The effects of multi-system dynamics on the diffusion of electrofuels

A maritime sector case study

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Abstract

While sustainability transition studies primarily analysed single socio-technical systems, this approach disregards the complexity of sustainability transitions that often involves actors, technologies, and institutions of multiple systems. Therefore, this thesis proposes an integral framework to understand better how multi-system dynamics affect the diffusion of innovations using: 1) institutional theory (the socio); 2) technological sector interactions (the technical); and 3) boundary-spanning and system-entangling activities of actors between multiple socio-technical systems. Following an abductive research design by iteratively analysing the acquired empirical data from 23 semi-structured interviews and 10 informal expert discussions using the qualitative analysis software of NVivo, a case study of the diffusion of electrofuels (e-fuels) into the maritime sector as one of the 'hard-to-abate' sectors is conducted to validate this novel approach. As the e-fuels system is centred between various up and downstream sectors and thereby subject to various socio-technical interactions, it poses an interesting case for assessing multi-system dynamics.

The results show that using these different theoretical concepts has uncovered the different natures and levels of socio-technical drivers and barriers for e-fuel adoption into the maritime sector stemming from multi-system interactions. Some fundamental interactions include the mismatching institutions between e-fuels and maritime actors, such as long versus short-term strategic orientation or different stances towards collaborations, which result in clear sociological barriers. Additionally, the competing and symbiotic relationships of technologies within the e-fuels sector (intra-sector), the mutual dependency of up and downstream technologies along the value chain (inter-sector), and the rivalling interests of e-fuel (components) by numerous end-user sectors (cross-sector) illustrates the technological embeddedness of the e-fuels system. Considering the socio-technical interactions mentioned above, the most prominent actors trying to bridge the gaps between the e-fuels and maritime systems include NGOs, industry associations, and research institutes. These actors possess a deeper understanding of the socio-technical barriers and pinpoint some unique leverage points for interventions. Therefore, this framework has formed the basis for defining specific policy objectives and interventions to address the different nature and levels of socio-technical drivers and barriers. In this regard, this research provided a comprehensive approach to understanding the effects of multi-system dynamics on the diffusion of innovations and has paved the way for future studies to explore the effects of multi-system dynamics in different environments and contexts.

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List of acronyms and definitions

Acronym/definition	Description
Bio-fuel	Fuels produced over a short period in contrast with fossil fuels. A distinction is made between different generations of bio-fuels: ▪ 1st generation bio-fuels are made from biomass grown on arable land; ▪ 2nd generation bio-fuel are made from biomass waste that does not function as nutrition; ▪ 3rd generation bio-fuels are made from algae and other micro-organisms; ▪ 4th generation bio-fuel are made from bio-genic feedstock molecules and renewable electricity (see e-fuel, PtX, RFNBO).
Bio-genic CO_2	Bio-genic CO_2 refers to the carbon stored in biomass originating from CO_2 that is removed from the atmosphere by photosynthesis which, under natural conditions, would eventually cycle back to the atmosphere as CO_2 because of the degradation process.
CAPEX	Capital expenditures
CCUS	Carbon Capture Utilisation & Storage
E-fuel	The abbreviation of electrofuel and defines the fuels made from renewable energy and the reforming of abundant feedstock molecules such as H_2O, CO_2 and N_2.
EC	European Commission
EU ETS	European Union Emission Trading System
FID	Financial Investment Decision
GHG emissions	Greenhouse gas emissions are gases that strengthen the greenhouse effect and, thereby, contribute to climate change.
Green corridor	Green corridors refer to the development of an integral approach between different geographical locations whereby energy-saving and emission reduction measures are deployed to reduce GHG emissions.
IMO	International Maritime Organisation
IRA	The abbreviation for the Inflation Reduction Act, a policy measure implemented by the United States to make the production of e-fuels more financially attractive.
MEP	Member of the European Parliament
MLP	The abbreviation for the Multi-Level Perspective, a transition study framework which describes landscape pressures, and the trans-positioning of socio-technical regime and socio-technical niche configurations.

NGO	Non-governmental organisation
OPEX	Operational Expenditures
PtG	The abbreviation of Power-to-Gas which represents gaseous energy carriers made from renewable energy sources.
PtL	The abbreviation of Power-to-Liquid which represents liquid energy carriers made from renewable energy sources.
PtX	The abbreviation of Power-to-X which encompasses all types of energy carriers made with the use of renewable energy sources. An umbrella term for Power-to-Liquid (PtL) and Power-to-Gas (PtG), electrofuels (e-fuels) and Renewable Fuels of Non-Biological Origin (RFNBO).
RED	The abbreviation for the Renewable Energy Directive and defines the legal framework for renewable energy across all sectors in the EU.
RFNBO	The abbreviation of Renewable Fuels of Non-Biological Origin and refers to the fuels which are produced using energy from renewable energy sources and feedstock molecules that do not originate from fossils or biomass.
TIS	The abbreviation of the Technological Innovation System theory which defines the critical innovation system processes for socio-technical niche development.

1. Introduction

The increasing demand for sustainability to mitigate climate change resulted in the tremendous growth of renewable energy sources (IEA, 2021). Simultaneously, several complications, such as grid instability, intensified because of the intermittent nature of renewables (Sinsel et al., 2020). To alleviate these problems, developing electrofuels (e-fuels) can be one of the potential solutions. E-fuels refer to the fourth generation of biofuels which are created by reforming abundantly available feedstock molecules (e.g. H_2O, CO_2, and N_2) with the use of renewable energy (Detz et al., 2018; Hosseini & Wahid, 2020; Patterson et al., 2019). The drawbacks of intermittent renewables could be mitigated by storing the renewable energy surplus in e-fuels for later use. Because the existing industrial processes already cover many of the technologically required steps for e-fuels production and their compatibility with current infrastructures, e-fuels may provide significant contributions to make various sectors more sustainable (Malins, 2017; Tatin et al., 2016). Despite the potential of e-fuels to decarbonise various sectors, e-fuels still face several financial, technological, political and societal challenges before being competitive in large-scale energy markets (Ardo et al., 2018; Detz et al., 2018). Hence, prioritising the integration of e-fuels into no-regret sectors[1] can be promising as this reduces their short-term scarcity and long-term uncertainty (Ueckerdt et al., 2021).

One of the interesting no-regret sectors is the maritime sector, as this is the backbone of international trade by accounting for 80% of the global trade volume and 70% of the global trade value (Foretich et al., 2021; Zhou et al., 2019), but is simultaneously responsible for 3% of all GHG emissions globally (IMO, 2020). For the maritime sector, several e-fuels are plausible such as e-methanol, green hydrogen and e-ammonia (*Appendix I – E-fuel types for the maritime sector*). Nevertheless, there is no precise scenario in which sustainable fuel will be the most prominent, and there is substantial uncertainty regarding reliable fuel supply (Foretich et al., 2021; Prussi et al., 2021). This uncertainty surrounding alternative marine fuels prolongs the transition pathway by hesitation and await among actors along the value chain (Xing et al., 2021). In addition to the uncertainty of sustainable marine fuels, the maritime sector may be competing for e-fuels with other sectors where similar or even more significant greenhouse gas reductions can be achieved (Lindstad et al., 2021). Accordingly, Al-Enazi et al. (2021) emphasised the need for a more interdisciplinary and multi-dimensional approach to assess the effects of the e-fuel supply chain on the maritime sector.

To better understand technology diffusion and the transformational context, the field of transition studies has proved to be especially useful. One of the critical transition frameworks is that of the Multi-Level Perspective (MLP), which describes how socio-technical transitions emerge from the interaction on three levels: the landscape, the socio-technical regime, and in technological niches (Geels & Schot, 2007; Smith et al., 2005). A socio-technical transition could be described as transforming from one dominant socio-technical regime to another. Socio-technical regimes are the semi-coherent set of formal and informal norms, values and rules (i.e. institutions) that guide actor behaviour and determine 'the rules of the game' (Geels, 2004, 2011; Smith et al., 2005). Particularly the socio-technical regime plays a critical role in the innovation diffusion process as this often resembles the efficiency and rigidity of the existing systemic structures. The more consolidated the regime is, the more difficult it is to initiate a socio-technological transition (Fuenfschilling & Truffer, 2014; Geels, 2011). Therefore, analysing the institutional context serves as a practical standpoint for analysing socio-technical transitions.

Whereas the field of transition studies primarily emphasises transitions of a single socio-technical system, some scholars advocate for a more holistic approach by taking the undervalued aspect of multi-system dynamics into account (Kanger et al., 2021; Köhler et al., 2019; Markard et al., 2020;

[1] No-regret sectors refers to sectors that often find difficulties in the abatement of fossil fuels as they are impossible to electrify. Among OECD countries, no-regret sectors account for a quarter of the total energy consumption (Ueckerdt et al., 2021).

Rosenbloom, 2020). Including multi-system dynamics in transition study analyses is especially relevant since changes in one socio-technical system can directly impact other socio-technical systems. This becomes particularly evident in the study of Raven & Verbong (2010), which illustrates how competition, symbiosis, integration and spill-over interaction patterns prevail between multiple socio-technical regimes. Similarly, Papachristos et al. (2013) synthesised thirteen transition studies and illustrated how the interaction between multiple niches and regimes affected adjacent niche developments. In addition, Andersen & Markard (2020) highlight how technological interactions can appear on intra-sector, inter-sector, and cross-sector levels. Stemming from these interaction patterns between multiple systems, shared institutions across systems (i.e. shared rules or meta-rules) can emerge, which guide actor behaviour (Kanger & Schot, 2019; Schot & Kanger, 2018). This suggests that multi-system dynamics should be included to better understand the processes and implications of socio-technical transitions (Bergek et al., 2015; Rosenbloom, 2020). Without this, transition studies focusing only on a single socio-technical can be inadequate.

Since prior exploratory works on multi-system dynamics often examined how distinct or parallel socio-technical systems affected each other, this research analyses the multi-system dynamics of the e-fuel and maritime sectors, which are more chain-linked (i.e. the e-fuels sector is a product and service provider to the maritime sector). Empirical and conceptual studies have highlighted the importance of the ties of involved actors along and between value chains in shaping sustainability transitions and that the technological developments need to be accommodated by market formation, value chain, regulatory- and institutional changes (Andersen et al., 2020; Köhler et al., 2019). Some examples are the studies of Sandén & Hillman (2011) which conceptualised the interrelatedness of technologies within and across value chains, or the works of Stephan et al. (2017) and Malhotra et al. (2019), which illustrated how different sectors interact along the value chain in the context of Technological Innovation Systems (TIS). Nevertheless, there is no profound framework to analyse such multi-system interactions (Andersen & Markard, 2020), not to mention the applicability of such frameworks for multi-faceted technologies such as e-fuels. Accordingly, this thesis tries to move beyond the standard user-producer interactions by analysing how the interactions between the e-fuels and maritime sectors, as well as that of adjacent sectors, affect the dynamics at the interface of these two sectors.

This research employs a combination of two theoretical approaches to explore multi-system dynamics. The first theoretical approach relates to institutional logics, which provides a tangible framework for identifying the central socially constructed norms, values and beliefs that shape actor behaviour (Thornton & Ocasio, 2008). The institutional logics approach makes similarities or distinct features of the e-fuels and maritime systems affecting the diffusion process apparent. The second theoretical approach relates to the technological interactions on an intra-sector, inter-sector, and cross-sector level, as this defines the important multi-system correlations between artefacts (Andersen & Markard, 2020). Considering the interrelatedness of technologies seen from a hierarchical value chain perspective (inter-sector), competing or symbiotic nature with other technologies (intra-sector) or broader applications in multiple sectors (cross-sector), the technological sector interactions approach is preferred in this research as it emphasises the multi-system aspects more when compared to common technological niche development theories such as the Technological Innovation System (TIS) framework. Accordingly, this research addresses the multi-system dynamics between the two focal sectors of this research (e-fuels & maritime) through both sociological (i.e. institutional logics) and technological (i.e. sector interactions) aspects.

Besides these two theoretical approaches for examining multi-system dynamics, scholars also emphasised the importance of bridging the gaps between multiple-sectors. Weakening the existing ties between currently connected systems or reinforcing new linkages with (yet) uncorrelated systems can be essential in easing socio-technical transitions (Kanger et al., 2021; Kivimaa & Kern, 2016). Here, boundary spanners are shown to be critical actors to minimise the gaps between systems by trying to align the institutions of such regimes and niches (Smink et al., 2015). In a similar vein, van der Vleuten

(2019) used the notion of system entanglers which not only emphasises the role of such actors in 'entangling' systems but also 'disentangling' existing ties between systems to allow for new linkages to emerge between other systems. Hence, such actors are exceptionally relevant in the maritime sector, which is heavily coupled with the fossil fuels regime but is eventually required to adapt towards the emerging e-fuels niche. Considering the factors mentioned above to achieve a deeper understanding of the implications of multi-system dynamics, this thesis addresses the following research questions:

How do multi-system dynamics affect the diffusion of e-fuels into the maritime sector?

1. What are the institutional logics of a) the e-fuels sector and b) the maritime sectors?
2. How do the institutional logics align or conflict?
3. What technological sector interactions are noticeable concerning the e-fuels sector?
4. Which actors have been active in aligning sociological or technological relationships at the interface of these two sectors?
5. What are the drivers and barriers to the diffusion of e-fuels in the maritime sector?
6. How can the sectors' respective institutional logics or technological sector interactions explain these drivers and barriers?
7. How can the alignment of institutional logics or technological sector relationships be supported to overcome barriers and stimulate the diffusion of e-fuels into the maritime sector?

A better understanding of multi-system dynamics can contribute to the transition study literature. By gaining more elaborate insights into how multiple systems interact and influence each other, we can improve how to approach and analyse complex multi-disciplinary societal problems such as sustainability. Therefore, such empirical studies can form the basis for defining a robust and substantiated approach for policymakers to address the inherent challenges of e-fuels integration in the maritime sector. Simultaneously, it could lead to a sensible an integral policy approach to potentially guide the e-fuels transition in other related sectors.

Chapter 2 highlights the relevant key innovation and transition theories to answer the research questions. Hereafter, *Chapter 3* encompasses the methods for addressing and operationalising the research questions. *Chapter 4* encompasses the analysis and findings of this research. *Chapter 5* describes the implications of this research and potential research avenues for future studies. At last, *Chapter 6* synthesises and summarises the findings of this research in the conclusion.

2. Theory

2.1. Sustainability transitions

To address a wide range of complex problems and global challenges, such as sustainability, a socio-technical system is an important concept as it provides a more tangible framework to interpret the complex interactions between social actors and technological systems (Davis et al., 2014). A socio-technical system is a configuration of actors, the institutions that guide their behaviour, artefacts and the physical infrastructure, aimed at fulfilling a societal function (e.g. transportation, nutrition, energy) (Geels, 2004). In the transition studies literature, Geels (2002) defined three dimensions that form the foundation of socio-technical systems in the Multi-Level Perspective (MLP) framework: the socio-technical landscape, the socio-technical regime and niches. The socio-technical landscape refers to the overarching external factors (e.g. economic growth, cultural norms and values, environmental problems), the socio-technical regime is the embodiment of semi-coherent rules that persist within different social groups, and niches resemble the new emerging technologies and industries (Geels, 2002). Considering these levels, a transition of a socio-technical system refers to the change from the current socio-technical regime to another. These transitions can emerge from the rising external pressures from the landscape, the internal conflicts within socio-technical regimes, the progression of the niche(s) or the combination of any of these factors (Konrad et al., 2008). In a broad sense, this high-level MLP framework provides guidance to assess and describe socio-technical system changes.

As a focal unit of analysis in transitions, socio-technical regimes are more specifically defined as three interconnected elements of (1) actor and social group networks, (2) the (in)formal, cognitive and normative rules that guide actor activities and (3) materials and technical elements as artefacts and infrastructures (Geels, 2006). These socio-technical regimes resemble the 'deep structure' that assures the persistence and reproduction of a semi-coherent set of rules (i.e. institutions) that guides the socio-technical system along the fulfilment of societal functions (Geels, 2011). The socio-technical system mainly progresses to more efficient and consolidated systems through incremental innovations. To a certain degree, these systems become locked-in, which impedes the development and integration of radical innovations as these often oppose the dominant socio-technical system configuration.

