly, infrastructure lock-in with regards to bunkering and fuelling infrastructure does not constitute a problem for wind propulsion or drop-in fuels (*IE3*), but is more complicated for other alternative fuels (*IE1*). Here, ports have a crucial role in providing new infrastructure and have to take risks doing so (*NGO*; *PA2*; *IE1*). A difficult question then becomes who finances this new infrastructure, which requires high upfront costs, especially in the case of cold ironing and electric ships, so agreements with shipping companies on guaranteed offtake might be needed (*PA1*; *PA3*). However, the event analysis showed a rapid extension of LNG bunkering at ports or in the form of ship-to-ship bunkering barges, which could also be implemented for other fuels. In the end, this barrier slows down adoption of new fuels but should not be seen as a major hindrance. As an interviewee from a port authority noted, “if these shipowners say that it’s going to be a growing demand of a certain type of fuel or different types of fuels, we won’t have any problem in providing the infrastructure” (*PA3*).

B3: Regarding high entry barriers, interviewees from innovative enterprises emphasised that they do not see it as a really big problem to enter into the shipping fuel market (*IE1*; *IE3*).

B5: Lack of supply of sustainable alternatives can be understood in two ways in shipping, as a lack of technological options or as a lack of fuel supply. In the first sense, it does not seem to be a problem, since both interviews and event analysis showed that there is quite an array of different options available, although only some of them are ready to be deployed. In a certain way, one could almost speak of an oversupply of different options, which leads to the aforementioned fear of betting on the wrong horse. This uncertainty of what will be the future of shipping makes actors rather cautious in committing to any technology (*NGO*; *EA1b*; *EA3*). One participant emphasised that “technology is not necessarily the issue” and “we’re sort of ready, we only don’t know which direction to start running” (*EA1b*). The problem of supply seems to lie rather with price (*PA3*) and scalability (*IE1*; *EA1b*), which relates to the second sense that lack of supply can be understood. The massive amounts of alternative fuel to be consumed by the shipping industry need to be produced somewhere and production needs to be scaled up rapidly. In this way a variety of different options might actually be helpful, since it simply enlarges the pool of overall available fuel.

B6: Vested interests favouring efficiency improvements to deep decarbonisation are definitely an issue in shipping, as the international shipping industry is well-organised and in the past has succeeded in slowing down action at the IMO (*EX*; *PA2*). The event analysis has also shown that particularly in earlier periods, much activity was surrounding incremental innovation, such as continuous fossil fuel use in the form of LNG or efficiency improvements. Some interviewees also saw these developments as limited short term solutions that might end up prolonging the inevitable exit from fossil fuels (*EX*; *PA1*). Another participant mentioned that incumbent engine makers "also withheld some types of technologies because it was not in their own interest" (*PM*). Nonetheless, some major industry actors seem to have moved to supporting more radical technological changes (*IE1*) and efficiency improvements, when compatible and combined with alternative fuels, can lead to significant emission reductions (*EA3*).

B8: With regards to limited national policy efforts, the event analysis has shown that despite political pressure lacking in many countries (*PA1*), some frontrunners are taking efforts to decarbonise their shipping sectors, particularly the UK and Scandinavian nations.

When it comes to ways to accelerate the shipping transition, hard-to-abate industry literature again proves a fruitful source for sector-specific advice (Åhman, 2020; C. Bataille et al., 2018; C. G. F. Bataille, 2020; Bauer & Fuenfschilling, 2019; Oberthür et al., 2020; Wesseling et al., 2017; Wesseling & Van der Vooren, 2017). A review of such articles resulted in a list of seven solutions identified as promising measures to support hard-to-abate transitions, as shown in table 5. With these solutions, there are some clear connections to creation & destruction functions: S1 corresponds to *C6: support from powerful groups/legitimation* on the creation side and *D3: reduced support for dominant regime technologies* on the destruction side. S2 is equivalent to *C2: establishing market niches/market formation* and S3 to *D1: control policies*, although the latter has a more general definition, with effects on *C2* and *C3* as well. S5 relates to *C5: resource mobilisation* and S6 to *C7: influence on the direction of search*, however with both having a strong emphasis on industry-government collaboration. Lastly, S7 forms part of *D4: changes in social networks, replacement of key actors*, which also includes the formation of new organisations or networks to take on tasks linked to system change, such as for example the creation of new infrastructure. In the following, these solutions are applied to the shipping sector and related to the previous analysis.

Table 5: Solutions identified in literature on hard-to-abate industries
(Åhman, 2020; Bataille et al., 2018; Bataille, 2020; Bauer & Fuenfschilling, 2019; Oberthür et al., 2020; Wesseling et al., 2017; Wesseling & Van der Vooren, 2017)

Solution	***Explanation***	***Mentioned in***	***Effect on functions***
S1: Mitigate the power of vested interests	Lobbying power of vested interests in the industry needs to be opposed.	Wesseling & Van der Vooren, 2017	+C6 +D3
S2: Market creation/demand-pull policies	To fix the lack of demand for clean innovations, governments need to step in, finance breakthrough technologies and	Wesseling & Van der Vooren, 2017; Wesseling et al., 2017; Bataille et al., 2018; Oberthür et al., 2020	+C2

	encourage uptake of low-carbon technologies.		
S3: Carbon pricing	To make low-carbon alternatives competitive on the long term, carbon pricing should be established on the full supply chain, thus including basic materials and transport.	Bataille et al., 2018; Bataille, 2020; Oberthür et al., 2020	+D1 +C2 +C3
S4: Global policy coordination	Efforts need to be undertaken at the global level and national policies and institutions need to be coordinated carefully.	Wesseling et al., 2017; Bataille et al., 2018; Bataille, 2020; Bauer & Fuenfschilling, 2019; Åhman, 2020	*no specific effect*
S5: Strong government-industry cooperation	Governments need to work closely with incumbent industries to create a transition from within the industry, e.g. by sharing risks and costs and pooling R&D efforts.	Wesseling et al., 2017; Bataille et al., 2018; Bataille, 2020; Oberthür et al., 2020; Åhman, 2020	+C5
S6: Stakeholder-oriented pathway processes/long-term strategies	All main stakeholders need to be involved in creating roadmaps and pathway processes that provide vision and planning on the long term, particularly with regards to creating necessary infrastructure.	Bataille et al., 2018; Bataille, 2020; Oberthür et al., 2020; Åhman, 2020	+C7
S7: Supporting institutions	Existing institutions should be used (or new ones created) to support the transition, again particularly with regards to creating infrastructure, e.g. for hydrogen.	Bataille et al., 2018; Bataille, 2020; Oberthür et al., 2020	+D4

S1: The power of the well-organised vested interests in shipping has to be mitigated in some way. Many national governments and are hesitant to act on shipping since that could lead to damage in a vital national industry and vested interests are evidently able to block much action at the IMO. However, there are some ways to fix this: Firstly, raising awareness around the issue of shipping could lead to a better translation of landscape pressure through consumers and civil society, potentially via cargo owners. Secondly, frontrunner governments that are willing to take action could bypass the IMO, by acting unilaterally, via regional organisations such as the EU or other new formats and organisations. Thirdly, advocacy coalitions for sustainable shipping technologies should work together to become a united lobby group themselves, which would be more productive than the infighting that seems to be taking place between some of them by focusing on the problems of the others.

S2: Market creation & demand-pull policies are clearly necessary in shipping, as the markets for sustainable shipping are seen as relatively small by interviewees, even though they are growing around frontrunners and early adopter sectors (*IE1*; *IE3*; *EA1a*). This aligns with the overall finding in the event analysis that market formation belongs to the less performed functions. Governance actors could correct this in two ways. Firstly, public procurement could take place by replacing port authorities' harbour craft and government-owned ships with vessels using sustainable technologies (*PA2*; *EA3*). Secondly, national governments and ports could provide more subsidies for sustainable shipping and partly finance innovation and technology (*PA2*; *IE1*). Together, these types of incentives could serve as the "carrot" to motivate frontrunners to develop and adopt sustainable technologies (*IE1*; *EA1*; *PA2*)

S3: Carbon pricing is frequently named as the complementary "stick" necessary to drive shipping actors towards decarbonisation (*EX*; *IE1*; *IE2*; *IE3*; *EA3*; *PA2*; *PM*), while industry actors caution that it needs to be applied universally (*EA1b*) and reasonably (*EA2*). This might be the crucial solution to the shipping transition, since, as one interviewee put it, "technology is not the problem, the problem is the cost of technology" (*PA3*). HFO is simply too cheap for sustainable alternatives to compete with it (*IE1*; *IE2*; *IE3*) up to a point that it is "basically free" (*EX*). As stated clearly in one report on the shipping transition, if there is no proper regulatory framework, "low oil prices always win" (Dönitz et al., 2020). Hence, raising fossil fuels to their "true price" (*PA2*) would be a key step for the shipping transition (*PA2*; *IE1*). A recent focus on some sort of carbon pricing was also found in the event analysis, where especially the last period showed a strong interest in such control policies (D1). Moreover, the apparent lack of price-performance improvements (C3) could be partially ameliorated with such a measure. Hence, carbon pricing appears to be seen undisputedly as a key measure, but the real difficulty might be in its introduction (*NGO*; *EA1a*). Talks about at the IMO about MBMs have been started as early as 2006 but did not reach a conclusion due to some countries' rejection and they are not very likely to succeed now either, despite a renewed interest (*NGO*). Therefore, inclusion of shipping into the EU ETS or national carbon pricing systems might be the most viable solution. Importantly, revenues from carbon pricing could also be essential to finance further technology development by mobilising massive amounts of resources (C5) (*EA3*) and answering the question of "who pays the party", as everybody seems to want to decarbonise shipping, but "nobody wants to pay for it" (*PA3*).