2.2. Multi-system dynamics

While socio-technical transitions are often analysed within one industry or sector, the interplay between multiple systems is considered an overlooked topic (Rosenbloom, 2019, 2020). Despite some exploratory studies on multi-system interactions, the main emphasis of transition studies has focused on single socio-technical systems (Grin et al., 2010; Kanger et al., 2021). Nevertheless, the effects of a socio-technical transition might span across various systems simultaneously. For instance, the interaction between regimes in multiple systems might result in 'meta-rules' which are defined as the shared rules, norms and values (i.e. institutions) among actors in distinct systems (Kanger & Schot, 2019; Schot & Kanger, 2018). Sandén & Hillman (2011) illustrated this in the case of alternative transport fuels in Sweden, whereby shared and symbiotic elements became prevalent among various socio-technical systems along the value chain. Accordingly, changes in one system might induce positive or negative externalities in related industries or sectors. This suggests that both the internal socio-technical system dynamics and the connections with other systems should be considered when studying transitions. Without integrating multi-system dynamics into transition studies, analyses can be inadequate by neglecting relevant interaction patterns that affect socio-technical systems, leading to inaccurate hypotheses regarding socio-technical transitions.

According to Raven & Verbong (2010), there are four different interaction patterns between multiple socio-technical regimes: competition, symbiosis, integration and spill-overs (see *Figure 1*). Herein, competition refers to the rivalry of two or more regimes that may fulfil the same societal function (i.e. electricity and natural gas, which both compete for heating and power). Symbiosis, on the other hand, refers to the improved benefits multiple regimes can experience when cooperating (i.e. stable and reliable ties between systemic components that reduce uncertainty). In the third interaction pattern, integration, multiple regimes can merge to some extent where the distinction between them and their components becomes less transparent (i.e. merger of companies from different industries or sectors). Noteworthy, however, is that disintegration might also prevail, resembling a regime's separation. Considering the chain-linked relationship between the e-fuels and maritime sectors, which is still in its infancy, the integration dynamics will likely prevail to a certain extent. However, Sutherland et al. (2015) describe this early stage as a phase of convergence which still makes changing and volatile landscape an interesting aspect to analyse. As for the spill-over interaction pattern, this refers to the transfer of rules from one regime to another. Accordingly, the spill-over interaction resembles meta-rules formation (Kanger & Schot, 2019; Schot & Kanger, 2018). Considering these regime interaction patterns, this may provide a more substantiated approach for analysing the multi-system dynamics in socio-technical transitions.

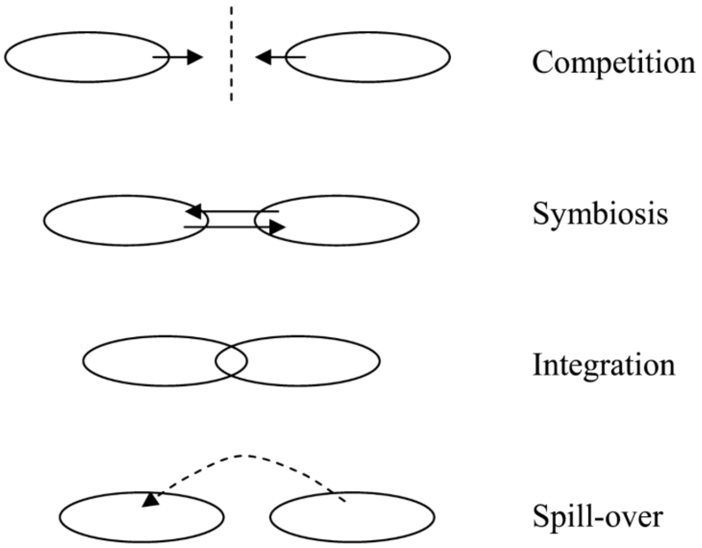

Figure 1. Schematic overview of multi-regime interactions according to Raven & Verbong (2010).

The multi-system interaction patterns also introduce new dynamics into the transition literature, such as the gradual evolution of systemic relationships. For instance, explorative research has shown how the relationship between regimes altered from a competitive to a more symbiotic interaction pattern (Geels, 2007). Another study by Raven (2007) showed how the two previously hardly connected socio-technical regimes of the electricity and gas distribution sectors developed a more symbiotic and integrated relationship. In a similar vein, Konrad et al. (2008) examined multi-regime dynamics in the German utility sectors of electricity, gas, drinking water, sanitation and telecommunication, whereby they indicated the emerging synergies and trade-offs regarding functional couplings (i.e. input-output relations between regimes such as supplier relations) and structural couplings (i.e. the actors, infrastructures or institutions shared by multiple regimes). Such studies amplify the interconnectedness of systems and their causal relationships. Accordingly, single socio-technical system transition policies are most likely insufficient without addressing the multi-system aspects (Kanger et al., 2021; Konrad et al., 2008).

2.2.1. Institutional logics

Whereas the MLP framework emphasises a niche versus regime dichotomy, this is not solely the mechanism that drives socio-technical transitions. Here, the configuration of socio-technical regimes can also be an essential aspect. For instance, socio-technical regimes are often depicted as relatively stable, uniformly aligned and homogeneous monolithic blocks, yet these may encompass contradicting institutional tensions (Fuenfschilling & Truffer, 2014). These tensions can occur in different institutional logics, which refer to the socially constructed formal and informal rules that provide individuals guidance, meaning and purpose (Thornton & Ocasio, 1999). Different institutional logics may be emerging and more prevalent based on the dynamics mentioned above of socio-technical transitions (i.e. landscape pressures, conflicting regime interests, or new emerging niche ideologies). Consequently, the multiple institutional logics may coexist, compete, contradict or complement each other and thereby reinforce or weaken the structure of the socio-technical system (Fuenfschilling & Truffer, 2014). Therefore, institutional logics affects the direction and configuration of socio-technical systems, making them relevant when analysing transitions.

Besides the cultural beliefs and values, various power structures within organisations and societal contexts (i.e. the distribution of authority) also significantly shape institutional logics (Thornton & Ocasio, 2008). According to Thornton & Ocasio (2008), power distributions can be powerful actors that stimulate particular institutional logics or the conflicting tensions that arise from these dominant logics with countervailing logics. Hence, powerful actors can significantly influence the behaviour of organisations and individuals. For instance, Pentland & Feldman (2005) argued that ongoing power struggles among organisational actors affect the persistence and evolution of organisational routines. Stemming from this, actors need to possess the ability to exert political, economic and institutional power to initiate change (Battilana et al., 2009; Smith et al., 2005). Therefore, indicating the most dominant actors and their degree of authority could help define which institutional logics are most prominent and how this affects the institutional landscape.

Previous studies of scholars on institutional contexts have led to several categories to identify the institutional logics of a sector, including: basis of strategy, efficiency focus, expertise, funding, informal control mechanisms, mission, sector logic, sources of authority, technologies, values, and view on business (Fuenfschilling & Truffer, 2014; Thornton et al., 2012; Thornton & Ocasio, 2008; Wesseling et al., 2022). These indicators are essential for analysing institutional logics as they reveal the fundamental principles, operations, resource allocation, power dynamics and objectives that guide actor behaviour. Accordingly, this has led to the conceptualisation of seven 'ideal-type' sector logics: community-logic, corporate-logic, family-logic, market-logic, profession-logic, religion-logic, and state-logic (Thornton, 2004; Thornton et al., 2012). These different sector logics represent the most common ideologies inherently connected to some of the actors within the system and are summarised in *Table 1*. Whereas institutional logics can be based on a variety of factors, including the history of organisations, the type of industry or sector, dominant culture and the broader economic and societal context (Thornton & Ocasio, 2008), the ideal-type logics concept provides a framework for researchers to analyse and understand the underlying principles that shape actor behaviour and decision-making. Accordingly, the analysis of institutional logics results in a well-substantiated approach to evaluate actor behaviour in socio-technical transitions (Thornton & Ocasio, 2008).

Table 1. Ideal-type sector logics, based on Thornton (2004) and Thornton & Ocasio (2012).

Ideal-type sector logic	Description
Community-logic	Addressing the value of creating social connections, shared values and collective action towards broader community objectives.
Corporate-logic	The prioritisation of efficiency, productivity and profitability.
Family-logic	Emphasis on strong and personal relationships to create a ‘family-like’ environment whereby loyalty and trust are paramount.
Market-logic	Indicating the importance of supply and demand mechanisms and the role of market forces in determining the outcomes.
Profession-logic	Highlighting the importance of expertise, specialised knowledge and ethical standards.
Religion-logic	Emphasis on the importance of spirituality, faith and moral values.
State-logic	Emphasising the governmental role and stressing the urgency to follow the rules and regulations.

In most cases, socio-technical systems are driven by only a few dominant sector logics (Thornton & Ocasio, 2008; Wesseling et al., 2022). This combination of one or more sector logics results in a specific field logic that represents the general sense of the actor rationalities, distribution of power, the main focus of problems and solutions, and rules of the game (Fuenfschilling & Truffer, 2014; Thornton & Ocasio, 2008). To illustrate this, Fuenfschilling & Truffer (2014, 2016) showed how multiple institutional logics coexist in the Australian water sector and how some are more dominant and seen as more legitimate. Once there are more shared beliefs and assumptions of the dominant institutional logics, this can create a sense of cohesion and common purpose within an industry or sector. As a result, some systems may be more conservative or solidified, affecting their response regarding institutional change in socio-technical transitions. Herein, socio-technical transitions refer to replacing the dominant field logic towards another (Fuenfschilling & Truffer, 2014; Fünfschilling, 2014). Hence, evaluating the dominance and perseverance of specific institutional logics can help understand and predict actor responses.

2.2.2. Sector interactions

Besides interactions between multiple niches and regimes, Andersen & Markard (2020) illustrated how technology interactions across sectors can affect socio-technical transitions. For instance, various technologies such as hydro, wind, solar and biogas can complement and compete as they fulfil similar or complementary roles at sectoral levels (Markard & Hoffmann, 2016; Sandén & Hillman, 2011). A noteworthy remark, however, is that this conceptualisation of a ‘sector’ stresses a different angle when compared with the 'sector' described in the ideal-type sector logics. Whereas sector logics emphasises the distinct nature of institutions of a particular sector, sector interactions refer to the technological dynamics and exchanges within and between sectors. Andersen & Markard (2020) distinguish intra-sector, inter-sector and cross-sector technology interactions.

Intra-sector interactions

From an intra-sector perspective, technology interactions are evaluated and seen through the lens of the value chain of the focal sector. Here, technologies can interact as technological developments in one technology might induce the requirement for innovations in other competing or complementary technologies (Geels, 2018; Markard & Hoffmann, 2016). Whereas competing technologies need innovations to remain competitive to prevent early, potentially undesired lock-in effects (Arthur, 1989), complementary technologies may benefit considering their compatibility advantage (Rogers, 2003). Such intra-sector technology interactions foster technological progress, competition and the emergence of dominant designs.

Inter-sector interactions

Regarding inter-sector technology interactions, contextual changes within the focal sector can induce noticeable consequences in up or downstream sectors (Andersen et al., 2020). For instance, the increasing need to decarbonise industries induces the demand for sustainable energy technologies, decreasing the need for fossil fuel technologies. Nevertheless, such technological changes often need to be accommodated by alterations in the other sector levels to prevent bottlenecks (Arthur, 2009; Hughes, 1987; Murmann & Frenken, 2006). If not accounted for, innovation overshooting may occur, which refers to the exceeding technological developments in upstream sectors which cannot be absorbed by the downstream sectors (Almudi et al., 2017). Consequently, the alignment and gradual of innovative activities across up and downstream sectors are necessary to facilitate technological development and diffusion (Andersen & Markard, 2020).

Cross-sector interactions

Considering the cross-sector interactions, these become increasingly more relevant as technologies progress along transitions and sector couplings start to play a role (Andersen & Markard, 2020). Cross-sector technology interactions refer to the convergence of various sectors that allow new novel technology applications to emerge. Some examples could be e-fuels, smart grids, agri-tech, and space & earth observation, whereby cross-sectoral demands and technologies come together. Especially for sustainability transitions, sector couplings are prompted to more easily facilitate the decarbonisation of multiple sectors at once (Ramsebner et al., 2021). Therefore, cross-sector interactions, as well as intra- and inter-sector interactions, are deemed relevant aspects to consider when governing socio-technical transitions.

2.2.3. Boundary spanners and system entanglers

Since sustainability transitions often relate to multiple systems, there seems to be increased importance for coordinating and aligning such systems. Kivimaa & Kern (2016), for example, argue for an integral approach whereby the existing linkages of the regime should be destabilised, and the emergence of new linkages with technological niches should be stimulated. For creating such systemic connections, boundary spanners can fulfil an influential role as mediators, individuals or organisations operating at the interface of such respective systems (Zietsma & Lawrence, 2010). This becomes apparent in a study by Smink et al. (2015) which illustrated how mismatching institutional logics between the natural gas regime and emerging bio-methane niche hindered the niche development and, thereby, the diffusion of the innovation. Here, the boundary spanners played a crucial role in facilitating communication and building relationships between the niche and regime to overcome the barriers of the conflicting institutional logics (Smink et al., 2015). This example highlights the importance of such boundary spanners in enabling niche development and explains that evaluating their role is vital in multi-system transition studies.

More recently, van der Vleuten (2019) introduced the concept of system entanglers, which closely resembles the boundary spanners concept. Here, system entanglers also function as inter-system intermediaries, which may create convergence that reinforces sector couplings but simultaneously create divergence by breaking down existing sector couplings (Kanger et al., 2021; van der Vleuten, 2019). To illustrate this, van der Vleuten (2019) showed how system entanglers actively identified current limitations, challenged established practices and norms, promoted disruptive innovations, advocated for institutional changes and simultaneously fostered collaborations and networks in Europe’s infrastructure transition. Whereas the boundary spanners concept primarily emphasises the creation of new linkages between systems, system entanglers highlight the role of creating connections and significantly underline the importance of disrupting and challenging existing system configurations. As a result, boundary spanners and system entanglers align the development and evolution of different socio-technical systems, making it more likely that a coordinated transition can occur. This conveys the idea that boundary spanners and system entanglers play a critical role in enabling socio-technical transitions.

2.3. Conceptual approach

In the following empirical analysis, this study tries to explain the effects of multi-system dynamics between the e-fuels and the maritime systems. Since e-fuels can play an essential role in the sustainability transition of the maritime sector, addressing the research questions could help indicate if and where the potentials lie for accelerating this transition.

First, the most dominant field logics can become apparent by analysing institutional logics of the e-fuels and maritime systems. This overview helps to identify to what extent the institutions of these two systems are aligned, which helps to understand the interactions between them and explain the effect on the diffusion of e-fuels into the maritime sector. For instance, if the institutions of both the e-fuels and maritime systems are only marginally aligned, adopting e-fuels is likely to experience significant barriers to adoption and vice versa. Considering competition, symbiosis, integration, and spill-over interactions provides a more elaborate approach to better understanding the complex interplay of various elements that affect the diffusion of e-fuels into the maritime sector. To illustrate, when similar field logics are present in each system, their relationship seems more likely to be more symbiotic. Contrarily, highly different institutions could result in more competitiveness between the two systems. Interpreting the nature of these system interactions based on the institutional logics of the e-fuels and maritime systems may provide important insights into the underlying mechanisms that drive or inhibit the transition process.

Second, the technological interactions within and between sectors can be interpreted using the sector interactions framework. By distinguishing between intra-sector, inter-sector, and cross-sector interactions, it can become clear what the implications are of the different types of interactions at each of these distinct levels. This allows for contextualisation of the underlying competing or complementary technological relationships of the e-fuels, the maritime, and the different up and downstream sectors along the value chain. As a result, this provides a more substantiated approach to evaluating the e-fuels niche's embeddedness.

Third, to better understand the alignment and coordination of the e-fuels and maritime systems, this research examines the role of boundary spanners and system entanglers active at the interface of these two systems. These actors may include advocacy groups, government agencies, industry associations and other stakeholders with a vested interest in adopting e-fuels in the maritime sector. By examining the prominence and activities of such actors, it becomes clearer how they affect the diffusion of e-fuels. Consequently, this helps to understand their role in this transition and what specific challenges they are addressing.