S4: Global policy coordination is good by all accounts, but not necessarily needed. If the IMO continues to move to slow, regional solutions are "the next best" (*PA2*). Restrictive national or port level regulations might lead to shipping actors simply switching harbours as far as possible (*PA2*), but it is not possible for shipping to avoid a whole continent (*EA3*). The introduction of regulation in significant markets such as Europe and the US would also likely lead to the rest of the world following suit on the long term, as it happened with tanker regulation in the past. Naturally, some regions in the world might lag behind due to a lack of capacity and/or willingness to act (*EA2*; *EA3*), but the establishment of a sustainable shipping sector in industrialised countries could still lead to significant worldwide emission reductions and lower the price of technology. The trend to some regions pressing ahead also clearly showed itself in the event analysis.

S5: Some government-industry cooperation is already taking place in shipping. R&D in sustainable shipping technologies is partly financed by governments, for instance in Sweden (*IE2*), in the Netherlands (*PM*) or at the EU level (*IE1*). Moreover, public actors such as universities and ports also collaborate frequently with companies on innovation (*NGO*; *IE1*; *IE2*; *IE3*; *PA2*; *PA3*). However, there should also be some caution taken here, as a too close cooperation also brings with it the danger of incumbents slowing down or influencing the direction of change into their favour (*PM*) and it is questionable when public authorities bear the brunt of investments in new technologies (*PA1*; *PA3*). Another form of cooperation which will probably become more frequent and tighter is between different businesses in shipping, as new technologies require coordination with customers, suppliers, engine makers, etc. (*IE3*; *EA3*), up to the point where a new ship becomes "almost a joint development" (*EA1a*).

S6: These developments relate to the necessity for stakeholder-oriented pathway processes & long-term strategies. Interviewed industry actors said governments should provide roadmaps with clear timelines and specific, achievable targets, combined with "carrot & stick" regulations such as subsidies and carbon pricing (*IE1*; *IE3*; *EA1a*; *EA2*). Such roadmaps could provide a vision that does justice to the complexity of the shipping transition, where cooperation of all relevant stakeholders is key. In the words of an interviewee, "someone simply has to integrate [technologies] into a working complete product [*Gesamtprodukt*] and you cannot do that in isolation, […] you have to think the whole supply chain through to the end, for a convincing concept to emerge, otherwise you end up with some isolated solutions [*Insellösungen*] that do not work either technically or economically" (*EA3*). Again, apart from the role of governance actors, the mentioned industry coalitions that have emerged in recent years could play a crucial role in this development.

S7: That leads to the important role of transition-supporting institutions. As evident in the historic event analysis, there were some change in social networks, creation of new fora to bypass traditional policy networks and formation of new networks and organisations to take on system change tasks (D4). This included new industry initiatives such as the World Ports Climate Action Program, the Getting to Zero Coalition and the Mission Possible Partnership, as well as industry calls for the creation of an IMRB under the auspices of the IMO. These relatively recent creations are all examples of frontrunners with higher ambitions for sustainable shipping than the bulk of industry actors and harbour a potential for developing concrete solutions. Moreover, the first gathering of the M7 and unilateral EU actions are both examples for industrialised countries pressing ahead with the shipping transition and bypassing the traditional shipping policy forum that the IMO represents. Finally, an important role could be played by port organisations such as ESPO and IAPH, who have already been active in terms of sustainability and are crucial when it comes to the provision of infrastructure for new technologies as well as enacting and enforcing environmental regulation (*PA3*).

Overall, this chapter has shown that there clearly are sustainable alternatives to the dominant shipping regime and these options are increasingly getting traction. Nevertheless, currently only a few of them are applied commercially and none of them are widespread. The event analysis made clear that creation & destruction functions are performed more and more, but destruction functions in particular are still lacking. However, insights from interviews and solutions taken from hard-to-abate industry literature provide workable solutions to ameliorate the underperformance of some functions and accelerate the shipping transition.

7. Conclusion and discussion

This thesis set out to answer the research question *What are the dynamics of the transition to sustainable international shipping and how can this transition be accelerated?* divided into the sub-questions *SQ1: Why is international shipping such a hard-to-abate industry?* and *SQ2: How can the shipping transition be accelerated?* To answer these questions, it drew on general socio-technical transition theory, particularly Kivimaa & Kern's creation & destruction functions, which in turn partly incorporate the TIS and MLP frameworks, as well as literature on the hard-to-abate sectors, to which the shipping industry belongs. The chosen mixed methods approach used literature analysis, expert interviews and historic event analysis to create an in-depth insight into the shipping regime, alternative technologies and how they interacted in the last three years since the initial IMO GHG strategy.

It became clear that international shipping is such a hard-to-abate sector for three main reasons: Firstly, the shipping industry is very complex, dispersed across different market segments and geographical locations and involves a variety of different stakeholders from different countries, making technological change difficult as it requires coordination between various actors and faces different conditions in different places and sub-sectors. Moreover, as most of its operations take place far away from the consumer, there is low landscape pressure to change. Secondly, the industry has developed a strong lock-in into fossil fuels by running on a very cheap oil waste product. This mode of operation enabled globalisation, which in turn increased demand for shipping and created strong growth, leading to better economies of scale and thereby to shipping becoming even cheaper. This long dominance of one regime technology also contribute to it being a very conservative sector. Thirdly, governance on environmental issues in international shipping is multi-layered and complicated, with the slow-moving international organisation IMO setting global minimum standards, while regional, national and port-level regulations represent stricter location-specific rules.

However, the shipping transition can be accelerated, as it has already begun with a wide range of alternative technologies available, with different emission reduction potentials and varying degrees of radicalness. Still, only few of them are already applied and none of them very widely. Rather incremental solutions such as LNG and efficiency solutions still dominate the scene, but recently radically different fuels such as hydrogen and ammonia are on the rise, while methanol and wind are also relevant options. The longevity of ships and infrastructure lock-in slow technological change and require different solutions for short-, mid- and long-term. A supply of technological options is there, but their price and scalability are still major hurdles. Moreover, the amount of potential options and the lack of a clear solution leads to a "fear of betting on the wrong horse" in the industry and this uncertainty makes actors cautious to invest in new technologies. There will probably be some coexistence of different solutions for different applications, which has been coined as "horses for courses".

Overall, events surrounding sustainable shipping have strongly increased in recent years and it appears to have become an important topic in the industry. All creation functions have been fulfilled to some extent, but most activity still revolves around entrepreneurial experimentation, influence on the direction of search and knowledge creation, development & diffusion, whereas market creation, resource mobilisation and legitimation are less present and price-performance improvements almost absent. Hence, a sufficient demand for alternative technologies is still lacking, although it is coming in some segments where landscape pressure is felt more due to closeness to consumers (e.g. cruises, ferries, container shipping) or where regulatory regimes are more strict (e.g. harbour craft, inland shipping). Destruction functions have only picked up very recently, with a focus on control policies, hence the regime is still not destabilised. This has implications for the MLP pathways: the lack of regime destabilisation and technological alternatives that are ready to be widely applied, price-competitive and scalable means that the technological substitution and de-alignment/re-alignment pathways are unlikely. They could only happen if the shipping regime is strongly destabilised through radical policy action. In accordance with hard-to-abate industries literature, a change from within the regime seems more likely, hinting towards the transformation or reconfiguration pathways. Vested interests have been able to block much substantial change on an IMO level, but some powerful industry actors seem to feel some landscape pressure and see the need to adapt on the long term. Hence, new coalitions, institutions and organisations that involve all stakeholders could be the way to drive the transition, with frontrunners transforming the industry from within. Moreover, substantial policy action that destabilises the regime and creates more noticeable landscape pressure on it is necessary. Otherwise the danger is that the dominant unsustainable regime is simply reproduced and only some efficiency and ex post measures which can be accommodated in the current regime are implemented.

7.1. Managerial and policy advice

The main advice that follows for companies in the shipping sector is thus to participate in existing coalitions and try to cooperate with customers, suppliers and other stakeholders on the implementation of new technologies and/or new business models, as some frontrunners already do. Particularly a closer cooperation with ports might be valuable, since they have a special role as access points to local/national subsidy schemes and port areas themselves are often innovation ecosystems or regional innovation systems. Alternative technological options are available and the sooner they start to be implemented by industry actors, the better. On the long term, shipping must adapt to the inevitable landscape pressure of climate change, since if it shows itself unable to do so, globalisation might partly reverse to more regional trading patterns and demand for shipping could simply be strongly reduced, as expected by some authors (Asariotis et al., 2020; Pettit et al., 2018).

Governance actors can support this transition process by using “the carrot and the stick”, where the former can take the shape of positive incentives such as subsidies, co-financing of R&D or reduced taxes and harbour fees to foster alternative technologies through creation activities, while the latter needs to entail control policies such as carbon pricing up to more extreme measures such as technology bans. This combination of demand-pull and regulation-push policies can support frontrunners and punish laggards, thereby driving the whole industry towards sustainability. Cooperation is also crucial for governance actors, as national governments and port authorities by themselves are limited to their own jurisdictions, particularly when implementing control policies. Hence, whereas positive incentives can work at the smallest level, negative incentives are the most effective when implemented as widely as possible. Therefore, achieving more stringent action at the global IMO level (or for ports at the IAPH) should be paramount, but the “next best” regional solutions at EU level (or the ESPO) might be more realistic. When it comes to the different technologies, the uncertainty as to what will be the “winning horse” means that policy should be open-ended and unbiased as far as possible, but there also seem to be some technologies which should be uncontroversial as they have some clear advantages, which includes electrification of inland shipping and short distance vessels, incorporating wind assisted propulsion as much as possible (since it requires no fuel infrastructure and has no scalability issues) as well as implementation of cold ironing in ports and other efficiency measures.

7.2. Limitations

This thesis has encountered some difficulties and limitations. One major limitation stems from the complexity of the shipping industry, which makes it almost impossible to pay justice to all its intricacies within the scope of a Master's thesis. Still, the attempt was made to include all relevant factors to the shipping transition, with the drawback that it was not possible to go into depth into specific areas, such as for example a focus on policies or a deeper TIS analysis of one alternative technology only. Such studies could be useful for the future.

Another issue was the limited amount of interviews and a potential bias in respondents. It turned out challenging to find willing participants, particularly from the category of incumbent companies. Many of those contacted indicated that they did not have time to talk to researchers or were not responsive at all. As an illustration, the response of one major shipping company to an interview request stated that in the "actual hyper-competitive time" they were "not keen to disclose any information" and "in view of the phenomenal acceleration of the shipping world lately" they had "no time to devote to researches or interviews". On the contrary, innovative entrepreneurial companies and port authorities showed a lot more willingness to discuss sustainability issues. Consequently, the number of interviews was lower than what was originally aimed for. Moreover, there might be a slight pro-sustainability bias in those that actually participated, since it could be that those were simply actors that had a higher interest in sustainability issues or whose organisations were more active on that front, thus painting a too optimistic picture of the willingness of shipping actors to change. Nevertheless, the interviews provided quite a wide array of different and sometimes contradicting perspectives, shedding light on examined issues from various viewpoints.

With regards to the event analysis, one limitation stems from the limited time period assessed. Other historic event analyses tend to look at a development over several decades (Negro et al., 2007; Reichardt et al., 2016). However, the chosen time period made sense both due to the focus being justified as the recent years since the IMO initial strategy have shown increased activity in sustainable shipping innovation and for the practical reason of the large amount of events making the choice for a longer time period much more time-intensive. Another limitation comes with the focus on one maritime news website, but as aforementioned, a comparison showed that events mentioned were largely congruent across different websites. The very low amount of price-performance improvement (C3) events could also stem from this type of event simply not being mentioned as a news item, so using another indicator for this function might have been better. Lastly, the use of industry news media brought with it the disadvantage of focusing mostly on positive news, with relatively few news items mentioning discontinuation of projects or failed pilots, resulting in a relatively low count of events with negative contributions to functions. Despite these limitations, the analysis could provide a good overview of what occurred in sustainable shipping in recent years. Some suggestions for further research to overcome these issues are given in the following.

7.3. Theoretical implications and avenues for further research

The results of this thesis also have some theoretical implications. For Kivimaa & Kern's creation & destruction functions, the application has shown that they are useful not only for the analysis of policy mixes, but also as a framework to look at transition dynamics in general. Moreover, the addition of the fifth destruction function *monitoring & prediction of emissions* could be a useful contribution to the framework, as it sheds light on the important task to assess the exact magnitude of an industry's problem and has strong implications for which sectors and which solutions should be prioritised when governing a transition. Interestingly, the science and measurement methodologies around emissions also seem to become a tool used by different advocacy groups to further their own goals. Furthermore, a further refinement of the creation & destruction functions would make them a promising candidate for a framework that fully incorporates both insights from MLP and TIS in a practical way.

The conclusions of hard-to-abate industries literature were also partially confirmed in this research, as the application of barriers & solutions showed. All issues affecting hard-to-abate industries in previous studies were encountered in some way in the analysis of the shipping sector, although some to a lesser extent. This demonstrates that sector-specific analyses are important for transition studies and that hard-to-abate industries seem to represent a very peculiar type of regime. Further research into this and other types of regimes would enrich transition literature and make the MLP more concrete and practical for policy advice, as it might be too general and abstract as a framework to apply to all industries that require transitions.

Another interesting finding was the key role that distance to the end consumer seems to play in the way that landscape pressures are perceived by actors and consequently also for the way that sustainability transitions proceed within an industry and within the whole economy. The shipping industry also shows how transitions unfold geographically, since a focus on sustainable shipping appears to originate in North West Europe and parts of North America and is likely to proceed to the whole of Europe first, possibly to other industrialised countries next and later towards less industrialised countries and the Global South, where capability and willingness to adapt is still lacking. This has major implications for the governance of global regimes, which might not necessitate global governance but rather regional governance. More precise research on the geography of transition, systematically assessing where events or projects are located and how this changes over time could be an interesting avenue for further research.

Furthermore, the role of ports seems to be quite an interesting one, that would deserve further attention. They are relevant for the governance of the global regime of shipping, since they represent interaction points between local/national governments and the shipping regime. This shows that governance of a global regime needs to come both bottom-up from these smaller actors and top-down from the international (i.e. global or regional) level. They can also be understood as important intermediaries for GIS, since they represent structural couplings between various innovation systems, such as national innovation systems, regional innovation systems and transnational TIS and GIS and are often the location for port innovation systems or innovation ecosystems themselves. There is already some literature conceptualising ports as innovation systems (Cahoon et al., 2013; Risitano, 2017) or ecosystems (Witte et al., 2018) and this could be linked to transition literature. Other candidates for intermediaries are the global coalitions formed by industry actors to advance sustainable shipping technology.

Another topic that deserves further attention is the role that investors and finance play in transitions. In shipping, there seems to be somewhat contradictory perceptions of the role of finance. On the one hand, they are seen as conservative actors unwilling to take a risk in their huge investments and preferring the established regime technology, but on the other hand some banks and other investors seem to change in this respect. The expectation of future regulation or a future transition appears to have reached a tipping point for some, making an investment in companies without a sustainability perspective more risky. More research into who finances alternative technologies and who finances continuous use of regime technologies could be revealing.

Lastly, the method of historic event analysis could also be done differently, in a more data-based quantitative fashion. Using data science and statistical methods, one could attempt to analyse larger amounts of news data and automatically code them to certain functions with the use of occurring keywords or natural language processing. This could allow for far more extensive historic event analyses taking into account larger amounts of data. Moreover, the identification of patterns and causalities between different events or event types, which has been done in a more interpretive fashion for this thesis, could possibly also be done using statistical methods, hereby strengthening the argument for causal links.

The bottom line of this thesis is that how shipping currently operates is unsustainable and its contributions to climate change will only increase if no serious action is taken. However, emerging alternative technologies show that this does not have to be the case and there is a real opportunity to decarbonise shipping. But this will not happen by itself and governance actors, i.e. governments, international organisations and port authorities, as well as corporations active in the shipping sector, whether as shipping companies, shipowner, shipbuilders or shipping customers, need to act to make the transition happen. More generally, hard-to-abate industry transitions are possible, but they work differently than in easier-to-abate sectors and require more regime destabilisation through substantial policy action on a global or regional level.

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Appendices

Appendix 1 – additional tables

Event frequency per category and period

category	period	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
general	I	2	0	4	0	0	0	1	0	2	0	4	1	4	1	17	2
	II	14	0	6	0	0	0	2	0	3	0	3	0	17	1	45	1
	III	9	0	2	0	0	0	0	0	9	0	5	1	14	0	39	1
	IV	5	0	1	0	1	0	0	0	7	0	1	0	7	1	22	1
	V	42	0	16	1	1	0	8	0	20	0	9	0	15	1	111	2
LNG	I	6	0	7	0	1	1	27	0	1	0	1	0	7	6	50	7
	II	7	0	6	0	3	0	73	1	3	0	4	0	15	6	111	7
	III	6	0	6	0	1	0	71	1	1	0	7	1	15	1	107	3
	IV	4	0	3	0	0	0	22	0	1	0	3	0	9	0	42	0
	V	12	0	8	0	1	1	43	0	1	0	7	1	13	7	85	9
hydrogen	I	2	0	0	0	0	0	2	0	0	0	0	0	2	0	6	0
	II	8	0	2	0	0	0	15	0	1	0	1	0	10	0	37	0
	III	9	0	1	0	1	0	11	0	1	0	6	0	9	0	38	0
	IV	4	0	0	0	0	0	5	0	0	0	1	0	7	0	17	0
	V	41	0	2	0	2	1	38	0	9	0	3	0	34	1	129	2
efficiency	I	3	0	4	0	0	0	9	0	1	0	1	1	5	0	23	1
	II	3	0	3	0	0	0	17	0	2	0	2	0	24	2	51	2
	III	9	0	0	0	1	0	20	0	1	0	2	0	25	3	58	3
	IV	5	0	0	0	0	0	8	0	0	0	0	0	0	0	13	0
	V	19	0	3	0	1	0	26	0	2	0	2	0	12	0	65	0
electric	I	4	0	4	0	0	0	7	0	0	0	0	0	5	0	20	0
	II	3	0	5	0	0	0	43	0	1	0	1	0	11	0	64	0
	III	6	0	9	0	0	0	26	0	0	0	3	0	7	0	51	0
	IV	5	0	1	0	0	0	7	0	0	0	0	0	4	0	17	0
	V	10	0	6	0	0	0	24	0	3	0	0	0	7	1	50	1
biofuel	I	1	0	1	0	0	0	2	0	0	0	1	0	3	0	8	0
	II	4	0	2	0	0	0	11	0	1	0	0	0	6	5	24	5
	III	3	0	1	0	0	0	14	0	0	0	2	0	8	0	28	0
	IV	1	0	1	0	0	0	7	0	0	0	0	0	1	0	10	0
	V	6	0	2	0	0	1	24	0	1	0	2	0	8	7	43	8
ammonia	I	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
	II	1	0	0	0	0	0	1	0	0	0	0	0	9	0	11	0
	III	3	0	0	0	0	0	3	0	1	0	1	0	9	0	17	0
	IV	5	0	0	0	0	0	2	0	0	0	0	0	6	0	13	0
	V	21	0	0	0	0	0	20	0	3	0	3	0	24	0	71	0
methanol	I	0	0	0	0	0	0	0	0	0	0	4	0	2	0	6	0
	II	5	0	2	0	0	0	2	0	1	0	1	0	2	1	13	1
	III	0	0	0	0	0	0	5	0	0	0	3	0	3	0	11	0
	IV	4	0	0	0	0	0	2	0	0	0	0	0	2	0	8	0
	V	1	0	2	0	0	0	14	0	4	0	2	0	12	2	35	2
wind	I	0	0	0	0	0	0	2	0	1	0	1	0	0	0	4	0
	II	4	0	0	0	0	0	10	0	0	0	1	0	1	0	16	0
	III	3	0	0	0	0	0	7	0	0	0	6	0	1	0	17	0
	IV	1	0	1	0	0	0	1	0	0	0	0	0	0	0	3	0
	V	4	0	0	0	0	0	18	0	0	0	5	0	4	0	31	0
ex post	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0
	III	1	0	0	0	0	0	2	0	0	0	1	0	1	0	5	0
	IV	2	0	0	0	0	0	1	0	0	0	0	0	1	0	4	0
	V	7	0	0	0	0	0	12	0	0	0	0	0	4	0	23	0
all	I	18	0	20	0	1	1	55	0	5	0	12	2	29	7	140	10
	II	50	0	26	0	3	0	174	1	12	0	14	0	93	14	372	15
	III	50	0	19	0	3	0	162	1	13	0	39	2	85	1	371	4
	IV	37	0	7	0	1	0	57	0	8	0	5	0	37	1	152	1
	V	167	0	39	1	5	3	219	0	44	0	34	1	140	20	648	25