To visualise the conceptual approach of this research for indicating if and where multi-system interactions appear, *Figure 2* depicts a schematic overview. In this figure, the e-fuels system represents an emerging niche that primarily replaces the fossil fuels system in its supplier position to various downstream systems of the value chain. It simultaneously creates new upstream linkages with renewable electricity and feedstock molecule systems. This simplified model illustrates the embeddedness of the e-fuels system and the interface of the e-fuels and maritime systems at which the boundary spanners and system entanglers are operating.

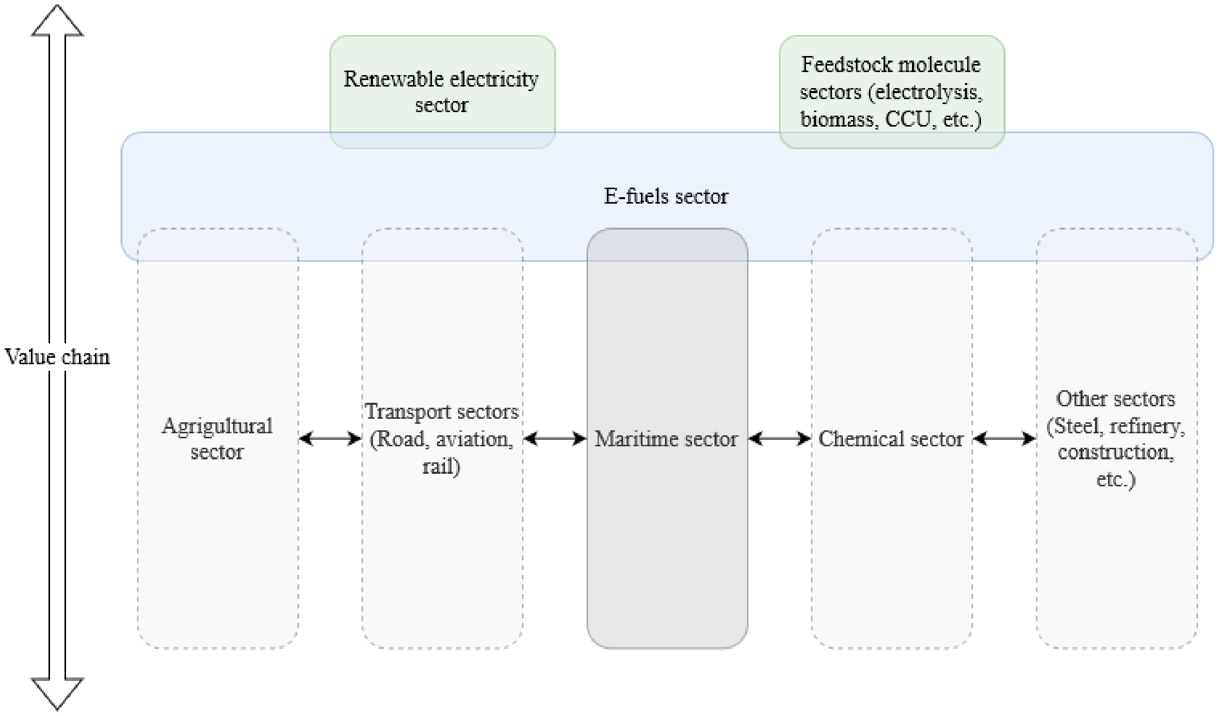

Figure 2. Illustration of how multi-system interactions can appear for the e-fuels and maritime sectors.

Following this conceptual approach, the sub-questions can be answered, which ultimately helps to answer the overarching research question. By better understanding the differences between the nature of interactions and at what levels interactions occur, this might provide valuable insights into the multi-system dynamics of socio-technical transitions for policymakers and scholars by contributing to the transition study literature. For example, these systems' interaction patterns can help policymakers recognise the socio-technical drivers and barriers that can be targeted to stimulate the transition to e-fuels. To illustrate this, favourable policies for a specific e-fuel can have direct positive or negative consequences for its complementary or competing technologies, such as batteries (inter-sector), its inherently related technologies for making them, such as electrolysis and Carbon Capture Utilisation & Storage (CCUS) (intra-sector), or its application in related sectors such as transportation or the chemical and steel industries (cross-sector). By envisioning the implications of interaction patterns and multi-system dynamics, policymakers can anticipate the potential consequences of various policy measures, making them more knowledgeable and effective policy interventions.

3. Methods

3.1. Research design

This study uses qualitative research methods to explore the effects of multi-system dynamics on the diffusion of e-fuels into the maritime sector. Qualitative research methods are particularly well-suited to analyse complex and dynamic systems, such as the multi-faceted and rapidly-evolving e-fuels sector, as it enables researchers to understand social phenomena from the perspectives of the people who experience them. Through this empirical research, new insights were acquired into the challenges and opportunities the maritime sector faces as it progresses towards more sustainable fuels, as well as to understand the diverse aspects shaping this transition.

This research consists of various analysis steps to create a structured overview and clear narrative answering the research questions, as illustrated in *Figure 3*. By following these steps, a more detailed assessment of the multi-system dynamics and their impact on the diffusion of e-fuels in the maritime sector could be made.

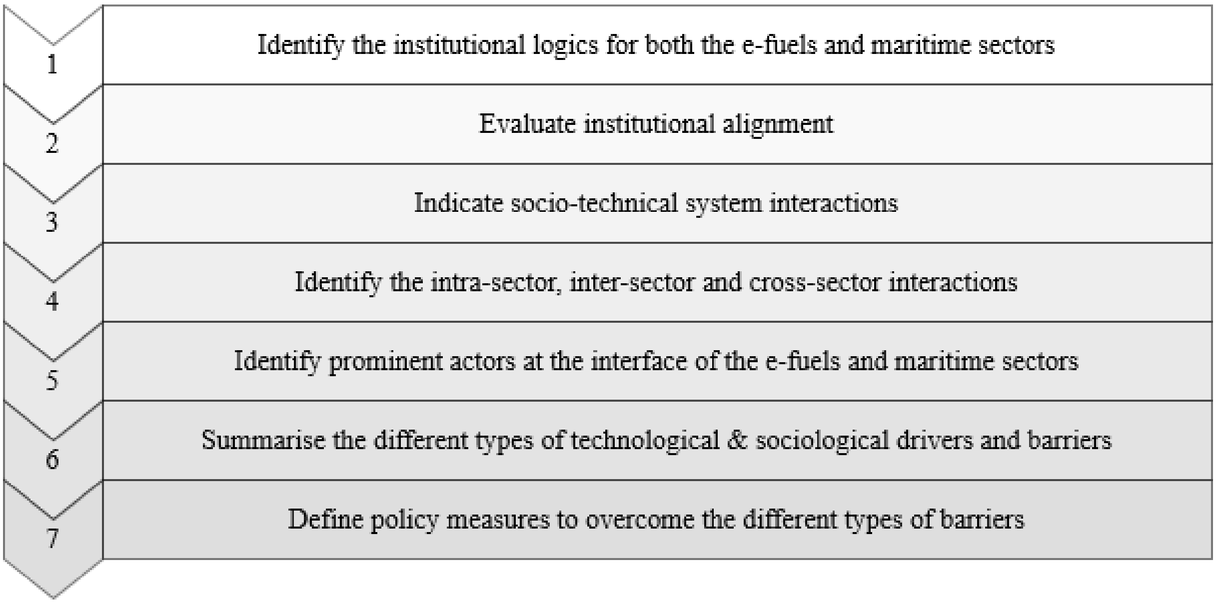

Figure 3. Research design for analysing multi-system dynamics.

3.2. Case selection

The delineation towards the e-fuels and maritime sectors would yield important insights into understanding multi-system transitions because e-fuels have the potential to reduce GHG emissions in the maritime sector significantly. However, it also involves developing and integrating new infrastructure and technologies and changes in regulations and business models. As one of the primary contributors to global trade and economy, the maritime sector is a crucial area for understanding the potential impacts of a transition to e-fuels and may provide insights into how systems are interconnected and influence each other. Identifying system interactions enables policymakers and other stakeholders to make a more informed approach when addressing the potential bottlenecks regarding the diffusion of e-fuels into the maritime sector. Drawing upon the findings of this thesis, this may result in a better understanding of multi-system dynamics, which is relevant to consider in other socio-technical transitions as well. Accordingly, this may help the diffusion of e-fuels and complementary technologies in various contexts.

To provide an understanding of what the e-fuels sector value chain looks like, *Figure 4* depicts a schematic overview. The current fossil fuels system is also indicated whereby the transition from a more linear fuel system transposes towards the more circular e-fuels system. For this research, several e-fuels are considered that have the largest potential to make the maritime sector more sustainable (e.g. carbon-based e-fuels, green hydrogen in various forms, and nitrogen-based e-fuels), which are further substantiated in *Appendix I – E-fuel types for the maritime sector*. The areas where sector interactions may appear are also visualised in this figure. For instance, inter-sector interactions are illustrated across the hierarchical green hydrogen value chain, whereby renewable electricity, electrolysis and other technologies are required for its production, storage, transportation and use. Similar inter-sector boundaries apply for the carbon- and nitrogen-based e-fuel trajectories but are, for simplicity, not illustrated in *Figure 4*.

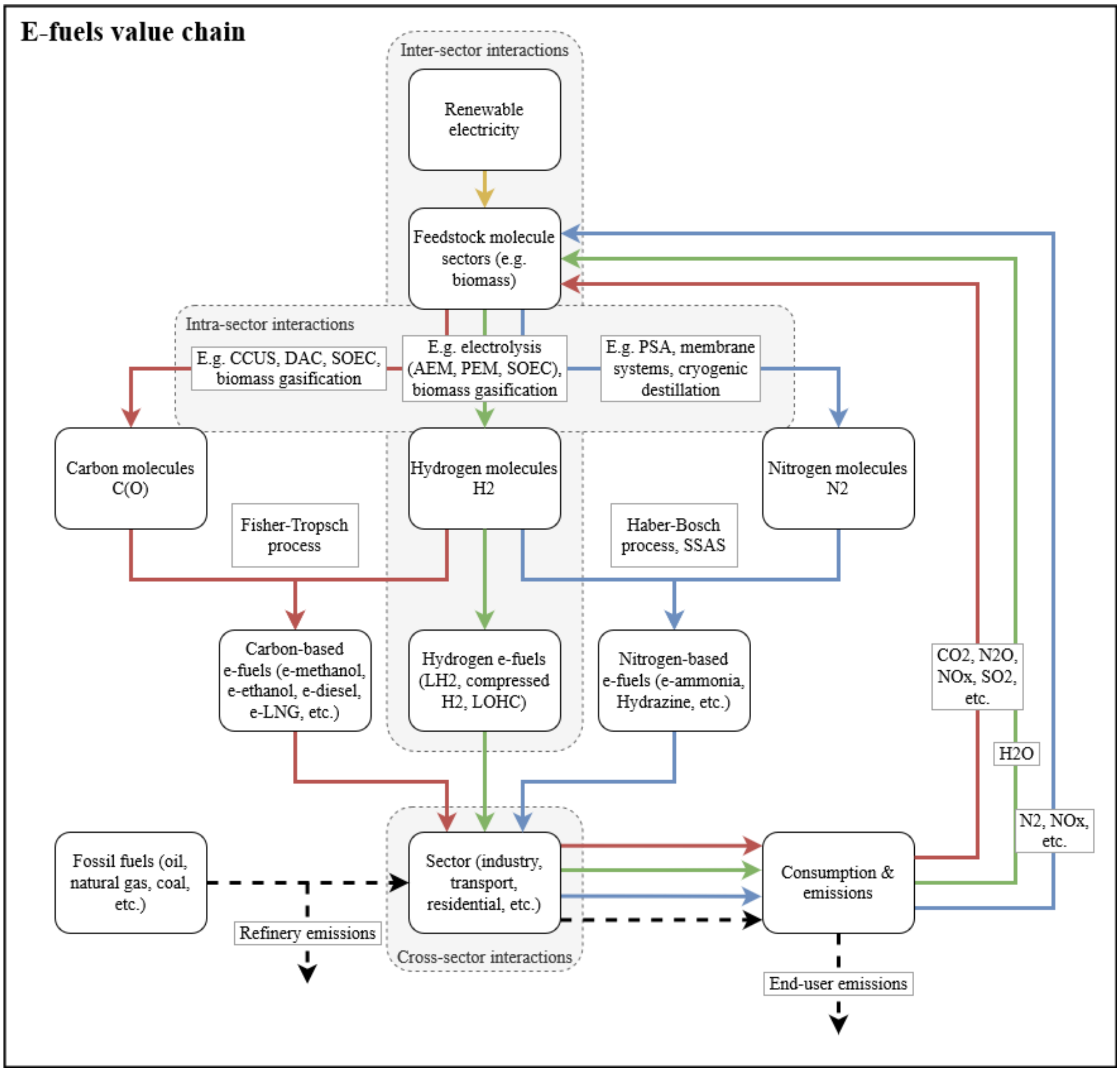

Figure 4. Visualisation of the e-fuels value chain based on reviewing literature, including Ababneh & Hameed (2022); Becker et al. (2012); Mikulčić et al. (2019); Patel & Patel (2014); Schmidt et al. (2017).

To illustrate some of the competing or complementary intra-sector interactions, Carbon Capture Utilisation & Storage (CCUS), Direct Air Capture (DAC), Solid Oxide Electrolysis Cells (SOEC) and biomass gasification can be competing for the role in providing the carbon molecules for the carbon-based e-fuel production process, or the complementary role of biomass gasification with all three proposed e-fuel trajectories as the residues of this thermochemical process is a mixture of gases (i.e. syngas) which is often composed of carbon monoxide (CO), methane (CH4) and hydrogen (H2). Similar to the inter-sector interactions, intra-sector interactions are only shown at the level of reforming feedstock molecules, but these may also occur on different levels of the value chain. Note, this thesis adds additional nuance to the intra-sector interactions concept by referring to specific value chain segments as this allows to demarcate different levels of intra-technology interactions concerning the overall e-fuels system.

Considering the interrelatedness of e-fuels as defined in this research, the notion of cross-sector interactions can become unclear since cross-sector interactions could also partly be considered as some of the abovementioned interactions. Therefore, this thesis defines cross-sector interactions as the interactions between the e-fuels and end-user sectors further down the value chain for simplicity. The visualisation of the e-fuels sector, as shown in *Figure 4,* demonstrates the complexity of the case study but amplifies the potential for exploring the effects of multi-system dynamics in more depth.

3.3. Data collection

To form the basis of this research, preliminary desk research is conducted. Documents for this desk research consisted of academic papers, consultancy reports, research projects and policy reports on regulations and programmes, which provided a general understanding of the current technological developments and applicability of various e-fuels in the maritime sector. Besides the secondary data acquired via desk research, primary data is collected by conducting 23 semi-structured interviews and 10 informal expert discussions with relevant stakeholders. The semi-structured interviews varied between a half hour to one and a half hours and were recorded and transcribed to enable more detailed analysis. The informal expert discussions took roughly half an hour on average and were directly summarised afterwards. *Table 2* provides an overview of the interviewed stakeholders in this research. A distinction is made between companies (i.e. industry players), intermediaries (e.g. alliances, NGOs, branch organisations, industry associations), research institutes and industrial actors governed by regional, national or international governments. Similarly, *Table 3* denotes the informal expert discussions that function as supplementary sources of information. The information from these discussions is less exhaustive and detailed than the recorded expert interviews, so these additional conversations are marked as 'informal' (i).

For these semi-structured interviews and informal expert discussions, there is made use of an interview guide that represents the key indicators for the institutional logics, sector interactions, and boundary spanners and system entanglers (see *Appendix II – Interview guide*). Noteworthy, however, is that there is a necessary distinction between the respondents who are either involved solely in the e-fuels or maritime sectors or are active at the interface of these two sectors, as previously illustrated in *Figure 2.* This distinction must be made to cope with the partially overlapping multi-system interactions, such as *integration,* as the e-fuels and maritime sectors are closely tied chain-linked sectors. Without considering this, identifying the dominant field logics for the separate e-fuels and maritime sectors would be more complex and less straightforward.

Table 2. Overview of the interview respondents.