category	period	D1+	D1-	D2+	D2-	D3+	D3-	D4+	D4-	*D5*	all +	all -
general	I	1	0	0	0	1	0	1	0	0	3	0
	II	1	0	0	1	2	0	3	0	2	8	1
	III	4	0	1	0	2	0	4	0	2	13	0
	IV	2	1	0	0	2	0	2	0	0	6	1
	V	26	6	4	3	9	0	2	0	4	45	9

	gen.	LNG	hydr.	elec.	effic.	biof.	am.	met.	wind	ex p.	all
I	17	50	6	20	23	8	1	6	4	0	140
II	45	111	37	64	51	24	11	13	16	2	372
III	39	107	38	51	58	28	17	11	17	5	371
IV	22	42	17	17	13	10	13	8	3	4	152
V	111	85	129	50	65	43	71	35	31	23	648

Event frequency per category and period, normalised according to period duration (I = 6 months, II = 9, III = 8, IV = 6, V = 10)

category	period	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -	D1+	D1-	D2+	D2-	D3+	D3-	D4+	D4-	*D5*	all +	all -
general	I	0,33	0,00	0,67	0,00	0,00	0,00	0,17	0,00	0,33	0,00	0,67	0,17	0,67	0,17	2,83	0,33	0,17	0,00	0,00	0,00	0,17	0,00	0,17	0,00	0,00	0,50	0,00
	II	1,56	0,00	0,67	0,00	0,00	0,00	0,22	0,00	0,33	0,00	0,33	0,00	1,89	0,11	5,00	0,11	0,11	0,00	0,00	0,11	0,22	0,00	0,33	0,00	0,22	0,89	0,11
	III	1,13	0,00	0,25	0,00	0,00	0,00	0,00	0,00	1,13	0,00	0,63	0,13	1,75	0,00	4,88	0,13	0,50	0,00	0,13	0,00	0,25	0,00	0,50	0,00	0,25	1,63	0,00
	IV	0,83	0,00	0,17	0,00	0,17	0,00	0,00	0,00	1,17	0,00	0,17	0,00	1,17	0,17	3,67	0,17	0,33	0,17	0,00	0,00	0,33	0,00	0,33	0,00	0,00	1,00	0,17
	V	4,20	0,00	1,60	0,10	0,10	0,00	0,80	0,00	2,00	0,00	0,90	0,00	1,50	0,10	11,1	0,20	2,60	0,60	0,40	0,30	0,90	0,00	0,20	0,00	0,40	4,50	0,90
LNG	I	1,00	0,00	1,17	0,00	0,17	0,17	4,50	0,00	0,17	0,00	0,17	0,00	1,17	1,00	8,33	1,17											
	II	0,78	0,00	0,67	0,00	0,33	0,00	8,11	0,11	0,33	0,00	0,44	0,00	1,67	0,67	12,3	0,78											
	III	0,75	0,00	0,75	0,00	0,13	0,00	8,88	0,13	0,13	0,00	0,88	0,13	1,88	0,13	13,4	0,38											
	IV	0,67	0,00	0,50	0,00	0,00	0,00	3,67	0,00	0,17	0,00	0,50	0,00	1,50	0,00	7,00	0,00											
	V	1,20	0,00	0,80	0,00	0,10	0,10	4,30	0,00	0,10	0,00	0,70	0,10	1,30	0,70	8,50	0,90											
hydrogen	I	0,33	0,00	0,00	0,00	0,00	0,00	0,33	0,00	0,00	0,00	0,00	0,00	0,33	0,00	1,00	0,00											
	II	0,89	0,00	0,22	0,00	0,00	0,00	1,67	0,00	0,11	0,00	0,11	0,00	1,11	0,00	4,11	0,00											
	III	1,13	0,00	0,13	0,00	0,13	0,00	1,38	0,00	0,13	0,00	0,75	0,00	1,13	0,00	4,75	0,00											
	IV	0,67	0,00	0,00	0,00	0,00	0,00	0,83	0,00	0,00	0,00	0,17	0,00	1,17	0,00	2,83	0,00											
	V	4,10	0,00	0,20	0,00	0,20	0,10	3,80	0,00	0,90	0,00	0,30	0,00	3,40	0,10	12,9	0,20											
efficiency	I	0,50	0,00	0,67	0,00	0,00	0,00	1,50	0,00	0,17	0,00	0,17	0,17	0,83	0,00	3,83	0,17											
	II	0,33	0,00	0,33	0,00	0,00	0,00	1,89	0,00	0,22	0,00	0,22	0,00	2,67	0,22	5,67	0,22											
	III	1,13	0,00	0,00	0,00	0,13	0,00	2,50	0,00	0,13	0,00	0,25	0,00	3,13	0,38	7,25	0,38											
	IV	0,83	0,00	0,00	0,00	0,00	0,00	1,33	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,17	0,00											
	V	1,90	0,00	0,30	0,00	0,10	0,00	2,60	0,00	0,20	0,00	0,20	0,00	1,20	0,00	6,50	0,00											
electric	I	0,67	0,00	0,67	0,00	0,00	0,00	1,17	0,00	0,00	0,00	0,00	0,00	0,83	0,00	3,33	0,00											
	II	0,33	0,00	0,56	0,00	0,00	0,00	4,78	0,00	0,11	0,00	0,11	0,00	1,22	0,00	7,11	0,00											
	III	0,75	0,00	1,13	0,00	0,00	0,00	3,25	0,00	0,00	0,00	0,38	0,00	0,88	0,00	6,38	0,00											
	IV	0,83	0,00	0,17	0,00	0,00	0,00	1,17	0,00	0,00	0,00	0,00	0,00	0,67	0,00	2,83	0,00											
	V	1,00	0,00	0,60	0,00	0,00	0,00	2,40	0,00	0,30	0,00	0,00	0,00	0,70	0,10	5,00	0,10											
biofuel	I	0,17	0,00	0,17	0,00	0,00	0,00	0,33	0,00	0,00	0,00	0,17	0,00	0,50	0,00	1,33	0,00											
	II	0,44	0,00	0,22	0,00	0,00	0,00	1,22	0,00	0,11	0,00	0,00	0,00	0,67	0,56	2,67	0,56											
	III	0,38	0,00	0,13	0,00	0,00	0,00	1,75	0,00	0,00	0,00	0,25	0,00	1,00	0,00	3,50	0,00											
	IV	0,17	0,00	0,17	0,00	0,00	0,00	1,17	0,00	0,00	0,00	0,00	0,00	0,17	0,00	1,67	0,00											
	V	0,60	0,00	0,20	0,00	0,00	0,10	2,40	0,00	0,10	0,00	0,20	0,00	0,80	0,70	4,30	0,80											
ammonia	I	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,17	0,00	0,17	0,00											
	II	0,11	0,00	0,00	0,00	0,00	0,00	0,11	0,00	0,00	0,00	0,00	0,00	1,00	0,00	1,22	0,00											
	III	0,38	0,00	0,00	0,00	0,00	0,00	0,38	0,00	0,13	0,00	0,13	0,00	1,13	0,00	2,13	0,00											
	IV	0,83	0,00	0,00	0,00	0,00	0,00	0,33	0,00	0,00	0,00	0,00	0,00	1,00	0,00	2,17	0,00											
	V	2,10	0,00	0,00	0,00	0,00	0,00	2,00	0,00	0,30	0,00	0,30	0,00	2,40	0,00	7,10	0,00											
methanol	I	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,67	0,00	0,33	0,00	1,00	0,00											
	II	0,56	0,00	0,22	0,00	0,00	0,00	0,22	0,00	0,11	0,00	0,11	0,00	0,22	0,11	1,44	0,11											
	III	0,00	0,00	0,00	0,00	0,00	0,00	0,63	0,00	0,00	0,00	0,38	0,00	0,38	0,00	1,38	0,00											
	IV	0,67	0,00	0,00	0,00	0,00	0,00	0,33	0,00	0,00	0,00	0,00	0,00	0,33	0,00	1,33	0,00											
	V	0,10	0,00	0,20	0,00	0,00	0,00	1,40	0,00	0,40	0,00	0,20	0,00	1,20	0,20	3,50	0,20											
wind	I	0,00	0,00	0,00	0,00	0,00	0,00	0,33	0,00	0,17	0,00	0,17	0,00	0,00	0,00	0,67	0,00											
	II	0,44	0,00	0,00	0,00	0,00	0,00	1,11	0,00	0,00	0,00	0,11	0,00	0,11	0,00	1,78	0,00											
	III	0,38	0,00	0,00	0,00	0,00	0,00	0,88	0,00	0,00	0,00	0,75	0,00	0,13	0,00	2,13	0,00											
	IV	0,17	0,00	0,17	0,00	0,00	0,00	0,17	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,50	0,00											
	V	0,40	0,00	0,00	0,00	0,00	0,00	1,80	0,00	0,00	0,00	0,50	0,00	0,40	0,00	3,10	0,00											
ex post	I	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00											
	II	0,00	0,00	0,00	0,00	0,00	0,00	0,22	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,22	0,00											
	III	0,13	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,00	0,13	0,00	0,13	0,00	0,63	0,00											
	IV	0,33	0,00	0,00	0,00	0,00	0,00	0,17	0,00	0,00	0,00	0,00	0,00	0,17	0,00	0,67	0,00											
	V	0,70	0,00	0,00	0,00	0,00	0,00	1,20	0,00	0,00	0,00	0,00	0,00	0,40	0,00	2,30	0,00											
all	I	3,00	0,00	3,33	0,00	0,17	0,17	9,17	0,00	0,83	0,00	2,00	0,33	4,83	1,17	23,3	1,67											
	II	5,56	0,00	2,89	0,00	0,33	0,00	19,3	0,11	1,33	0,00	1,56	0,00	10,3	1,56	41,3	1,67											
	III	6,25	0,00	2,38	0,00	0,38	0,00	20,3	0,13	1,63	0,00	4,88	0,25	10,6	0,13	46,4	0,50											
	IV	6,17	0,00	1,17	0,00	0,17	0,00	9,50	0,00	1,33	0,00	0,83	0,00	6,17	0,17	25,3	0,17											
	V	16,7	0,00	3,90	0,10	0,50	0,30	21,9	0,00	4,40	0,00	3,40	0,10	14,0	2,00	64,8	2,50											