Respondent	Respondent type	Work field/expertise
RES1	Intermediary	Maritime & governance
RES2	Company	E-fuels & maritime
RES3	Intermediary	E-fuels, maritime & governance
RES4	Company	Maritime
RES5	Research institute	Maritime
RES6	Company	E-fuels
RES7	Industry/government	Maritime & governance
RES8	Company	Maritime
RES9	Research institute	Maritime, e-fuels & governance
RES10	Company	Maritime
RES11	Company/Research institute	Maritime
RES12	Intermediary	Maritime & governance
RES13	Intermediary	Maritime & governance
RES14	Industry/government	Maritime & governance
RES15	Company	E-fuels
RES16	Industry/government	Maritime & governance
RES17	Company	E-fuels
RES18	Company	E-fuels
RES19	Intermediary	E-fuels & governance
RES19	Company	E-fuels & maritime
RES20	Company	Maritime
RES21	Company	E-fuels
RES22	Company	E-fuels

Table 3. Overview of the informal expert discussion respondents.

Respondent	Respondent type	Work field/expertise
RES23(i)	Intermediary	Maritime, e-fuels & governance
RES25(i)	Company	E-fuels
RES26(i)	Company	E-fuels
RES27(i)	Company	E-fuels
RES28(i)	Company	E-fuels
RES29(i)	Intermediary/government	Maritime, e-fuels & governance
RES30(i)	Company	E-fuels
RES31(i)	Company	E-fuels
RES32(i)	Company	E-fuels
RES33(i)	Industry/government	Maritime & governance

3.4. Data analysis

For analysing the 23 expert interviews and the 10 informal expert discussions, the qualitative analysis software of NVivo is used. Considering these different data sources' differing reliability and viability, they were coded separately. However, both followed *Appendix III – Coding scheme*, which encompasses the key indicators for identifying institutional logics, the multi-system interaction patterns, and boundary spanners and system entanglers. For deriving new insights from qualitative data sources, Bryman (2016) describes several coding processes for analysing qualitative data, such as open coding, axial coding, selective coding, and theoretical coding, which are used in this thesis. This has allowed us to: a) capture the key concepts, themes and patterns in smaller text fragments; b) develop a preliminary theoretical model that highlights the interactions between the coded fragments; c) validate and refine the theoretical model; and d) creating new theoretical insights that could contribute to the multi-system dynamics transition literature. Noteworthy, however, is that these coding phases are not exclusively done consecutively but more simultaneously and iteratively to strengthen the robustness of this analysis.

To examine institutional logics, Reay & Jones (2016) illustrated three methods for identifying and analysing institutional logics, namely: pattern-matching, pattern-deducing and pattern-inducing. Here, pattern-matching and pattern-deducing aim to test hypotheses in practice to validate existing theories (Reay & Jones, 2016). On the contrary, pattern-inducing aims to develop theory and expand existing theories by contributing new findings (Reay & Jones, 2016). For analysing the institutional logics in the e-fuels and maritime sectors, an initial approach of pattern-matching and pattern-deducing is used based on prior works on institutional theory. Therefore, this research adapted the prior works on institutional logics of Fuenfschilling & Truffer (2014), Thornton & Ocasio (2008) and Wesseling et al. (2022), which provided several key categories for identifying institutional logics. The used categories in this thesis from these prior studies include *basis of strategy, efficiency focus, expertise, funding, informal control mechanisms, mission, sector logic, sources of authority, technologies, values*, and *view on business*.

However, as one of the main objectives is to understand the effects of multi-system dynamics better and develop new theoretical insights, pattern-inducing is also a prominent factor in this research. This resulted in alterations to some institutional logics concepts, which are referred to differently in this thesis. For instance, the notion of *structural overlap* as described by Thornton & Ocasio (2008) represents a part of multi-system dynamics or Thornton & Ocasio (2008) highlighting *institutional entrepreneurs* which are here referred to as boundary spanners and system entanglers. In addition, the implications of the institutional alignment of the e-fuels and maritime systems are interpreted by broadening the focus and extrapolating the regime interactions framework defined by Raven & Verbong (2010) concerning a developing niche (i.e. e-fuels). Hence, this approach provides new theoretical insights into the sociological aspects of multi-system dynamics.

Similarly, the analysis of technical interactions of multi-system dynamics also initially follows deductive reasoning by coding along the sector interactions framework described by Andersen & Markard (2020). To extend the existing literature, an inductive approach is added by exploring the nuance of technology interactions seen through different value chain segments. Therefore, this approach improves the technical multi-system dynamics aspect by providing a more extensive overview of technological relationships and interactions.

At last, the role of boundary spanners and system entanglers is evaluated by interpreting their prominence at the interface of the e-fuels and maritime systems concerning the socio-technical interactions. In principle, their activities, such as conducting institutional work to create convergence and divergence between systems as described by van der Vleuten (2019) and Zietsma & Lawrence (2010) are evaluated. Contextualising their focus and efforts in relation to the socio-technical system interaction frameworks described above results in a more comprehensive overview to interpret the implications of their activities concerning multi-system dynamics.

As multi-system dynamics analyses have received sparse attention in the transition studies literature, no conventional research approach exists to assess them (Rosenbloom, 2020). Therefore, this research explores a new approach to analysing multi-system dynamics and their effects on socio-technical transitions. By starting deductively from existing theoretical concepts and hereafter inductively expanding the analysis process, this research follows and abductive research approach as defined by Dubois & Gadde (2002). This allows to validate existing theories while simultaneously extending the field of transition studies by highlighting the potential added value of synthesising such theoretical frameworks. Ultimately, the findings of this research clearly indicate the effects of multi-system dynamics that can help decision-making and policy-making processes stimulate the diffusion of e-fuels in the maritime sector and potentially other related sectors.

3.5. Research quality

Bryman (2016) describes reliability and validity as the most prominent criteria for evaluating research quality. To assure reliability, resembling the repeatability of a study, this thesis highlights the type and expertise of the respondents (see *3.3. Data collection*), the asked questions asked concerning multi-system dynamics (*Appendix II – Interview guide*), and a detailed overview of what indicators for the different theoretical concepts are used during the coding process (*Appendix III – Coding scheme*). These aspects ensure that conducting a similar study would yield comparable results but is subject to deviations considering different respondents.

For addressing validity, a distinction is made between internal and external validity. To assure internal validity, referring to the justification of made claims about causal relationships between concepts, this thesis uses acknowledged transition study literature for measuring concepts during the analyses (i.e. institutional logics, multi-system interactions, and boundary spanners and system entanglers). Building upon established theories and concepts enables the identification of causal relationships and prevents confounding variables, thereby improving the internal validity of the findings.

To address the external validity in this research (i.e. the ability to generalise findings), purposive sampling is used to include a wide variety of relevant stakeholders with a vested interest in e-fuels adoption in the maritime sector and potentially other sectors (see *3.3. Data collection*). This allows the relevant characteristics and experiences to be included in evaluating multi-system dynamics. To a certain extent, the findings of the semi-structured interviews and informal expert discussions are triangulated by reviewing academic literature and policy documents. Consequently, this facilitates a targeted and focused approach that ensures that findings are generalisable in similar contexts.

4. Results

To provide a straightforward narrative on how multi-system dynamics affect the diffusion of e-fuels in the maritime sector, the institutional logics of both the e-fuels and maritime sectors, as well as the alignment of these institutional logics and interaction patterns stemming from this, are described first in *4.1. Institutional logics*. The technology interactions are described using the sector interactions framework in *4.2. Sector interactions*. In *4.3. Boundary spanners and system entanglers*, the role and activities of the most prominent actors at the interface of the e-fuels and maritime systems are discussed. Based on these preceding sections, *4.4. Drivers and barriers* summarises the key factors that affect the diffusion of e-fuels into the maritime system by distinguishing the nature and level of the socio-technical drivers and barriers. At last, *4.5. Policy objectives & measures* contextualises the mentioned policy issues and suggestions by respondents based on the identified socio-technical interaction patterns, forming the basis for the proposed policy recommendations to reinforce the drivers and overcome the barriers.

4.1. Institutional logics

4.1.1. E-fuels sector

While synthetic fuels have been known for decades, their sustainable counterparts made with renewable electricity (i.e. e-fuels) have only gained increasing attention over the previous years. This growing attention for these sustainable fuels stems from the increasing pressures of climate change as they enable sustainable means for various (hard-to-abate) sectors to defossilise. This becomes evident in the steep increase of new publications concerning these types of fuels. Whereas 2010 encompassed approximately 1.800 new publications, in 2015 this grew to roughly 7.100, and in 2022 this number neared almost 20.000 new publications[2]. Considering this increasing interest and relation to numerous up and downstream systems along the value chain, diverse institutional pressures shape the e-fuels niche. As a result, the respondents' insights have led to identifying three prominent field logics in the e-fuels system: *engineering logic*, *business logic*, and *unification logic*. To indicate the core differences and similarities of these field logics, *Table 4* summarises their key components which are further substantiated in the corresponding sub-sections. However, neither of these identified field logics is found to be dominant at the current stage of the e-fuels niche. This may be inherent to the notion of a niche which resembles the infancy and flexibility of a newly emerging system.

Engineering logic

The engineering logic addresses the technical and energetic efficiency-oriented approach among actors within the e-fuels system. While significant defossilisation gains can still be acquired in not hard-to-abate sectors, direct electrification is often preferable before engaging in e-fuel production. To mitigate this effect of reduced e-fuel demand, actors stress the urgency for energy-efficient e-fuel production to enable emission reduction in hard-to-abate sectors. This becomes apparent in the approach of e-fuel actors by striving for efficient e-fuel production plants by developing their projects with state-of-the-art technologies and where the inputs for e-fuels (i.e. renewable electricity, water and bio-genic CO_2) are more easily accessible (RES15; RES17; RES23). As a result, e-fuel production plants are often announced where these input conditions are most viable (e.g. North-Africa, Australia, Scandinavia, Chili).

[2] Based on the findings of Nexis Uni using the search query: "*Electrofuels or e-fuels or eFuels or Power-to-X or Power-to-Liquid or Power-to-Gas or P-t-X or P-t-L or P-t-G or RFNBO or Renewable Fuel of Non-Biological Origin or Recycled Carbon Fuels*"

Table 4. The prominent field logics in the e-fuels sector.

Categories	Engineering logic	Business logic	Unification logic
Basis of strategy	Focus on the most viable technologies and geographical locations for e-fuel production	Improve bankability and reliable e-fuel off-take agreements	Connect with up and downstream sectors, collective approach
Efficiency focus	Energy-efficient e-fuel plants	Reducing e-fuel input costs (i.e. renewable energy, water and bio-genic CO_2)	GHG emission reduction
Expertise	Technical and scientific know-how often originating from oil, gas, energy, and chemical sectors	Economic	Technical and economic
Funding	Angel investors, corporate funding	Angel investors, venture capitalists	Angel investors, venture capitalists
Informal control mechanisms	Professional standards, personal and professional networks	Financial analysts (of shareholders), market signals and competition	Community
Mission	Develop efficient (large) operational e-fuel plants	Cost-effective CO_2 reduction, reduce CAPEX/ OPEX	Cost-effective CO_2 reduction through collective action
Sector logic	Profession-logic, corporate-logic	Market-logic, state-logic	Community-logic, state-logic
Sources of authority	Shareholders, board of directors	Shareholders, board of directors	Shareholders, board of directors
Technologies	Utilising the most energetic and financially attractive technologies	Cost-effective CO_2 reduction technologies	Cost-effective CO_2 reduction technologies
Values	Energetic efficiency	Economic performance	Environmental sustainability, shared responsibility
View on business (strategic orientation)	Long-term	Long-term	Long-term

What defines actors that pursue the engineering logic is that these often originate from the oil, gas, energy or chemical sectors and possess a lot of technical and scientific know-how related to (e-)fuels (RES17). Such actors are either a group of individuals starting a new organisation or are a spin-off from larger corporate organisations of those sectors and primarily form the source of authority (RES23;

RES26(i)). Accordingly, e-fuel actors often find funding from angel investors or corporate funding, guiding them to focus more on developing technological and energetically efficient e-fuel production plants. Besides the development of production plants based on their in-depth knowledge and expertise, such e-fuel actors also fulfil an essential educative role for industry players on how to manage and implement e-fuels, as well as educating policymakers on e-fuel technologies and in what way regulatory frameworks affect their business (RES1; RES2; RES18; RES19; RES22). These examples effectively demonstrate some key characteristics of the ideal-type profession and corporate sector logics.

Business logic

As for the business logic, this relates to the emphasis on the market mechanisms defined by the e-fuels system actors. One of the main concerns of the e-fuels niche is the supply and demand agreements. Considering the high capital expenditures (CAPEX) for developing and building e-fuel plants and relatively high operational expenditures (OPEX), the e-fuel actors often indicated the importance of arranging long-term off-take agreements to minimise their financial risks (RES3; RES15; RES17). However, e-fuels are still more expensive than conventional fossil fuels, and this often makes it difficult to arrange such long-term off-take agreements because it is uncertain if and when the prices of e-fuels will be somewhat similar to fossil fuels. Therefore, one of their priorities is to decrease the CAPEX and OPEX of the e-fuel plants by developing more standardised and scalable designs to benefit from economies of scale to make them more bankable (RES15; RES17). Like the engineering logic, e-fuel actors pursuing the business logic also stressed the importance of e-fuel production inputs but approached this from a more financial standpoint instead of energy efficiency. For instance, the war in Ukraine has negatively affected electricity prices which caused more rivalry between the e-fuel and other sectors for renewable electricity, resulting in an even higher price for e-fuels as renewable electricity may account for 40% of the e-fuel production costs in some cases (RES15; RES16; RES17; RES21).

On the contrary, the Inflation Reduction Act (IRA) in the United States (US) significantly brings down the production costs of e-fuels through subsidies and provides a massive boost to the e-fuels sector in the US (RES3; RES15; RES22). Consequently, many European e-fuel actors are moving towards the US as it is financially more attractive (RES3). These examples highlight some of the key characteristics of the ideal-type market sector logic and give the understanding that actors highly value economic performance and cost-effectiveness.

Besides the financial aspects driving the business logic, the ideal-type state-logic is a prominent aspect. The market-logic and state-logic are inherently related as the goals and practices originating from the state-logic can directly affect those resembled in the market-logic. This is resembled by e-fuels actors indicating that formulating an appropriate regulatory framework and the coercive pressures stemming from it defines how their operational processes are arranged. For instance, subsidising e-fuels or penalising fossil fuels may be required to make e-fuels more competitive as it is currently not a level playing field (RES6; RES16; RES33(i)). Moreover, while (sub-)quotas or mandates for demand-side sectors can mitigate some of these market failures, the current implemented and proposed policies are often non-binding or non-exhaustive (RES1; RES3; RES12; RES13; RES19). This conveys the idea that the state-logic infuses some of the institutional values within the e-fuels sector as e-fuel actors stressing the importance of the government facilitating the necessary regulatory framework. Without appropriate policy measures, e-fuel actors are restricted, which impedes the overall development of the e-fuels sector.

Unification logic

The unification logic is based on the ideal-type community- and state- sector logics and emphasises the importance of collective efforts and governmental guidance towards broader societal goals. Considering the embeddedness of the e-fuels sector between the upstream value chain sectors of renewable electricity and feedstock molecule sectors and various downstream user sectors, as illustrated in *Figure 2*, multiple respondents mentioned the importance of aligning the values and shared objectives (RES1; RES6; RES9; RES19; RES29(i)). We see this unification logic in the case of e-fuel actors participating in joint ventures with upstream sectors such as solar- and (offshore) wind park developers (RES17; RES27(i); RES30(i); RES32(i)), e-fuel actors directly engaging in making partnerships with downstream user sectors such as the steel, refinery, and chemical industries (RES22; RES23; RES30(i)), or e-fuel actors closely working together in end-to-end initiatives with both up and downstream sectors (RES6; RES15; RES29(i)). As a result, the respondents often described their intrinsic motivation and organisational purpose to pursue shared climate responsibility, leading them to engage in such collective efforts.

Despite the community mindset, inadequate policy measures often impede the collaboration processes. Where actors try to set-up cooperatives, ambiguous policies create uncertainty among sectors along the value chain which slow down project developments. For example, this becomes evident in the case of lacking policy regulations on the safety aspects of e-fuels and their use in various sectors (RES1; RES2; RES3; RES9; RES19), as well as the ambiguity regarding the green certification label of e-fuels (RES1; RES3; RES6). As a result, e-fuel actors also stress the urgency to implement a regulatory framework that reduces such uncertainties to facilitate the development of the e-fuels sector.

4.1.2. Maritime sector

In the maritime sector, three prominent field logics have been identified: *capitalist logic*, *secure logic*, and *sustainability logic*. Some of the key characteristics of each field logic are summarised in *Table 5*, primarily based on the findings of the semi-structured interviews and informal expert discussions. Where the capitalist logic has been dominant for decades, the secure- and sustainability logic has gained increased attention over the previous years with the increasing pressures of climate change and the need for sustainable shipping. Concerning these different field logics, the larger maritime organisations primarily tend towards the capitalist logic and only recently acknowledged the sustainability logic. In the value chain's smaller to medium-sized market segments, there is still a substantial emphasis on the capitalist logic, but the secure logic also plays a more prominent role here.

Capitalist logic

The maritime sector primarily builds on the corporate- and family- sector logics. In principle, most maritime organisations find their existence based on family-like business structures (RES4; RES10; RES11). In smaller maritime organisations, employees often spend decades, if not their lifetime, in the maritime sector or the same business, thereby sustaining previous generations' sedimented habits (RES2; RES8; RES10). However, maritime organisations have grown into larger corporate businesses in the medium to larger market segments, but the family members are often still heavily involved in the strategy and decision-making processes (RES4; RES11). Stemming from these family-like influences, maritime organisations develop close relationships with a few actors in their environment and highly value loyalty and trust (RES5; RES10).

As the maritime sector grew to one of the critical industries that now form the backbone of global trade and the world economy, so did the emphasis on staying competitive in the market by decreasing freight transportation costs. This defines some of the key principles of the corporate sector logic whereby organisations focus more on efficiency improvement, increasing the profitability of the operational processes, and evading risks and uncertainty. As a result, the maritime sector has been known for its low willingness to pay higher fuel prices and has, therefore, been operating based on the cheapest and dirtiest heavy (fossil) fuels (RES4). Considering the availability of fossil fuels in contrast with e-fuels, this provides no incentives for maritime actors to pursue as this invokes significant risks for the reliability of their operations (RES4; RES9; RES12; RES14; RES21). Consequently, most of the maritime sector does not engage with using e-fuels and initially focuses on incremental innovations for energy and fuel-saving measures to reduce GHG emissions for compliance with the increasingly more stringent regulations (RES9; RES10). By implementing such energy-saving measures first, however, fuel consumption may be decreased 10-20%, reducing the enormous volumes for maritime and lowering the adoption barrier for e-fuels considering the current limited availability of e-fuels (RES5; RES10; RES11).

Table 5. The prominent field logics in the maritime sector.

Categories	Capitalist logic	Secure logic	Sustainability logic
Basis of strategy	Maintain or improve market share, increase profit margins, reduce risks	Arranging reliable offtake agreements, using safe fuels & equipment	Reduce CO_2 emissions, comply with regulations, collaboration
Efficiency focus	Finding the cheapest mode of freight transportation which has been done for generations (often incremental innovations)	Economic efficiency, technical applicability	(Cost-)efficient CO_2 reduction
Expertise	Technical and economic experience	Technical and economic experience	Technical experience
Funding	Organisational capital	Organisational capital	Organisational capital, shareholders, angel investors, venture capitalists
Informal control mechanisms	Corporate- and family-rooted business structure	Consumer demands, corporate business standards	Community & societal pressures
Mission	Short-term economic profits	Protect organisational standards	Cost-effective CO_2 reduction
Sector logic	Corporate-logic, family-logic	Market-logic, profession-logic, state-logic	Community-logic, state-logic, corporate-logic
Sources of authority	Board of directors, family shareholders	Board of directors	Sustainable-minded board of directors and shareholders
Technologies	Cost-effective technological improvements	Validated and reliable technologies	Cost-effective CO_2 reduction measures
Values	Economic performance, loyalty and trust	Sustaining the business	Environmental sustainability
View on business (strategic orientation)	Short-term fuel contracts, long-term ship design	Short-term fuel contracts, long-term ship design	Long-term

In addition to the low e-fuel availability, the maritime actors indicated that implementing e-fuels is a radical innovation for their businesses. The technology and integration drastically differ from their existing operational processes, creating high uncertainty and risks for the maritime actors. For instance, the implementation of e-fuels would require changes in ship design, engines and propulsion systems, the education of staff on how to manage e-fuels, new certification and regulations, and uncertainty about (longer-term) e-fuel prices and which e-fuel will be superior (RES5; RES9; RES10; RES20; RES24(i)). Considering the long lifespan of ships of several decades, the investments must be made cautiously and would require state-of-the-art ship designs for new-build ships to prevent unforeseen investment and operational losses in the long run (RES5; RES8; RES9). Hence, the CAPEX for e-fuel ships can be 2-3 times higher than conventional fossil fuel ships, but it eventually depends on the OPEX of ships, which determines if it is a viable investment for maritime actors to pursue e-fuels (RES5; RES9). In this regard, the short-distance shipping segments of the maritime sector (e.g. ferries, inland) are more eligible to adopt e-fuels as the end-consumer is more directly involved and the scale and demanded volumes of e-fuels are substantially smaller than deep-sea. Here, the formation of collaborations of maritime actors may benefit the maritime sector as it helps to reduce the CAPEX and OPEX of e-fuel ships, but the collaborations often get aborted as it progresses as it forms increasingly more risks of losing the competitive advantages of the involved maritime organisations (RES5; RES8; RES12). For example, whereas the automotive industry may acquire their return on investment for developing a specific car model through mass production, the investment costs for developing a new ship may only be retrieved from one or a few ships (RES5). Providing other maritime organisations (i.e. competitors) with in-depth knowledge of efficient and e-fuel-compatible ship designs can pose significant threats to your organisational existence (RES5). As a result, the progress in e-fuel-compatible ships and their application remains marginal.

However, there is one type of maritime actor that does take some first steps for employing e-fuels: the largest maritime organisations. These actors integrate the accumulating e-fuel production into their portfolio and create e-fuel-compatible ships. The main reasons to invest in e-fuels for these larger organisations are to preserve and increase their market share, gain a competitive advantage and prevent the reliability of other actors (RES1; RES5; RES11; RES15). Whereas the smaller maritime organisations do not have the (financial) resources to engage in e-fuels, the larger maritime organisations see this as an opportunity to exploit and gain the experience and knowledge of e-fuels into their assets. In addition, the largest maritime organisations can more easily cope with the high investment costs than smaller maritime organisations by spreading it over a more extensive fleet. Despite the investments being made by such actors for these, more often, long-distance trips, these large maritime actors face tremendous challenges in acquiring sufficient e-fuels on an international scale in contrast with the more short-distance shipping market segments. Nevertheless, this mindset of being competitive and staying ahead of the market resembles the corporate-sector logic present in this market segment of the maritime sector.

Secure logic

The secure field logic emphasises the market-logic, profession-logic and state-logic. This becomes evident out of the emphasis of maritime actors on the market forces, organisational standards and regulations that determine the preference and use of fuels in the maritime sector. For example, the downstream supply and demand interactions between the consumer market and the maritime sector along the value chain force maritime actors to pursue the cheapest and fastest mode of freight transportation (RES5; RES21). Consequently, the maritime sector must focus on economic efficiency by reducing their prices and delivery times to remain competitive. Here, the consumers often do not want to pay the higher green premium prices for sustainable fuels such as biofuels and e-fuels (RES15; RES21). As a result, the maritime sector is run on paper-thin margins, leaving minimal flexibility and incentives to adopt e-fuels into their businesses.

In addition, the maritime sector also emphasises the importance of upstream demand and supply mechanisms (i.e. fuel supply) which significantly affect their daily operations. This became apparent when the maritime actors highlighted the lacking e-fuel availability, which can be either insufficient for the bulk volumes of ships or the absence of e-fuels at different bunkering locations (RES12; RES14; RES16; RES33(i)). Considering the international nature of the maritime sector, the maritime actors see the limited widespread availability of e-fuels on the market in different geographical regions as a restraining factor. For maritime actors, the availability of fuels is critical for their operational processes, which is why currently, fossil fuels are preferred as conventional diesel internationally available for bunkering. Even when e-fuels become more widely available, some maritime actors anticipate not being first in line for acquiring e-fuels in comparison with other e-fuel demanding sectors such as steel, cement, chemicals or fertilisers which are deemed to have more financial flexibility when compared to the maritime sector which is bound by strong consumer forces to reduce shipping costs (RES3; RES12; RES21). For these reasons, maritime actors are hesitant to adopt e-fuels as the e-fuel suppliers cannot guarantee the international supply of some e-fuels and their availability for the maritime sector.

Even within the maritime sector, the maritime actors describe the supply and demand forces that affect the different market segments of the maritime industry. Consisting of numerous market segments (e.g. deep-sea, short-sea, feeder services, inland, et cetera), the maritime sector could be fragmented, whereby each market segment has unique properties and requirements (RES5; RES9; RES12). Concerning the demand and supply for e-fuels, a lot of smaller market segments are concerned they cannot adopt e-fuels before 2030-2040 as the first large proportions that do go to the maritime sector will be secured by the larger maritime organisations (RES13; RES21). These examples of internal supply and demand forces within the maritime sector and the up and downstream value chain relationships highlight some critical characteristics rooted in the market sector logic.

Besides the market forces that maritime actors specify as one of the important reasons for maritime fuel preference, maritime actors also mentioned professional standards and expertise as other essential components. Building on the consumer demands for cheap and fast freight transportation, the maritime actors emphasise the practicality of fuels, enabling them to meet customer needs. When considering e-fuels, for example, additional complications emerge, such as the requirement for more bunkering stops or reduction in cargo capacity since e-fuels have a lower volumetric energy density than conventional diesel (RES2; RES7; RES9; RES10; RES13; RES16; RES24(i)). Moreover, the safety standards and methods to handle the e-fuels induces additional challenges for the maritime sector (e.g. the toxicity of e-ammonia). Consequently, these maritime actors emphasised the relevance of convenient fuels for their operational processes.

Related to the practicality of fuels in the maritime sector, the maritime actors stress the urgency of developing a proper regulatory framework. This means that policymakers must define the guidelines that are currently not in place but deemed necessary to facilitate e-fuels diffusion into the maritime sector. This is best illustrated by the maritime actors, which point out the uncertainties on how e-fuel emissions are evaluated and calculated (i.e. well-to-tank or well-to-wake emissions) and the undeveloped safety guidelines for in both harbours and on the ships (RES1; RES7; RES12; RES14; RES19). Whereas some of these guidelines are in development at the global IMO level, the development and adoption of such policies are slow (RES1). In addition to the absence of maritime actors' requested global IMO regulations, they also indicate current flaws in existing policies. For example, the European Union Emission Trading System (EU ETS) only accounts for ships with a gross tonnage (GT) of 5000 and above. While such regulations provide some restrictions to the larger maritime segments, these policy measures are non-exhaustive as the smaller maritime segments are not obliged to comply with the regulations to make their fleet more sustainable (RES3; RES9; RES12; RES13). This conveys the idea that maritime actors emphasise the vital role of the government as inadequate policy measures currently bind them.

Sustainability logic

With the increasing pressures of climate change, recent developments in the maritime sector have caused an uprising in the attention to sustainability measures for shipping. This has created the effects of more maritime actors pursuing energy consumption and GHG emission reduction technologies. This becomes evident in the deployment of scrubbers to filter the exhaust gasses of heavy fuel engines, air lubrication to reduce drag, slow steaming, and the pursuit of sustainable fuels (RES9; RES10; RES12; RES14). Similar to the secure logic, the sustainability logic also emphasises the governance's relevance but is specifically related to compliance with (international) climate regulations. Consequently, most of these progressive steps towards sustainable shipping originate from societal pressures, more stringent regulations, and the increasing awareness of the pollution that the maritime sector causes, which have led to the development of an intrinsic motivation among some maritime actors to reduce GHG emissions (RES7; RES8; RES11; RES14; RES16). This demonstrates some of the characteristics and motives behind the maritime sector's newly emerging sustainability field logic.

Despite the increasing deployment and inquiry of such technologies, this is only a relatively recent development in the maritime sector. To illustrate this, specific sustainability departments have only been introduced in the recent 5-10 years in most maritime organisations (RES4; RES11; RES21). Considering the influences of the more dominant capitalist and secure field logics, the objectives for achieving emission reductions must be cost-effective and compliant with the regulations in place. One clear distinction with the capitalist field logic, however, is that the sustainability field logic emphasises the importance of collective effort and collaboration in becoming more sustainable, which contrasts with the capitalist field logic that evades cooperation to minimise risks on their competitive advantage. While such collaborations are increasingly emerging, such as the creation of green corridors, the progressions can be quite slow as most maritime actors are still quite conservative and deterring radical innovations such as e-fuels (RES4; RES11). This conveys the idea that with the growing sustainability logic within the maritime sector, institutional interference with existing practices will likely intensify over the following years.

4.1.3. Institutional alignment

According to the overviews of the institutional logics of the e-fuel and maritime sectors, the institutional alignment could be derived. While the categories for institutional logics can be found, it has to be acknowledged that the ideal-type logics are analytical concepts and may not be observed in its purity in the real world (Kieft et al., 2020; Thornton & Ocasio, 2008). This leaves some room for discrepancies whereby slight deviations may occur concerning the ideal-types. Moreover, while the institutional logics approach is predominantly used for indicating the dominant field logics for socio-technical regimes in more mature socio-technical systems, it is more challenging to utilise for a niche such as e-fuels which is highly volatile and less consolidated. This becomes apparent from the influences the e-fuels sector encounters from all up and downstream sectors along the value chain (e.g. renewable electricity, maritime, steel, fertiliser), which have all different interests and accompanying institutional logics. Considering these factors, the identified field logics of the e-fuels sector share some similarities, making the distinction between them less clear-cut. As a result, the institutional context of the e-fuels sector is a mixture of several coexisting field logics whereby no single field logic is dominant (yet). Consequently, technical engineering, profitability and cooperation seem equally important at this early stage for developing the e-fuels sector.

However, in the maritime sector, the dominance of the field logics was more well-defined. In the maritime sector, the capitalist field logic is the most dominant as there is a clear emphasis on finding the cheapest freight transportation mode and increasing its paper-thin profit margins. Over the previous decades, market forces have guided the maritime sector to be highly competitive and improve economic performance (Hoffman & Kumar, 2013). In addition, the focus of the secure logic on the effects of market forces and organisational expertise has led to the self-centred ideology of maritime organisations. As a result, maritime actors are often unwilling to delve into joined cooperatives to achieve goals beyond their own business's benefits, such as enabling the maritime sector to become sustainable (i.e. their competitors). This has led to the short-term focus on the maritime sector and neglecting long-term objectives. Despite the growing awareness and urgency among the maritime actors for diverting to sustainable fuels, the financial component and availability of fuels remain some of the critical factors impeding the diffusion of e-fuels into the maritime sector.

The institutional logics of the e-fuels and maritime sectors are partially aligned in some aspects. To provide a concise overview of the key differences and similarities between the institutional logics of the e-fuels and maritime sectors, *Table 6* synthesises the field logics for these two focal sectors. Note that this overview comprises the most prominent institutions based on the varying degrees of dominance of each respective sector's different field logics as far as possible. Some aligned aspects of the e-fuels and maritime sectors are the overlapping corporate-logic, market-logic, profession-logic and state-logic. For instance, the e-fuels and maritime sectors search for efficient and cost-effective enterprises, emphasise the importance of market forces, and indicate the importance of coordinated regulations at an international level, such as an EU level but preferably at the global IMO level. These aspects primarily resemble the engineering and business field logics of the e-fuels sector and the maritime sector's two prominent capitalist and secure field logics. The alignment of such logics allows for a smoother collaboration between these two focal sectors.