	gen.	LNG	hydr.	elec.	effic.	biof.	am.	met.	wind	ex p.	all
I	2,83	8,33	1,00	3,33	3,83	1,33	0,17	1,00	0,67	0,00	23,3
II	5,00	12,3	4,11	7,11	5,67	2,67	1,22	1,44	1,78	0,22	41,3
III	4,88	13,4	4,75	6,38	7,25	3,50	2,13	1,38	2,13	0,63	46,4
IV	3,67	7,00	2,83	2,83	2,17	1,67	2,17	1,33	0,50	0,67	25,3
V	11,1	8,50	12,9	5,00	6,50	4,30	7,10	3,50	3,10	2,30	64,8

total event occurrences per category

category	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	D	D1+	D1-	D2+	D2-	D3+	D3-	D4+	D4-	D5	total C	total -C	total D	total -D
general	72	0	29	1	2	0	11	0	41	0	22	2	57	4		34	7	5	4	16	0	12	0	8	234	7	75	11
LNG	35	0	30	0	6	2	236	2	7	0	22	2	60	20											396	26		
hydrogen	63	0	5	0	3	1	70	0	11	0	11	0	62	1											225	2		
efficiency	40	0	10	0	2	0	81	0	6	0	7	1	66	5											212	6		
electric	28	0	24	0	0	0	107	0	4	0	4	0	34	1											201	1		
ammonia	30	0	0	0	0	0	26	0	4	0	4	0	49	0											113	0		
biofuel	15	0	7	0	0	1	58	0	2	0	5	0	26	12											113	13		
methanol	10	0	4	0	0	0	23	0	5	0	10	0	21	3											73	3		
wind	12	0	1	0	0	0	38	0	1	0	13	0	6	0											71	0		
ex post	10	0	0	0	0	0	17	0	0	0	1	0	6	0											34	0		

total monthly event frequency

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -	D1+	D1-	D2+	D2-	D3+	D3-	D4+	D4-	D5	all +	all -
4-2018	3	0	2	0	0	0	3	0	1	0	3	0	10	1	22	1	0	0	0	0	0	0	0	0	0	0	0
5-2018	2	0	2	0	1	1	17	0	1	0	4	0	5	2	32	3	0	0	0	0	0	0	0	0	0	0	0
6-2018	2	0	3	0	0	0	11	0	0	0	2	0	4	2	22	2	1	0	0	0	0	0	0	0	0	1	0
7-2018	5	0	6	0	0	0	6	0	0	0	1	2	1	0	19	2	0	0	0	0	0	0	0	0	0	0	0
8-2018	4	0	4	0	0	0	9	0	3	0	1	0	4	2	25	2	0	0	0	0	1	0	0	0	0	1	0
9-2018	2	0	3	0	0	0	9	0	0	0	1	0	5	0	20	0	0	0	0	0	0	0	1	0	0	1	0
10-2018	5	0	2	0	2	0	13	0	3	0	3	0	13	2	41	2	0	0	0	0	0	0	1	0	0	1	0
11-2018	11	0	1	0	0	0	24	0	1	0	1	0	9	2	47	2	0	0	0	0	0	0	0	0	0	0	0
12-2018	2	0	3	0	0	0	10	0	1	0	1	0	3	1	20	1	0	0	0	0	0	0	0	0	0	0	0
1-2019	6	0	7	0	0	0	25	0	2	0	2	0	16	2	58	2	1	0	0	0	1	0	0	0	0	2	0
2-2019	3	0	1	0	0	0	15	0	2	0	0	0	10	0	31	0	0	0	0	0	0	0	0	0	2	2	0
3-2019	8	0	5	0	0	0	24	1	0	0	1	0	6	0	44	1	0	0	0	0	0	0	1	0	0	1	0
4-2019	6	0	3	0	0	0	14	0	1	0	2	0	9	4	35	4	0	0	0	0	0	0	1	0	0	1	0
5-2019	6	0	0	0	0	0	23	0	2	0	2	0	8	0	41	0	0	0	0	0	0	0	0	0	0	0	0
6-2019	3	0	4	0	1	0	26	0	0	0	2	0	19	3	55	3	0	0	0	1	1	0	0	0	0	1	1
7-2019	8	0	4	0	0	0	22	0	0	0	3	0	16	0	53	0	1	0	0	0	0	0	0	0	1	2	0
8-2019	1	0	3	0	0	0	10	0	0	0	1	0	0	0	15	0	0	0	0	0	0	0	0	0	1	1	0
9-2019	11	0	2	0	0	0	31	0	2	0	4	0	11	0	61	0	0	0	0	0	0	0	2	0	0	2	0
10-2019	9	0	1	0	0	0	17	0	1	0	6	0	24	0	58	0	1	0	0	0	0	0	1	0	0	2	0
11-2019	2	0	1	0	1	0	20	1	1	0	9	2	10	0	44	3	1	0	0	0	0	0	0	0	0	1	0
12-2019	10	0	2	0	1	0	29	0	3	0	7	0	10	0	62	0	1	0	0	0	0	0	1	0	0	2	0
1-2020	2	0	1	0	1	0	13	0	5	0	3	0	7	1	32	1	0	0	1	0	1	0	0	0	0	2	0
2-2020	7	0	5	0	0	0	20	0	1	0	6	0	7	0	46	0	0	0	0	0	1	0	0	0	0	1	0
3-2020	7	0	2	0	0	0	9	0	3	0	0	0	2	0	23	0	1	0	0	0	1	0	0	0	0	2	0
4-2020	6	0	0	0	0	0	7	0	0	0	0	0	6	1	19	1	0	0	0	0	0	0	0	0	0	0	0
5-2020	7	0	4	0	0	0	8	0	1	0	1	0	17	0	38	0	0	0	0	0	0	0	0	0	0	0	0
6-2020	4	0	1	0	0	0	14	0	1	0	1	0	5	0	26	0	0	0	0	0	0	0	0	0	0	0	0
7-2020	10	0	0	0	1	0	14	0	3	0	3	0	4	0	35	0	1	1	0	0	1	0	2	0	0	4	1
8-2020	3	0	0	0	0	0	5	0	0	0	0	0	3	0	11	0	0	0	0	0	0	0	0	0	0	0	0
9-2020	12	0	3	0	0	0	15	0	0	0	0	1	14	1	44	2	3	0	0	0	0	0	0	0	0	3	0
10-2020	24	0	3	1	2	1	20	0	0	0	3	0	11	0	63	2	1	3	2	1	1	0	0	0	0	4	4
11-2020	7	0	3	0	1	1	19	0	4	0	6	0	12	2	52	3	5	1	0	1	0	0	0	0	3	8	2
12-2020	12	0	3	0	0	0	19	0	3	0	3	0	8	1	48	1	1	0	0	0	1	0	0	0	0	2	0
1-2021	15	0	3	0	0	0	21	0	5	0	2	0	2	0	48	0	1	0	1	0	2	0	1	0	1	6	0
2-2021	19	0	5	0	0	0	30	0	0	0	5	0	9	2	68	2	2	0	0	0	0	0	1	0	0	3	0
3-2021	16	0	3	0	1	0	37	0	8	0	4	0	16	1	85	1	3	0	0	0	1	0	0	0	0	4	0
4-2021	22	0	6	0	0	0	20	0	5	0	3	0	24	9	80	9	4	0	0	0	1	0	0	0	0	5	0
5-2021	16	0	1	0	1	0	17	0	7	0	5	0	14	2	61	2	4	0	1	0	1	0	0	0	0	6	0
6-2021	24	0	9	0	0	1	21	0	12	0	3	0	30	2	99	3	2	2	0	1	2	0	0	0	0	4	3

monthly event frequency: general

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -	D1+	D1-	D2+	D2-	D3+	D3-	D4+	D4-	*D5*	all +	all -
4-2018	0	0	1	0	0	0	0	0	0	0	3	0	1	0	5	0	0	0	0	0	0	0	0	0	0	0	0
5-2018	1	0	0	0	0	0	0	0	1	0	1	0	1	1	4	1	0	0	0	0	0	0	0	0	0	0	0
6-2018	1	0	1	0	0	0	1	0	0	0	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	1	0
7-2018	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
8-2018	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2	0	0	0	0	0	1	0	0	0	0	1	0
9-2018	0	0	1	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	1	0	0	1	0
10-2018	4	0	0	0	0	0	0	0	0	0	1	0	1	0	6	0	0	0	0	0	0	0	1	0	0	1	0
11-2018	3	0	1	0	0	0	1	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0
12-2018	0	0	2	0	0	0	0	0	0	0	1	0	2	0	5	0	0	0	0	0	0	0	0	0	0	0	0
1-2019	2	0	1	0	0	0	0	0	1	0	0	0	3	0	7	0	1	0	0	0	1	0	0	0	0	2	0
2-2019	0	0	0	0	0	0	0	0	1	0	0	0	5	0	6	0	0	0	0	0	0	0	0	0	2	2	0
3-2019	1	0	2	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	1	0	0	1	0
4-2019	1	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	1	0	0	1	0
5-2019	1	0	0	0	0	0	1	0	1	0	0	0	2	0	5	0	0	0	0	0	0	0	0	0	0	0	0
6-2019	2	0	0	0	0	0	0	0	0	0	0	0	4	1	6	1	0	0	0	1	1	0	0	0	0	1	1
7-2019	1	0	0	0	0	0	0	0	0	0	0	0	3	0	4	0	1	0	0	0	0	0	0	0	1	2	0
8-2019	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0
9-2019	2	0	0	0	0	0	0	0	1	0	0	0	3	0	6	0	0	0	0	0	0	0	2	0	0	2	0
10-2019	2	0	0	0	0	0	0	0	1	0	1	0	2	0	6	0	1	0	0	0	0	0	1	0	0	2	0
11-2019	0	0	0	0	0	0	0	0	1	0	0	1	5	0	6	1	1	0	0	0	0	0	0	0	0	1	0
12-2019	2	0	1	0	0	0	0	0	2	0	3	0	1	0	9	0	1	0	0	0	0	0	1	0	0	2	0
1-2020	0	0	0	0	0	0	0	0	3	0	1	0	0	0	4	0	0	0	1	0	1	0	0	0	0	2	0
2-2020	2	0	0	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0	0	0	1	0	0	0	0	1	0
3-2020	0	0	0	0	0	0	0	0	3	0	0	0	0	0	3	0	1	0	0	0	1	0	0	0	0	2	0
4-2020	1	0	0	0	0	0	0	0	0	0	0	0	1	1	2	1	0	0	0	0	0	0	0	0	0	0	0
5-2020	0	0	1	0	0	0	0	0	1	0	0	0	2	0	4	0	0	0	0	0	0	0	0	0	0	0	0
6-2020	2	0	0	0	0	0	0	0	1	0	0	0	3	0	6	0	0	0	0	0	0	0	0	0	0	0	0
7-2020	1	0	0	0	1	0	0	0	2	0	1	0	1	0	6	0	1	1	0	0	1	0	2	0	0	4	1
8-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
9-2020	5	0	1	0	0	0	1	0	0	0	0	0	0	1	7	1	3	0	0	0	0	0	0	0	0	3	0
10-2020	7	0	3	1	0	0	0	0	0	0	1	0	1	0	12	1	1	3	2	1	1	0	0	0	0	4	4
11-2020	2	0	3	0	1	0	1	0	1	0	3	0	1	0	12	0	5	1	0	1	0	0	0	0	3	8	2
12-2020	1	0	1	0	0	0	1	0	1	0	1	0	0	0	5	0	1	0	0	0	1	0	0	0	0	2	0
1-2021	3	0	1	0	0	0	0	0	2	0	0	0	1	0	7	0	1	0	1	0	2	0	1	0	1	6	0
2-2021	5	0	4	0	0	0	1	0	0	0	1	0	1	0	12	0	2	0	0	0	0	0	1	0	0	3	0
3-2021	5	0	1	0	0	0	0	0	4	0	0	0	3	0	13	0	3	0	0	0	1	0	0	0	0	4	0
4-2021	7	0	0	0	0	0	1	0	2	0	0	0	4	0	14	0	4	0	0	0	1	0	0	0	0	5	0
5-2021	2	0	0	0	0	0	2	0	2	0	2	0	1	0	9	0	4	0	1	0	1	0	0	0	0	6	0
6-2021	5	0	2	0	0	0	1	0	8	0	1	0	3	0	20	0	2	2	0	1	2	0	0	0	0	4	3

monthly event frequency: LNG

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	0	0	0	0	0	0	3	0	0	0	0	0	3	1	6	1
5-2018	0	0	2	0	1	1	7	0	0	0	1	0	0	1	11	2
6-2018	0	0	1	0	0	0	7	0	0	0	0	0	2	2	10	2
7-2018	2	0	1	0	0	0	2	0	0	0	0	0	0	0	5	0
8-2018	2	0	3	0	0	0	4	0	1	0	0	0	1	2	11	2
9-2018	2	0	0	0	0	0	4	0	0	0	0	0	1	0	7	0
10-2018	1	0	0	0	2	0	7	0	1	0	1	0	4	1	16	1
11-2018	2	0	0	0	0	0	10	0	1	0	0	0	1	1	14	1
12-2018	0	0	0	0	0	0	6	0	0	0	0	0	0	0	6	0
1-2019	0	0	1	0	0	0	7	0	0	0	0	0	1	2	9	2
2-2019	0	0	1	0	0	0	8	0	1	0	0	0	1	0	11	0
3-2019	1	0	1	0	0	0	10	1	0	0	1	0	2	0	15	1
4-2019	2	0	1	0	0	0	6	0	0	0	0	0	3	1	12	1
5-2019	1	0	0	0	0	0	8	0	0	0	1	0	1	0	11	0
6-2019	0	0	2	0	1	0	11	0	0	0	1	0	2	1	17	1
7-2019	1	0	1	0	0	0	12	0	0	0	1	0	4	0	19	0
8-2019	0	0	1	0	0	0	3	0	0	0	0	0	0	0	4	0
9-2019	2	0	1	0	0	0	14	0	0	0	2	0	4	0	23	0
10-2019	1	0	0	0	0	0	7	0	0	0	0	0	0	0	8	0
11-2019	0	0	0	0	0	0	9	1	0	0	1	1	3	0	13	2
12-2019	1	0	1	0	1	0	11	0	1	0	2	0	2	0	19	0
1-2020	0	0	0	0	0	0	8	0	0	0	0	0	2	1	10	1
2-2020	1	0	2	0	0	0	7	0	0	0	1	0	0	0	11	0
3-2020	1	0	0	0	0	0	4	0	0	0	0	0	1	0	6	0
4-2020	2	0	0	0	0	0	2	0	0	0	0	0	2	0	6	0
5-2020	0	0	2	0	0	0	4	0	0	0	1	0	3	0	10	0
6-2020	0	0	1	0	0	0	6	0	0	0	1	0	1	0	9	0
7-2020	1	0	0	0	0	0	5	0	1	0	1	0	1	0	9	0
8-2020	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
9-2020	2	0	1	0	0	0	3	0	0	0	0	1	2	0	8	1
10-2020	0	0	0	0	0	1	5	0	0	0	1	0	3	0	9	1
11-2020	0	0	0	0	0	0	6	0	0	0	2	0	1	2	9	2
12-2020	1	0	0	0	0	0	5	0	0	0	0	0	0	0	6	0
1-2021	1	0	1	0	0	0	6	0	0	0	0	0	0	0	8	0
2-2021	3	0	1	0	0	0	4	0	0	0	1	0	0	1	9	1
3-2021	3	0	1	0	1	0	9	0	1	0	2	0	1	0	18	0
4-2021	0	0	2	0	0	0	2	0	0	0	1	0	3	2	8	2
5-2021	1	0	0	0	0	0	2	0	0	0	0	0	1	1	4	1
6-2021	1	0	2	0	0	0	1	0	0	0	0	0	2	1	6	1