Despite these institutional overlaps, there are also some clear differences noticeable. For example, e-fuel actors often describe the importance of creating more long-term and dedicated relationships among all actors along the value chain. This more long-term and integral approach reduces the risks for the e-fuels actors and is primarily characterised by its respective business and unification field logics. Contrarily, the maritime actors primarily have a short-term oriented approach which causes misalignment between the e-fuels and maritime systems. This difference is best illustrated by the maritime actors, which find difficulties in engaging in long-term fuel contracts and obligations as their current fuel contracts are based on terms of roughly three months at maximum, which is in contrast to the preferred ten or more year contracts of e-fuel suppliers that require long-term contracts to minimise their risk on investment (RES17). Considering the uncertainty about changing fuel prices and e-fuel availability, the maritime sector is not used to making long-term fuel offtake arrangements as this opposes the prominent capitalist and secure field logics.

Table 6. Synthesis of the institutional field logics of the e-fuels and maritime sectors.

Categories	E-fuels sector (engineering, business, unification field logics)	Maritime sector (capitalist, secure, sustainability field logics)
Basis of strategy	Create energy-efficient and cost-efficient e-fuel plants, connect with up and downstream sectors	Reduce transport costs, cost-effective (sustainable) innovations, mitigate organisational risks
Efficiency focus	Improve bankability for scaling-up e-fuel plants to reduce GHG emissions	Increase short-term profit margins, maintain or improve market share
Expertise	Economic experience, technical experience from oil, gas, energy, and chemical sectors	Technical and economic experience
Funding	Angel investors, venture capitalists, corporate funding	Organisational capital
Informal control mechanisms	Professional standards, community, financial analysts (of shareholders)	Corporate- and family-rooted business structure, consumer demands, business standards, financial analysts
Mission	Cost-effective GHG emission reduction of industries	Short-term economic profits
Sector logic*	++market / ++state / ++ profession / +community / +corporate	++corporate / ++market / +profession / +state / +family
Sources of authority	Shareholders, board of directors	Board of directors
Technologies	Cost-effective and energy-efficient CO_2 reduction technologies	Cost-effective and certified technologies
Values	Environmental sustainability, economic performance, shared responsibility, energetic efficiency	Economic performance
View on business (strategic orientation)	Long-term	Short-term fuel contracts, long-term ship design

**More '+' signs indicate the higher prominence of a certain sector logic*

In addition to the different views on business, the e-fuels sector focuses more on collaborative efforts and approaching challenges together. This difference is indicated by the presence of the community sector logic in the e-fuels sector and its absence in the maritime sector. While it partly exists in the sustainability field logic of the maritime sector, this is still negligible considering the dominance of the corporate sector logic. For example, actors of the e-fuels sector emphasise the importance of forming partnerships which help them to proceed as this provides technical (i.e. seeing what is appliable in consumer sectors) and economical (i.e. providing them more certainty by arranging off-take agreements) support. However, The maritime sector is more individualistic and unwilling to risk its competitive advantage by sharing its knowledge and expertise with others.

Moreover, whereas e-fuel actors perceive financial pressures and obligations from their investors and shareholders, maritime actors endure the pressures of consumer demands and financial analysts. This results in a difference in efficiency focus as the e-fuels sector aims for bankable and scalable e-fuel production plants, and the maritime sector focuses on increasing short-term profits and sustaining or improving their market share.

4.1.4. Socio-technical system interactions

Considering the competition, symbiosis, integration and spill-over interaction patterns described by Raven & Verbong (2010), several socio-technical interactions concerning the e-fuels and maritime sectors have been noticed and are further specified in the following subsections.

Competition

The maritime sector endures several pressures that discourage the use of fossil fuels. These socio-technical interactions enable the e-fuels system to become more competitive with the fossil fuels system in fulfilling the role of bunkering ships. Such tensions become evident in various ways. Firstly, stricter environmental policy regulations and emission targets induce regulatory pressures on the maritime sector to adopt sustainable fuels such as e-fuels (RES1; RES19). Secondly, the increasing public awareness of the environmental impact of polluting ships exerts pressure on maritime actors to divert from fossil fuels (RES16). Lastly, the growing demand for sustainable shipping practices by environmentally conscious consumers and organisations stimulates the use of e-fuels (RES21). As a result of these different socio-technical pressures, the increasing awareness and directionality towards e-fuels form clear drivers for the diffusion of e-fuels into the maritime sector.

Nevertheless, the mismatch between the institutional logics of the e-fuels and maritime systems induces competing system interactions. These institutional tensions reside in the differences in long-term and short-term views on business or the different stances toward collaborations by the e-fuels and maritime actors. For instance, whereas the maritime actors are accustomed to short-term fuel contracts, this fundamentally differs from the e-fuel actors' perception by striving for long-term fuel offtake agreements (RES3; RES14; RES15; RES17; RES21). In addition, maritime actors prefer low-cost fuels and are unwilling to, or sometimes cannot, pay higher green premium prices for e-fuels (RES9; RES15; RES21). Concerning the stance towards collaborative efforts, maritime organisations are more individualistic and less willing to share intellectual property rights with other parties as it poses risks to their competitive advantage (RES4; RES5; RES8). This more self-centred approach of the maritime system opposes the openness of e-fuels actors, which are more inclined to collaborate and emphasise the importance of collective action to achieve common objectives. Consequently, these institutional differences form clear barriers to the diffusion of e-fuels into the maritime sector.

Symbiosis

Considering the embeddedness of the e-fuels system and the requirement for expensive inputs with energy-inefficient processes, the e-fuels system is subject to high risks and potential governance failures. Mitigating these issues requires collective efforts and investments by the stakeholders along the up and downstream segments of the value chain. This leads to e-fuels actors striving for more symbiotic relationships between different systems as mutual benefits can be acquired. In some form, these symbiotic relationships between the e-fuels and maritime systems are being built as both sectors try to create green corridors to enable the diffusion of e-fuels into the maritime sector (RES1; RES8; RES9; RES11; RES13). Such integral approaches form synergies for both the e-fuels and maritime systems as the demand for e-fuels by the maritime sector stimulates investments in research, development and infrastructure creation of e-fuels (RES5; RES9; RES11). In addition, the maritime sector may also encounter symbiotic interactions with similar sectors, such as the aviation sector. Both hard-to-abate sectors are highly driven by cost-efficiency and comprise extremely competitive environments (RES3). While being some of the most promising sectors for e-fuel applications, cooperation between the maritime and aviation sectors can result in shared benefits by aligning the interests of the involved respective systems. Accordingly, such symbiotic interactions drive the diffusion process of e-fuels into the maritime sector.

Nevertheless, numerous socio-technical barriers also inhibit the adoption of e-fuels. Considering the unwillingness of maritime actors to pay higher green premium prices for e-fuels, this restricts the benefits of symbiotic relationships that may result in achieving mutual benefits, such as emission reductions and the creation of e-fuels infrastructure (i.e. production, distribution, and storage). Without regulations and mandates on e-fuel use, maritime actors will continue the wait-and-see approach (RES1). Vice versa, e-fuel actors will not supply the maritime sector without supply mandates because it is less cost-effective, as other sectors may be more likely to pay more for e-fuels (RES1; RES17). In addition to mandates, inadequate policy standards and certification processes for e-fuels in the maritime sector lead to uncertainty and potential market fragmentation (RES2; RES9; RES12). Without clear definitions of how e-fuels are regulated, maritime actors are hesitant to introduce e-fuels into their vessels as this forms unnecessary risks for their organisations (see secure logic). At last, different commercial interests and priorities in sustainable development cause tensions between e-fuels and maritime actors (RES5; RES11; RES15; RES26(i); RES29(i)). The differences between the e-fuels and maritime actors become apparent in the views on e-fuel pricing or perceived urgency to meet climate agreements. These examples of socio-technical differences between the e-fuels and maritime systems prevent symbiosis.

Integration

An interesting new dynamic is emerging to overcome some barriers to e-fuel adoption and bridge the institutional differences between the e-fuels and maritime sectors. Whereas the conventional bunkering of fossil fuels for ships is arranged through fuel brokers, the large multi-national maritime corporations are integrating e-fuel practices within their assets (RES11; RES15). By funding research & development and accumulating the competencies related to e-fuels production and management, the e-fuels and maritime systems are becoming more intertwined. This approach can be explained with the defined capitalist and secure field logics of the maritime sector as this resembles mitigating the uncertainty and risks related to high e-fuel prices, offtake agreements and reliability of e-fuel supply. Unifying such organisations can streamline operations and promote e-fuel diffusion into the maritime sector (RES16; RES33(i)). Consequently, this integration dynamic forms an essential driver of e-fuels diffusion into the maritime sector and conveys that the institutions of the e-fuels and maritime systems are slowly becoming more aligned.

However, it must be acknowledged that such organisations' mergers and close connectivity can often be a challenging and prolonged process. For example, limited knowledge and experience in handling or using e-fuels within the maritime sector may pose challenges during integration (RES10; RES18; RES22). Moreover, the maritime actors' perceived safety risks and limited understanding of e-fuel technologies (e.g. toxicity, risk of leaks, required e-fuel inputs, et cetera) restricts e-fuel integration to the maritime sector (RES1; RES2; RES20; RES21). This results in resistance to adopting e-fuels as maritime organisations are concerned about compatibility and reliability issues (RES5; RES8; RES11). Similarly, e-fuel actors are not always confident about how e-fuels can be handled on ships (RES17; RES22; RES33(i)). In addition, integrating e-fuel and maritime systems can be challenging to coordinate, stemming from the different organisational structures, logistics or infrastructural requirements related to each respective system (RES14; RES15; RES16; RES22; RES33(i)). For example, maritime business models' consolidated principles might not easily adapt to novel practices stemming from the e-fuels niche (RES15). Therefore, these examples illustrate several socio-technical barriers impeding e-fuels diffusion into the maritime sector related to the integration dynamic.

Spill-over

Considering spill-over effects, a multitude of socio-technical interactions are prevalent. First, advancements in the e-fuels sector and the facilitation of knowledge exchange can potentially drive innovation in the maritime sector. For instance, innovations related to e-fuels management can help maritime sectors to envisage e-fuels use and learn about the potential implications for the maritime sector (RES2; RES8; RES11). For this reason, e-fuel actors are fulfilling an educative role to convey the potential of e-fuels within the maritime sector as it progresses maritime development and opens up new markets for the e-fuels niche (RES15; RES17; RES22). In addition, maritime actors also continuously look at related industries, such as automotive, which helps them refine their operational processes and equipment (RES5; RES11). Hence, related industry developments can help mitigate the adoption barriers for e-fuels in the maritime sector.

Despite these positive spill-over effects, it has to be acknowledged that institutional differences are likely to remain or might even intensify. The e-fuels sector has many ties to (potential) up and downstream sectors and endures different institutional pressures. For instance, the e-fuels sector comprises institutions from the oil, gas, energy and chemical sectors (RES3; RES17; RES27(i)). Consequently, the logics stemming from these systems can differ from the maritime system's institutions. Moreover, previously unrelated sectors to the maritime sector, such as timber, agriculture and construction sectors, suddenly become part of the same value chain by sharing similar interests to the e-fuels sector. Differences in institutions of such systems become evident in the cases of the agricultural sector, which is more progressive and willing to engage with e-fuels when compared to the rather conservative and withholding maritime sector (RES17) or the perceivably less cost-efficiency-driven sectors such as the chemical, steel or refinery industries (RES3; RES12; RES21). Accordingly, spill-over effects to the e-fuels sector from other end-user sectors with differing institutions than the maritime sector can result in continuous institutional misalignments between the e-fuels and maritime sectors.

Besides the spill-over effects from other systems with vested interests in the e-fuels niche, the spill-over interactions between the e-fuels and maritime systems can also be restricted based on the different natures of these systems. This is best illustrated by the conservativeness of the maritime sector, which inhibits knowledge transfer and, thereby, the adoption of innovations such as e-fuels (RES4; RES9; RES15; RES17; RES20; RES22). As a result, this impedes the institutional alignment of these two systems, thereby forming barriers to e-fuel diffusion.

4.2. Sector interactions

4.2.1. Intra-sector interactions

Intra-sector technology interactions were noticed on different levels of the e-fuels value chain. At the beginning of the e-fuels value-chain, for example, intra-sector interactions appear between the different biomass sectors as the relevance of these sectors increases with the emergence of the e-fuels sector. This becomes evident when the timber sector notices the increasing value of their organic (waste) products, enabling them to leverage higher costs for their source of bio-genic CO_2 (RES15). Such sectors are aware of the problematic situation the e-fuels and maritime sectors are in now as they struggle to acquire sufficient (bio-genic) CO_2 to produce their carbon-based e-fuels (RES21). For instance, CO_2 acquisition technologies besides biomass gasification are still inadequately developed or highly inefficient such as CCUS technologies at incineration and powerplants, only able to extract CO_2 from the exhaust gasses that only contain low CO_2 concentrations between 10-15% (RES16), or DAC which has even a 2-4 times lower efficiency than such CCUS which makes them nonsensical (RES16; Ababneh & Hameed, 2022).

Moreover, obtaining CO_2 from flue gases originating from fossil fuels is only permitted till 2035, whereafter such sources of CO_2 may not be considered for making e-fuels (RES1; European Parliament, 2003, Annex I of Directive 2003/87/EC; Gas Infrastructure Europe, 2022). Considering the current situation, however, it has to be acknowledged that competition between these technologies is marginal. As carbon source technologies are increasingly requested, investments in even the lesser efficient technologies, such as DAC, are still being made (RES3). This conveys the idea that the current situation facilitates the coexistence of these different technologies.

A pattern similar to the carbon-acquiring technologies is noticeable for electrolyser technologies. With the exceptionally high demand for green hydrogen, which could be used directly in various sectors as well as its function as one of the primary inputs for carbon-based and nitrogen-based e-fuels, PEM and SOEC electrolysers are already sold out for the following years 1-5 years (RES22; RES28(i)). AEM electrolysers, however, are less requested considering their lower compatibility with renewables' intermittency, which provides an impulse for more technological innovations of this electrolyser type (RES28(i); Schmidt et al., 2017). Despite the advocacy and preference for both PEM and SOEC electrolysers, these technologies do not encounter competing technology interactions as both are currently highly demanded to meet the requested volumes of green hydrogen, thereby facilitating the coexistence of such technologies.

However, there are noticeable complementary and competing interactions at the level of the different e-fuels. This becomes evident as there are competing interactions between e-fuels and battery technologies in different sectors. In the transportation sector, for example, battery electric vehicles (BEVs) and internal combustion engine (ICE) vehicles driven by e-fuels can be used in road transportation. For this reason, the German car industry lobbied to prevent the complete EU ban on ICE engines (RES3; RES31(i); Ravi et al., 2023). Despite e-fuels being less efficient and less preferable in road transportation than BEVs (Brynolf et al., 2022), the German car industry only accepted the ICE ban on the condition that new ICE vehicles may still be sold if they run on carbon-neutral fuels such as e-fuels (Ravi et al., 2023). Such lobbying initiatives indicate the strategies of incumbent regimes that try to maintain competition between technologies on an intra-sector level. More related to the case of the maritime sector as the focal no-regret sector of this research, battery technologies may also be competing with e-fuels. Despite the reach of battery-powered ships being less when compared to e-fuels, battery-powered ships show potential in inland or short-sea shipping as it does not cause any forms of emissions and can be safer as it does not involve toxic fuels or has the risk of fuel spillage (RES7; RES13; RES21).

Besides these competing interactions between e-fuels and battery technologies, the different types of biofuels may also be complementary and competing. Considering the exceeding demand for sustainable fuels for the maritime in contrast to the fuel availability, earlier generations of biofuels and the carbon-based, nitrogen-based, and hydrogen-based e-fuels can all be perceived as complementary technologies in the sense that combined they can help to overcome the associated barrier of lacking sustainable fuel supply. Contrarily, this also forms additional uncertainty and hurdles for the e-fuels sector stemming from the different engine types and their fuel-specificity. This issue becomes evident from the competition between these different types of fuels based on their very different characteristics, such as safety, toxicity, applicability, volumes, efficiency, prices, et cetera (RES21; RES24(i); Solakivi et al., 2022). As a result, there will be a broad fuel mix within the maritime sector for the following decades, whereby different e-fuels will dominate over different timeframes. To illustrate what the changing fuel mix within the maritime sector may look like, *Figure 5* depicts an estimated prevalence of each fuel type over time.

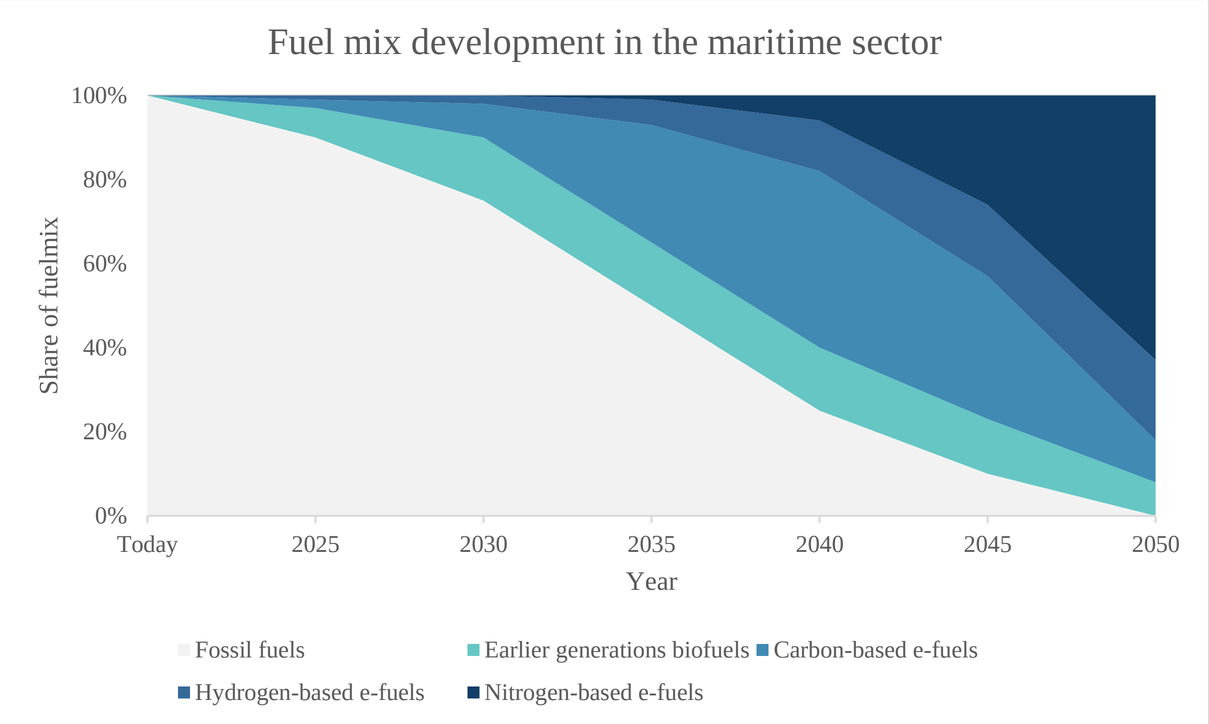

Figure 5. Projection of the potential fuel mix development in the maritime sector.

In the short-term (today-2030), earlier generations of biofuels will be preferred as these are direct drop-in fuels and are more compatible with the existing infrastructure in contrast with the limited drop-in availability of some e-fuels such as e-methanol (RES4; RES21; Solakivi et al., 2022). Hence, the earlier generations of biofuels are implemented more easily over the following years, but the required biomass volumes for these fuels are insufficient and require the addition of other sustainable fuels for the maritime sector (RES21). In the medium-term (2030-2040), carbon-based e-fuels are expected to become more prevalent and dominant as the technology for carbon-based e-fuels is ready but mainly requires sufficient carbon availability to enable a scalable production process. With the increasing orders for carbon-based e-fuel(-ready) ships such as e-methanol and e-LNG by numerous actors within the maritime sector (RES1; RES11; RES14; RES16; RES21), the share of these fuels in the maritime fuel mix is likely to increase. In the long-term (2040-onward), the share of nitrogen-based e-fuels is estimated to become more dominant. The reason for this is that these fuels, such as e-ammonia, are cheaper and more efficient to produce, do not have the complications of carbon requirements and emissions, but are challenged by the insufficiently developed technologies for their use and toxicity risks (RES2; RES21; RES24(i)). Overall, some forms of hydrogen-based e-fuels, such as liquid or compressed hydrogen, have challenges such as low energy density, cryogenic storage, boil-off losses or tank embrittlement (RES2; RES22; Morales-Ospino et al., 2023), but will slowly grow and maintain its relevance in inland and short-sea shipping as it causes zero emissions (RES1; RES19; RES23; RES24(i)). Other forms of hydrogen-based e-fuels such as LOHC also bring some advantages for these smaller market segments as these result in very low risks and completely zero GHG emissions, but these oily substances have to be ‘hydrogenised’ whereby the substance also has to be transported while not functioning as a fuel (RES2; RES20; RES21; Niermann et al., 2019; Rao & Yoon, 2020). Based on all the different characteristics and challenges of the different fuel types, competing interactions occur, which induces technological developments in the different types of fuels (e.g. improving quality and efficiency of carbon acquiring technologies, technology developments for e-ammonia to mitigate toxicity risks or overall efficiency improvements for the different e-fuel production processes to become cheaper and more competitive).

4.2.2. Inter-sector interactions

Inter-sector interactions appear between the different sectors along the e-fuels value chain. Here, some beneficial synergies are emerging. For example, with the exponential growth of renewable energy sources such as wind and solar, an increasing intermittent power supply leads to additional complications of grid instability or energy losses due to the curtailment of renewable power plants. Consequently, developers and builders of renewable energy projects are exploring solutions to mitigate these risks and are sometimes even obliged to win tenders in the EU or to get permits (RES25(i); RES27(i); RES30(i)). With the complementarity of electrolysers as one of the downstream value chain technologies to produce green hydrogen, the surplus or renewables can be stored for later use or producing hydrogen derivatives (i.e. different e-fuel types). Hence, to further scale up renewable energy sources, there is an increasing need for electrolysers and other feedstock molecule technologies for carbon-based and nitrogen-based e-fuels as these facilitate a more convenient method for energy/hydrogen storage (RES3; RES18; RES24(i); RES28(i)).

Despite the potential to produce e-fuels, the inter-sector interactions at the beginning of the e-fuel production process are currently forming a bottleneck. Concerning some of the above-mentioned intra-sector interactions of carbon acquisition technologies and different electrolyser types, the lack of these highly demanded technological elements have its repercussions in the downstream segments of the value-chain. For instance, solar PV and wind turbines' technological maturity and massive deployment exceed the Technological Readiness Level (TRL), compatibility and scalability of e-fuel technologies. Sufficient electrolyser capacity to meet the requested demands or set electrolyser capacity goals into the deployment of Gigawatt (GW) scales seems unachievable as there is no electrolyser mass production yet (RES22; RES28(i); RES30(i)). This electrolyser capacity deficiency has consequences for other technologies further down the value chain. With inadequate volumes of green hydrogen, for example, exploring and investing in the technologies for producing, managing or using the hydrogen derivatives is deemed unreasonable and irrational (RES16; RES18; RES25(i)). These examples effectively show that current deficiencies in upstream parts of the e-fuel value chain do not accommodate the development of downstream technologies and sectors.

Besides the differing availability and maturity of technologies at the different hierarchical levels of the e-fuels value chain, the current mismatching regulations on an inter-sector level cause additional complications. For example, the bureaucratic policy system in the EU may not always subsidise or approve current renewable power plants to be used for e-fuel production (RES3; RES26(i)). The consequence is that the development process of e-fuel plants is often prolonged and increases investment costs as it would often require newly built renewable power plants (RES3). This gives the understanding that the policy frameworks that address different parts of the value chain are not aligned and induces barriers to emerge for the development of the e-fuels sector.

4.2.3. Cross-sector interactions

With the potential applicability of e-fuels in a wide variety of (hard-to-abate) sectors, several cross-sector technology interactions are prevalent across the value chain. One aspect that illustrates this is the clear competing demand for the different e-fuels and their components (i.e. renewable electricity). This becomes evident as a large proportion of renewable electricity is used for direct electrification in residential areas, road transport or industries, as it is the most efficient and preferable (RES3; RES21). The part of the remaining renewable electricity can be converted into hydrogen through electrolysis, which also encounters competing demands. Here, green hydrogen can be consumed in industries such as the steel, chemical, and refinery sectors (RES21). The remainder of the hydrogen can be combined with the Fisher-Tropsch or Haber-Bosch processes to make its derivatives, such as e-methane, e-methanol or e-ammonia. Similarly, these e-fuels also encounter competing demands from various sectors. The carbon-based e-fuels, for example, are increasingly more demanded by the chemical, pharmaceutical, aviation and even the toys industries, with actors such as LEGO moving towards e-methanol for sustainable plastics production (RES3; RES15; RES21). The nitrogen-based e-fuels, on the other hand, are increasingly more requested by the chemical, fertiliser and energy storage sectors (RES16; RES21; RES24(i)). At last, the maritime sector could negotiate for the remainder of the different available e-fuel types, if any, as the maritime sector is an industry which is not known to pay high prices for their fuel. Consequently, the availability of e-fuels for the maritime sector may initially be marginal and deemed insufficient for the largest share of the maritime sector before 2030-2040 (RES21). While some maritime actors are aware of the competing demands between different sectors, most maritime organisations are often unaware of this interaction (RES21). To visualise these competing demands and presumed distribution of e-fuels and their components as described above, *Figure 6* depicts these flows in a Sankey diagram.

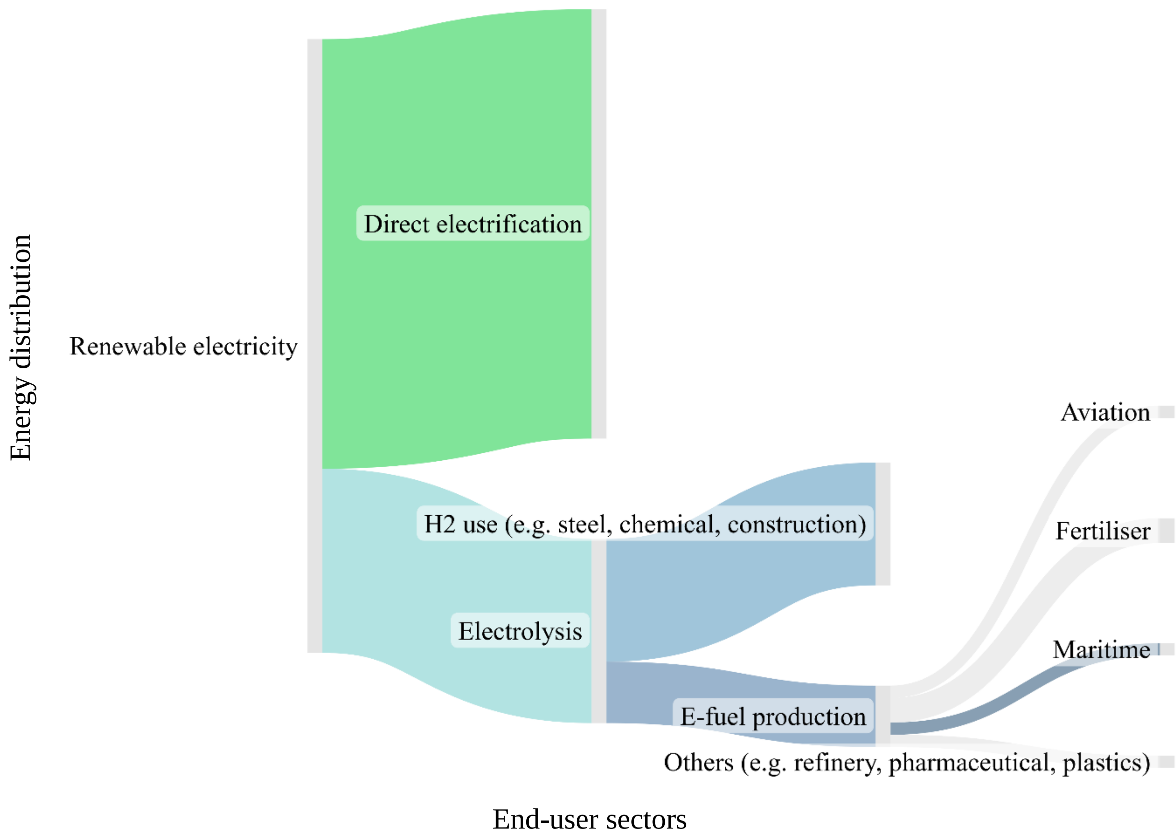

Figure 6. Estimated distribution of e-fuel (components) by various competing sectors.

In addition to the lower willingness and sometimes even inability to pay higher prices for e-fuels by the maritime sector, the (initial) implementation of the different e-fuels in other sectors may seem more reasonable. This becomes evident in the case of e-ammonia as one of the probable fuel solutions for the maritime sector. The current maritime sector does not require e-ammonia, nor does it have the appropriately developed infrastructure such as ammonia engines (i.e. low TRLs) (RES8; RES10; RES16; RES24(i)). This contrasts with, for example, the fertiliser sector, whereby ammonia is already one of their primary demanded and used products (RES16). Hence, the viability of e-ammonia applications in the maritime sector is perceived as a long-term solution (RES24(i)). As the direct use of e-ammonia is currently not feasible and more seen as a long-term approach, there is less urgency for rapid e-ammonia development in the maritime sector when compared with other e-fuels. For instance, the technology for methanol ships is mature and available for commercial deployment, which becomes apparent as numerous e-methanol (ready) ships are being ordered by large maritime organisations (RES4; RES8; RES11; RES15). In addition, there are existing ships operating on LNG which could also be provided by e-LNG (RES21). These examples convey the idea that the different TRLs within different sectors may positively or negatively affect the diffusion of specific e-fuel types.

Stemming from the different uses of e-fuels in various sectors, there is also more prevalence in specific e-fuel type development. To illustrate this, the e-ammonia market is expected to grow exponentially as the fertiliser industry demands it, but more importantly, by sectors which deem e-ammonia as one of the most viable hydrogen carriers (RES3; RES6; RES19; RES24(i)). The reason for this is that the production of e-ammonia does not have the difficulties of carbon-based e-fuels that have the challenge of acquiring sufficient (bio-genic) CO_2 as nitrogen molecules could be extracted from the air. Moreover, with the growing demand for e-ammonia and already made investments in e-ammonia production plants, various studies provide future projections and estimate that the costs of e-ammonia will be substantially lower than carbon-based e-fuels (RES1; RES22; RES24(i)). Considering the emphasis of the maritime sector on economic performance, e-ammonia is therefore also seen as advantageous over the other e-fuel alternatives in the long-term once the technology for e-ammonia ships is mature enough and sufficient e-ammonia production is available (RES24(i)). On the contrary, despite carbon-based e-fuels such as e-methanol being requested by several sectors, the maritime sector is predominantly driving the e-methanol market. However, this relies on a few progressive actors to initiate the development and deployment of e-methanol ships. As a result, these cross-sectoral differences in specific e-fuel demands influence the development adoption rates of e-fuels.

Regarding TRLs of e-fuel applications in different sectors, different sectors may also consider the developments in other sectors. For instance, maritime actors indicated that technological knowledge about engines, technical designs and efficiency improvements from other related sectors, such as automotive, are considered during the development of ships (RES5; RES11). Similarly, for the development of ammonia engines, maritime actors and equipment manufacturers referred to the engagements with actors from the existing ammonia sector to learn from their expertise and knowledge about managing and using the substance (RES4; RES18; RES22). Considering these interactions, policy measures in specific sectors may indirectly impact related industries such as the maritime sector. To illustrate this, the EU policies that favour and focus on electrification through BEVs may disincentivise the exploration of this sector towards e-fuel applications (RES3). As a result, less knowledge is developed regarding e-fuel engines and other applications which might benefit the maritime sector. This explains that enabling or restricting policies delineated to a specific sector may still cause cross-sectoral interactions and affect technological development and diffusion.