monthly event frequency: hydrogen

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	1	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0
5-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6-2018	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
7-2018	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0
8-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2018	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
10-2018	0	0	0	0	0	0	2	0	0	0	0	0	1	0	3	0
11-2018	2	0	0	0	0	0	2	0	0	0	0	0	2	0	6	0
12-2018	1	0	0	0	0	0	2	0	0	0	0	0	0	0	3	0
1-2019	1	0	2	0	0	0	2	0	0	0	0	0	0	0	5	0
2-2019	1	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0
3-2019	2	0	0	0	0	0	1	0	0	0	0	0	2	0	5	0
4-2019	1	0	0	0	0	0	3	0	0	0	0	0	1	0	5	0
5-2019	0	0	0	0	0	0	2	0	1	0	1	0	1	0	5	0
6-2019	0	0	0	0	0	0	1	0	0	0	0	0	2	0	3	0
7-2019	3	0	0	0	0	0	0	0	0	0	0	0	1	0	4	0
8-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
9-2019	2	0	0	0	0	0	6	0	0	0	1	0	0	0	9	0
10-2019	0	0	0	0	0	0	0	0	0	0	1	0	5	0	6	0
11-2019	1	0	0	0	1	0	1	0	0	0	1	0	0	0	4	0
12-2019	1	0	0	0	0	0	1	0	0	0	1	0	1	0	4	0
1-2020	0	0	0	0	0	0	1	0	1	0	0	0	1	0	3	0
2-2020	2	0	1	0	0	0	1	0	0	0	2	0	1	0	7	0
3-2020	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
4-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-2020	1	0	0	0	0	0	1	0	0	0	0	0	4	0	6	0
6-2020	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
7-2020	2	0	0	0	0	0	1	0	0	0	1	0	1	0	5	0
8-2020	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0
9-2020	0	0	0	0	0	0	1	0	0	0	0	0	4	0	5	0
10-2020	4	0	0	0	1	0	3	0	0	0	0	0	3	0	11	0
11-2020	2	0	0	0	0	0	4	0	1	0	0	0	1	0	8	0
12-2020	4	0	0	0	0	0	1	0	1	0	1	0	2	0	9	0
1-2021	5	0	0	0	0	0	3	0	1	0	1	0	0	0	10	0
2-2021	5	0	0	0	0	0	6	0	0	0	0	0	2	1	13	1
3-2021	5	0	1	0	0	0	10	0	1	0	0	0	4	0	21	0
4-2021	5	0	0	0	0	0	5	0	2	0	0	0	5	0	17	0
5-2021	4	0	0	0	1	0	2	0	1	0	1	0	4	0	13	0
6-2021	7	0	1	0	0	1	3	0	2	0	0	0	9	0	22	1

monthly event frequency: efficiency

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	1	0	0	0	0	0	0	0	1	0	0	0	2	0	4	0
5-2018	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3	0
6-2018	1	0	0	0	0	0	0	0	0	0	1	0	1	0	3	0
7-2018	1	0	2	0	0	0	2	0	0	0	0	1	0	0	5	1
8-2018	0	0	1	0	0	0	2	0	0	0	0	0	2	0	5	0
9-2018	0	0	1	0	0	0	2	0	0	0	0	0	0	0	3	0
10-2018	0	0	1	0	0	0	3	0	1	0	1	0	4	0	10	0
11-2018	0	0	0	0	0	0	1	0	0	0	0	0	2	0	3	0
12-2018	1	0	0	0	0	0	1	0	0	0	0	0	1	0	3	0
1-2019	1	0	1	0	0	0	4	0	1	0	1	0	5	0	13	0
2-2019	0	0	0	0	0	0	1	0	0	0	0	0	2	0	3	0
3-2019	0	0	1	0	0	0	1	0	0	0	0	0	2	0	4	0
4-2019	0	0	0	0	0	0	0	0	0	0	0	0	2	1	2	1
5-2019	1	0	0	0	0	0	3	0	0	0	0	0	4	0	8	0
6-2019	0	0	0	0	0	0	3	0	0	0	0	0	2	1	5	1
7-2019	1	0	0	0	0	0	2	0	0	0	0	0	3	1	6	1
8-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
9-2019	1	0	0	0	0	0	5	0	1	0	0	0	1	0	8	0
10-2019	3	0	0	0	0	0	1	0	0	0	0	0	4	0	8	0
11-2019	1	0	0	0	0	0	4	0	0	0	1	0	3	1	9	1
12-2019	1	0	0	0	0	0	3	0	0	0	0	0	7	0	11	0
1-2020	0	0	0	0	1	0	1	0	0	0	0	0	4	0	6	0
2-2020	2	0	0	0	0	0	3	0	0	0	1	0	3	1	9	1
3-2020	3	0	0	0	0	0	1	0	0	0	0	0	0	0	4	0
4-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
5-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
6-2020	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3	0
7-2020	1	0	0	0	0	0	3	0	0	0	0	0	0	0	4	0
8-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2020	3	0	0	0	0	0	3	0	0	0	0	0	2	0	8	0
10-2020	5	0	0	0	1	0	0	0	0	0	1	0	1	0	8	0
11-2020	1	0	0	0	0	0	2	0	0	0	0	0	1	0	4	0
12-2020	3	0	0	0	0	0	2	0	0	0	0	0	0	0	5	0
1-2021	1	0	0	0	0	0	2	0	1	0	0	0	1	0	5	0
2-2021	2	0	0	0	0	0	2	0	0	0	0	0	0	0	4	0
3-2021	1	0	0	0	0	0	3	0	0	0	1	0	3	0	8	0
4-2021	2	0	0	0	0	0	3	0	0	0	0	0	2	0	7	0
5-2021	0	0	1	0	0	0	5	0	1	0	0	0	0	0	7	0
6-2021	1	0	2	0	0	0	4	0	0	0	0	0	2	0	9	0

monthly event frequency: electric

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	1	0	1	0	0	0	0	0	0	0	0	0	1	0	3	0
5-2018	0	0	0	0	0	0	4	0	0	0	0	0	2	0	6	0
6-2018	0	0	1	0	0	0	1	0	0	0	0	0	0	0	2	0
7-2018	1	0	1	0	0	0	1	0	0	0	0	0	0	0	3	0
8-2018	2	0	0	0	0	0	1	0	0	0	0	0	0	0	3	0
9-2018	0	0	1	0	0	0	0	0	0	0	0	0	2	0	3	0
10-2018	0	0	1	0	0	0	1	0	1	0	0	0	0	0	3	0
11-2018	0	0	0	0	0	0	4	0	0	0	0	0	2	0	6	0
12-2018	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
1-2019	1	0	1	0	0	0	10	0	0	0	1	0	5	0	18	0
2-2019	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5	0
3-2019	0	0	0	0	0	0	4	0	0	0	0	0	0	0	4	0
4-2019	2	0	2	0	0	0	4	0	0	0	0	0	1	0	9	0
5-2019	0	0	0	0	0	0	8	0	0	0	0	0	0	0	8	0
6-2019	0	0	1	0	0	0	6	0	0	0	0	0	3	0	10	0
7-2019	1	0	3	0	0	0	3	0	0	0	0	0	1	0	8	0
8-2019	1	0	1	0	0	0	4	0	0	0	0	0	0	0	6	0
9-2019	0	0	1	0	0	0	2	0	0	0	0	0	0	0	3	0
10-2019	1	0	1	0	0	0	2	0	0	0	1	0	5	0	10	0
11-2019	0	0	1	0	0	0	3	0	0	0	2	0	0	0	6	0
12-2019	1	0	0	0	0	0	7	0	0	0	0	0	0	0	8	0
1-2020	2	0	1	0	0	0	1	0	0	0	0	0	0	0	4	0
2-2020	0	0	1	0	0	0	4	0	0	0	0	0	1	0	6	0
3-2020	1	0	1	0	0	0	2	0	0	0	0	0	0	0	4	0
4-2020	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
5-2020	2	0	0	0	0	0	0	0	0	0	0	0	2	0	4	0
6-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
7-2020	1	0	0	0	0	0	4	0	0	0	0	0	0	0	5	0
8-2020	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
9-2020	1	0	1	0	0	0	3	0	0	0	0	0	1	0	6	0
10-2020	0	0	0	0	0	0	6	0	0	0	0	0	0	0	6	0
11-2020	0	0	0	0	0	0	1	0	0	0	0	0	2	0	3	0
12-2020	1	0	2	0	0	0	2	0	0	0	0	0	1	0	6	0
1-2021	1	0	1	0	0	0	3	0	0	0	0	0	0	0	5	0
2-2021	0	0	0	0	0	0	3	0	0	0	0	0	1	0	4	0
3-2021	0	0	0	0	0	0	1	0	1	0	0	0	0	0	2	0
4-2021	2	0	2	0	0	0	4	0	1	0	0	0	1	1	10	1
5-2021	3	0	0	0	0	0	0	0	1	0	0	0	0	0	4	0
6-2021	2	0	0	0	0	0	1	0	0	0	0	0	1	0	4	0