4.3. Boundary spanners and system entanglers

4.3.1. Intermediaries

Some of the most prominent actors that bridge the gaps between the e-fuels and maritime sectors are intermediaries, including NGOs and industry associations. Such organisations function as boundary spanners and system entanglers by engaging in various means of creating convergence between the e-fuels and maritime sectors but simultaneously create a divergence in existing system configurations of end-user sectors to make room for the e-fuels niche to emerge. Some of the found NGOs encompass Transport & Environment (T&E), Institute for European Environmental Policy (IEEP), European Environmental Bureau (EEB), Seas at Risk, and Clean Arctic Alliance. Considering the industry associations, some of the identified actors include the eFuel Alliance, Hydrogen Europe, Sustainable Energy Council, European Community Shipowners' Associations (ECSA), and Royal Association of Netherlands Shipowners (KVNR). The role of the intermediaries in aligning the e-fuels and maritime sectors becomes evident in various ways.

First, several industry associations create convergence by actively stimulating use cases by connecting stakeholders along the value chain, including renewable energy suppliers, e-fuel producers and end-user sectors where e-fuels show significant potential or are even unavoidable (e.g. maritime and air transport or the chemical, steel, aluminium and construction industries)(RES3; RES19). As these intermediaries facilitate the creation of various consortia and alliances, e-fuel actors can more easily connect with actors in various up and downstream sectors. In doing so, these intermediaries try to balance the desires of the industries and governments by advocating for both-sided compromises, leading to a more coordinated approach that suits the involved stakeholders (RES1).

Second, these industry associations create convergence by organising network events such as conferences and exhibitions, participating in discussion boards, and providing educative training programmes for ministries, associations and private companies (RES1; RES3; RES19). These activities bring together the stakeholders from renewables, OEMs, governments, and end-users such as maritime actors, enabling them to connect and potentially form new partnerships that stimulate e-fuel development and diffusion. Such network events facilitate knowledge exchange and help the actors better understand the different systems' potential complementarity.

Third, NGOs and industry associations create convergence and divergence by indicating flaws in existing EU and IMO policies. This becomes apparent by writing joint industry letters with both e-fuel and maritime actors (i.e. convergence) on what regulatory measures they propose to policymakers, such as a 6% e-fuel sub-quota by 2030 for the maritime sector (RES1; RES3; RES19). Despite the lower introduced sub-quota in the FuelEU Maritime as part of the Fit for 55 package[3], the intermediaries are considered among the leading proponents that have leveraged such e-fuel sub-quotas for the maritime sector (RES1). Simultaneously, the joint industry letters highlight the current discrepancies in the existing regulatory framework when introducing e-fuels into the maritime sector, such as the uneven level playing field when comparing e-fuels with fossil fuels (RES1; RES3; RES19). Moreover, the intermediaries emphasise such deficiencies in established practices and advocate for institutional changes to stimulate the diffusion of e-fuels by engaging in news & press releases, conducting studies, publishing white papers, and making brochures (RES1; RES3). Some examples are the remarks on the uncompetitive EU approach when compared to the IRA as introduced in the US for producing e-fuels at lower costs, the non-binding or unambitious sub-quotas for e-fuel in user-sectors, lacking certification policies of e-fuels, underdeveloped safety and management protocols for e-fuels, and the complex and bureaucratic EU approach for acquiring permits and subsidies (RES1; RES3; RES19; RES24(i)).

[3] The Fit for 55 is a package designed by the European Commission to reduce the EU greenhouse gas emissions by 55% by 2030.

These examples provide some clear boundary-spanning and system (dis)entangling activities that intermediaries pursue and give the understanding that these actors are fulfilling a critical role in aligning the interests of various industries and governments. Whereas the NGOs are more active concerning the sector interactions (i.e. technical) regulations, the industry associations emphasise bridging the socio-technical system interactions by connecting the stakeholders.

4.3.2. Research institutes

When introducing e-fuels into the maritime sector, research institutes such as TNO and MARIN provide knowledge and education to e-fuels, maritime, and governmental actors. This means that such actors try to mitigate some of the cognitive and technological barriers by researching unknown topics and technologies that currently induce uncertainty related to e-fuel applications in the maritime sector. This becomes particularly evident in the case of research related to some key topics such as ship designs, e-fuel mechanics, e-fuel engines, handling and safety precautions of e-fuels and bunkering (RES5, RES9; RES11; RES18; RES24(i)). In doing so, the research institutes bring together the knowledge base of various sectors and provide integral studies that help the actors to understand the inherent changes related to e-fuels in the maritime sector. Whereas the e-fuels and maritime sector actors benefit from understanding the technical feasibility, politicians benefit from understanding the implications of introducing e-fuels better, forming the basis for their approach to designing adequate policy measures (RES5; RES9). This suggests that research institutes serve an important role in coordinating the interests of multiple sectors by mitigating their concerns.

Similar to intermediaries, research institutes also engage and initiate consortia, alliances and partnerships. Considering the complexity of aligning the e-fuels and the maritime sectors, research institutes value an interdisciplinary approach where the stakeholders along the value chain are included (RES9; RES11; RES24(i)). Some examples of this are Green Maritime Methanol for stimulating e-methanol use in the maritime sector, EverLoNG as a joint project with various partners to scale up CCUS on (e-)LNG-fuelled ships, or VoltaChem as an integral innovation programme by connecting the electricity, equipment and chemical sectors (RES9). Collaborating with industrial actors provides the researchers with a practical playground to examine their research topics (RES5; RES11). The advantage is that the practical experiments provide real-world examples, making introducing e-fuels into the maritime sector more tangible for industry players and policymakers (RES5; RES9; RES11). This conveys the idea that research institutes fulfil a valuable boundary-spanning role in connecting the e-fuels and the maritime sectors.

4.3.3. Governments

Despite being less conspicuous in this research, governments also play a boundary-spanning and system-entangling role. First, this became apparent when the European Commission initiated the European Sustainable Shipping Forum (ESSF), a partnership between the European government, maritime organisations, and research institutes to stimulate sustainable practices in the maritime sector, such as e-fuels. Regarding these multi-disciplinary and international forums to stimulate sustainable practices in the maritime sector, the research institutes are the frontiers that often take the lead (RES5). Facilitating such platforms enables dialogue, knowledge exchange and coordination between the different stakeholders and effectively connecting them.

Reflecting on different governmental approaches, such as the IRA in the United States, this forms a clear incentive for e-fuel development to become more competitive with fossil fuels. As a result, this brings the e-fuels and maritime systems closer together by lowering the adoption barrier for the maritime sector (RES3; RES22). Nevertheless, the role of the government in other contexts for bridging the gaps between the e-fuels and maritime sectors is sometimes deemed inadequate. For instance, the European government takes a more passive role by providing limited directionality for the e-fuels and maritime systems by taking a technology-neutral stance (RES19). Consequently, this leads to more ambiguous policies and creates resistance among maritime actors related to the uncertainties related to e-fuels.

Therefore, scholars have also indicated that governments may need to be more active when governing socio-technical transitions (Braams et al., 2021). In doing so, boundary-spanning and system-entangling activities from a regulatory perspective can be improved.

4.3.4. E-fuel and maritime actors

With the maritime sector as one of the potential adopters of e-fuels, several maritime actors are directly engaging in aligning the interests of the e-fuels and the maritime sector themselves. Particularly the larger shipping organisations such as Maersk, Mediterranean Shipping Company (MSC) and CMA CGM are pioneering the development of e-fuel-compatible ship designs, funding research and trying to integrate the e-fuel production supply into their assets (RES11; RES15; RES21). Integrating e-fuel production into their portfolio fundamentally differs from the maritime sector's existing fuel supply, which is supplied through fuel brokers that enable the bunkering of ships (RES15). This demonstrates one of the new approaches to creating connections between the e-fuels and maritime sectors, thereby bridging the gaps between these two sectors.

However, the e-fuels and maritime actors encounter difficulty aligning all the stakeholders along the value chain. For instance, it can take a while before Financial Investment Decisions (FIDs) are made for e-fuel infrastructure in the maritime sector (e.g. e-fuel compatible engines, storage, distribution networks, bunkering facilities) considering the uncertainty and the high investment costs related to e-fuels (RES29(i)). Here, a delay by one of the actors restricts the decision-making in other sectors along the value chain. Reluctance of FIDs or unwillingness to commit to certain agreements originates from the mismatching logics between the sectors and the technological uncertainty of which will be the prominent e-fuel for the maritime sector. This has led to the consequence of a ‘wait-and-see’ attitude among many maritime actors at the end of the e-fuel value chain (RES1). Consequently, this makes the diffusion of e-fuels in the maritime sector a thorny process and also stresses the importance of the intermediaries, research institutes, and governments, which are more clearly devoted and experienced in mitigating such uncertainties rooted in systemic differences.

4.4. Drivers and barriers

The key institutional (socio) and technological (technical) drivers and barriers are summarised in *Table 7* to make the effects of the multi-system dynamics more tangible. Here, the institutional interactions are described using the interactions framework of Raven & Verbong (2010) and the technological interactions are indicated using the sector interactions framework of Andersen & Markard (2020). More substantiated policy measures could be developed by distinguishing between these types of drivers and barriers to spur the diffusion of e-fuels into the maritime sector and potentially other sectors. Noteworthy, however, is that sector interactions can be partially overlapping, as indicated in *3.2. Case selection*. For example, different electrolyser technologies can interact with each other within their respective value chain segment of providing feedstock molecules (intra-sector) but can also interact with up and downstream value chain segments (inter-sector). Hence, technology interactions may not exclusively be related to one specific type of sector interaction but can be interpreted based on the focus of analysis (e.g. within or across hierarchical value chain segments).

Table 7. Overview of the drivers & barriers of e-fuels diffusion into the maritime sector.

Interaction type	Drivers	Barriers
Competition	The maritime sector's increasing environmental regulations and emission targets discourage fossil fuel usage and drive the demand for cleaner fuel alternatives such as e-fuels (RES1; RES19).	Maritime actors prefer low-cost, short-term fuel contracts, whereas the e-fuels sector prefers long-term fuel contracts (RES3; RES14; RES15; RES17; RES21).
	Increasing public awareness and concerns about the pollution of ships pressure maritime actors towards adopting cleaner fuels (RES16).	The maritime sector is often unwilling to, or cannot, pay higher green premium prices for e-fuels (RES9; RES15; RES21).
	Growing demand for sustainable shipping practices by environmentally conscious consumers and organisations disincentivises fossil fuel usage and stimulates e-fuel usage (RES21).	Shipping organisations are more individualistic and less willing to share intellectual property rights as it poses risks to their competitive advantage (RES4; RES5; RES8).
Symbiosis	Green corridors are developing, reinforcing the synergy between the e-fuels and maritime sectors (RES1; RES8; RES9; RES11; RES13).	Without regulations and mandates on e-fuel use, maritime actors will continue the wait-and-see approach (RES1). Vice versa, e-fuel actors will not supply the maritime sector without supply mandates because it is less cost-effective, as other sectors will likely pay more for e-fuels than the maritime sector (RES1; RES17). This inhibits the potential mutual benefits that both sectors can achieve when collaborating.
	The influence of the maritime sector and its ability to create e-fuels demand can drive investments in research, development and infrastructure creation of e-fuels (RES5; RES9; RES11).	The maritime sector's lack of e-fuel infrastructure impedes collaborative efforts (RES18).
	Shared institutions of various e-fuel-demanding sectors, such as maritime and aviation, form mutual benefits by striving for similar objectives related to e-fuel adoption (RES3).	

	Industry associations are organising dedicated network events to reinforce the connections between the e-fuels and maritime sectors by bringing actors and technologies of the different systems together (RES3; RES19). Intermediaries (e.g. NGOs and industry associations) write joint industry letters indicating the shared intentions and objectives of the involved stakeholders (RES1; RES3; RES19).	Inadequate policy standards and certification processes for e-fuels in the maritime sector lead to uncertainty and potential market fragmentation (RES2; RES9; RES12). Competing commercial interests related to price agreements between e-fuels and maritime actors impede collaborative efforts (RES15; RES26(i); RES29(i)). Different priorities in sustainable development cause institutional tensions between e-fuels and maritime actors (RES5).
Integration	Strategic partnerships between e-fuel producers, shipping organisations, and ports can streamline operations and promote e-fuel diffusion into the maritime sector (RES16; RES33(i)). Boundary-spanning and system-entangling activities of several large maritime organisations try to integrate e-fuels production into their assets to reduce fuel supply uncertainty (RES11; RES15).	Limited knowledge and experience in handling and using e-fuels within the maritime sector may pose technical challenges during integration (RES10; RES18; RES22). There are insufficient spaces and logistical challenges associated with integrating e-fuel (production) facilities within or near port areas (RES14; RES16; RES22; RES33(i)). Differences in business models between the e-fuels and maritime sectors pose challenges for coordinated operational processes & logistics (RES15). Perceived safety risks and limited understanding of e-fuel technologies (e.g. toxicity, risk of leaks, required e-fuel inputs, et cetera) by maritime actors restricts e-fuel integration to the maritime sector (RES1; RES2; RES20; RES21). Maritime actors resist adopting e-fuels as they are concerned about compatibility and reliability issues (RES5; RES8; RES11). E-fuel actors are not always confident about how e-fuels can be handled on ships (RES17; RES22; RES33(i)).
Spill-over	Technological advancements in the e-fuels sector, considering production, storage and utilisation, may lead to innovations in the maritime sector (RES8; RES11).	The inertia and conservativeness of the maritime sector inhibit knowledge transfer and the adoption of new technologies such as e-fuels (RES4; RES9; RES15; RES17; RES20; RES22).

	Knowledge exchange from the e-fuels sector to policymakers and maritime actors decreases the uncertainty regarding e-fuels (RES1; RES2; RES19; RES22).	The e-fuels sector comprises institutions from the oil, gas, energy, and chemical sectors, which may differ from the maritime sector's institutions (RES3; RES17; RES27(i)).
Intra-sector	The enormous demand for feedstock molecule technologies reduces the negative consequences of competition and stimulates a more symbiotic relationship that facilitates their coexistence to (partly) meet the excessive feedstock molecule demands (RES6). Shipowners anticipate retrofits to e-ammonia by 130 ammonia retrofit-ready ships being ordered in 2022 (RES1).	Industrial CO_2 may only be used until 2035 for e-fuel production in the EU (RES1; European Parliament, 2003, Annex I of Directive 2003/87/EC; Gas Infrastructure Europe, 2022). E-fuel feedstock molecule technologies such as electrolysers, CCUS, and DAC still have high investment and operational costs (RES6; RES15; RES25(i); RES31(i)). There is an insufficient educated labour force with the required specialised knowledge and skills for developing and deploying e-fuel technologies (RES18; RES22). Most e-fuel technologies still encounter significant energy conversion losses, rendering them impractical in many cases (RES16; RES23(i); Schmidt et al., 2017; Ueckerdt et al., 2021). There are no clear certifications or quality standards for e-fuel and its production technologies which is crucial to ensure compatibility with the (existing) infrastructure and build trust among consumers and stakeholders (RES1; RES2; RES3; RES6; RES9; RES19).
Inter-sector	Renewable energy sources are becoming more developed, scalable and cheaper, thereby reducing the input costs for e-fuel production (RES6; RES15; RES16; RES19). Direct Air Capture (DAC) technologies are being funded and emerging, which can be critical for making carbon-based e-fuels (RES3).	Insufficient CO_2 is available for carbon-based e-fuel production (RES1). Direct Air Capture (DAC) technologies are not very mature, resulting in less available technologies for acquiring sufficient CO_2 for carbon-based e-fuels (RES1). E-fuel infrastructure is often not ready (e.g. ammonia engines are not developed, storage & bunkering facilities are not in place, et cetera) (RES1; RES8; RES14; RES16; RES33(i)). Insufficient electrolyser capacity is available to produce sufficient green hydrogen for producing its derivatives (RES6; RES22; RES28(i)).

		Considering the substantial fuel requirements of ships, there is a lack of sufficient available e-fuels for the maritime sector (RES1; RES9; RES12; RES21). The scalability of most e-fuel feedstock molecule technologies is still marginal as there is no mass production of such equipment (e.g. TRL is still too low, PEM electrolysers require scarce materials, et cetera) (RES5; RES9; RES15; RES22; RES28(i)). Inconsistent and inadequate policies and regulations at different sectors along the value chain hinder the development of e-fuel plants (e.