monthly event frequency: ammonia

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
5-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10-2018	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
11-2018	0	0	0	0	0	0	1	0	0	0	0	0	2	0	3	0
12-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-2019	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
3-2019	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
4-2019	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
5-2019	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
6-2019	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0
7-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2019	2	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0
10-2019	1	0	0	0	0	0	0	0	0	0	0	0	4	0	5	0
11-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
1-2020	0	0	0	0	0	0	2	0	1	0	0	0	2	0	5	0
2-2020	0	0	0	0	0	0	0	0	0	0	1	0	2	0	3	0
3-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
4-2020	2	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0
5-2020	1	0	0	0	0	0	0	0	0	0	0	0	4	0	5	0
6-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
7-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
8-2020	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
9-2020	0	0	0	0	0	0	1	0	0	0	0	0	2	0	3	0
10-2020	3	0	0	0	0	0	2	0	0	0	0	0	0	0	5	0
11-2020	1	0	0	0	0	0	0	0	1	0	0	0	3	0	5	0
12-2020	0	0	0	0	0	0	2	0	1	0	0	0	2	0	5	0
1-2021	2	0	0	0	0	0	3	0	0	0	0	0	0	0	5	0
2-2021	2	0	0	0	0	0	4	0	0	0	0	0	1	0	7	0
3-2021	1	0	0	0	0	0	4	0	0	0	0	0	3	0	8	0
4-2021	4	0	0	0	0	0	0	0	0	0	1	0	4	0	9	0
5-2021	3	0	0	0	0	0	3	0	0	0	1	0	3	0	10	0
6-2021	5	0	0	0	0	0	1	0	1	0	1	0	6	0	14	0

monthly event frequency: biofuel

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
5-2018	1	0	0	0	0	0	0	0	0	0	1	0	1	0	3	0
6-2018	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
7-2018	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
8-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2018	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
10-2018	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
11-2018	1	0	0	0	0	0	3	0	0	0	0	0	1	1	5	1
12-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
1-2019	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
2-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
3-2019	2	0	1	0	0	0	4	0	0	0	0	0	0	0	7	0
4-2019	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1
5-2019	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0
6-2019	0	0	1	0	0	0	1	0	0	0	0	0	3	1	5	1
7-2019	0	0	0	0	0	0	1	0	0	0	0	0	2	0	3	0
8-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
9-2019	1	0	0	0	0	0	3	0	0	0	0	0	1	0	5	0
10-2019	0	0	0	0	0	0	2	0	0	0	1	0	4	0	7	0
11-2019	0	0	0	0	0	0	2	0	0	0	1	0	0	0	3	0
12-2019	2	0	0	0	0	0	3	0	0	0	0	0	1	0	6	0
1-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-2020	0	0	1	0	0	0	2	0	0	0	0	0	0	0	3	0
3-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
4-2020	1	0	0	0	0	0	2	0	0	0	0	0	1	0	4	0
5-2020	0	0	1	0	0	0	1	0	0	0	0	0	0	0	2	0
6-2020	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0
7-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
8-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2020	0	0	0	0	0	0	1	0	0	0	0	0	2	0	3	0
10-2020	1	0	0	0	0	0	3	0	0	0	0	0	1	0	5	0
11-2020	0	0	0	0	0	1	4	0	0	0	0	0	0	0	4	1
12-2020	0	0	0	0	0	0	3	0	0	0	0	0	0	1	3	1
1-2021	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
2-2021	2	0	0	0	0	0	3	0	0	0	1	0	1	0	7	0
3-2021	0	0	0	0	0	0	3	0	1	0	0	0	0	1	4	1
4-2021	1	0	2	0	0	0	1	0	0	0	0	0	0	3	4	3
5-2021	0	0	0	0	0	0	2	0	0	0	0	0	0	1	2	1
6-2021	1	0	0	0	0	0	4	0	0	0	1	0	4	1	10	1

monthly event frequency: methanol

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-2018	0	0	0	0	0	0	0	0	0	0	1	0	1	0	2	0
6-2018	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
7-2018	0	0	0	0	0	0	0	0	0	0	1	0	1	0	2	0
8-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2018	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
10-2018	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
11-2018	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0
12-2018	0	0	1	0	0	0	0	0	1	0	0	0	0	0	2	0
1-2019	1	0	1	0	0	0	0	0	0	0	0	0	1	0	3	0
2-2019	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
4-2019	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1
5-2019	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
6-2019	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
7-2019	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
8-2019	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
9-2019	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
10-2019	0	0	0	0	0	0	3	0	0	0	0	0	1	0	4	0
11-2019	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0
12-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
1-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
4-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
5-2020	1	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0
6-2020	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0
7-2020	1	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0
8-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
10-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11-2020	0	0	0	0	0	0	0	0	1	0	1	0	3	0	5	0
12-2020	0	0	0	0	0	0	1	0	0	0	1	0	1	0	3	0
1-2021	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
2-2021	0	0	0	0	0	0	2	0	0	0	0	0	1	0	3	0
3-2021	0	0	0	0	0	0	3	0	0	0	0	0	1	0	4	0
4-2021	0	0	0	0	0	0	1	0	0	0	0	0	2	2	3	2
5-2021	1	0	0	0	0	0	2	0	2	0	0	0	2	0	7	0
6-2021	0	0	2	0	0	0	3	0	1	0	0	0	2	0	8	0

monthly event frequency: wind

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-2018	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
6-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8-2018	0	0	0	0	0	0	1	0	1	0	1	0	0	0	3	0
9-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11-2018	2	0	0	0	0	0	1	0	0	0	1	0	0	0	4	0
12-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
2-2019	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3-2019	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3	0
4-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
5-2019	1	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0
6-2019	0	0	0	0	0	0	4	0	0	0	0	0	0	0	4	0
7-2019	1	0	0	0	0	0	2	0	0	0	2	0	0	0	5	0
8-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2019	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2	0
10-2019	1	0	0	0	0	0	2	0	0	0	1	0	0	0	4	0
11-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
12-2019	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
1-2020	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
2-2020	0	0	0	0	0	0	1	0	0	0	1	0	1	0	3	0
3-2020	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
4-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-2020	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0
6-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2020	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
10-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
11-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
12-2020	2	0	0	0	0	0	2	0	0	0	0	0	0	0	4	0
1-2021	1	0	0	0	0	0	2	0	0	0	1	0	0	0	4	0
2-2021	0	0	0	0	0	0	4	0	0	0	2	0	1	0	7	0
3-2021	0	0	0	0	0	0	3	0	0	0	1	0	1	0	5	0
4-2021	0	0	0	0	0	0	2	0	0	0	1	0	1	0	4	0
5-2021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6-2021	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3	0

monthly event frequency: ex post

month	C1+	C1-	C2+	C2-	C3+	C3-	C4+	C4-	C5+	C5-	C6+	C6-	C7+	C7-	all +	all -
4-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10-2018	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
11-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12-2018	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
6-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-2019	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
10-2019	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11-2019	0	0	0	0	0	0	0	0	0	0	1	0	1	0	2	0
12-2019	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
1-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
2-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6-2020	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0
7-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
8-2020	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
9-2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10-2020	3	0	0	0	0	0	1	0	0	0	0	0	2	0	6	0
11-2020	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
12-2020	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
1-2021	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0
2-2021	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0
3-2021	1	0	0	0	0	0	3	0	0	0	0	0	0	0	4	0
4-2021	1	0	0	0	0	0	3	0	0	0	0	0	1	0	5	0
5-2021	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
6-2021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 2 – Translated interview quotes

Table 6: Translations of interview quotes	
Translation	***Original quote***
“still a real oldschool sector, that does not yet feel pressure to rethink its way of doing things” (*PA1*)	"noch so eine echte Oldschool-Branche [...], die noch überhaupt keinen Druck verspürt um umzudenken."
"founding myth" (*EA3*)	"Gründungsmythos"
“a very unfortunate mix of different properties” that “sounds more like a horror cabinet” (*EA3*)	"eine sehr unglückliche Mischung von verschiedenen Eigenschaften" die "klingt eher wie so ein Horrorkabinett"
“actually prolongs and legitimates the continuation of fossil fuel use” (*PA1*)	“das verlängert und legitimiert eigentlich nur die Verlängerung der Nutzung von fossilen Kraftstoffen“
“Well, there is virtually nothing happening [laughter]” (*EA3*)	"Also es passiert ja praktisch gar nichts [Gelächter]"
"not a topic" (*EA3*)	"kein Thema"
“someone simply has to integrate technologies into a working complete product [*Gesamtprodukt*] and you cannot do that in isolation, […] you have to think the whole supply chain through to the end, for a convincing concept to emerge, otherwise you end up with some isolated solutions [*Insellösungen*] that do not work either technically or economically” (*EA3*)	"es muss eben auch jemand [...] integrieren zu einem funktionierenden Gesamtprodukt und man kann das eben auch nicht in Isolation machen, [...] man muss eben auch die gesamte Versorgungskette zu Ende denken, dass da irgendwo ein überzeugendes Konzept entsteht, sonst entstehen da irgendwelche Insellösungen die dann entweder technisch oder wirtschaftlich nicht funktionieren"

Appendix 3 – Informed consent form

Utrecht University **INFORMED CONSENT FORM for participation in:**

Sustainable Shipping

To be completed by the participant:

I confirm that:

- I am satisfied with the received information about the research;
- I have been given opportunity to ask questions about the research and that any questions that have been risen have been answered satisfactorily;
- I had the opportunity to think carefully about participating in the study;
- I will give an honest answer to the questions asked.

I agree that:

- the data to be collected will be obtained and stored for scientific purposes;
- the collected, completely anonymous, research data can be shared and re-used by scientists to answer other research questions;
- video and/or audio recordings may also be used for scientific purposes.

I understand that:

- I have the right to withdraw my consent to use the data;
- I have the right to see the research report afterwards.

Name of participant: ___________________________________

Signature: _____________________________________ Date, place: ___ / ___ / ____, ____________

To be completed by the investigator:

I declare that I have explained the above mentioned participant what participation means and the reasons for data collection.
I guarantee the privacy of the data.

Name: ___________________________

Date: ___ / ___ / _____(dd/mm/yyyy)

Signature: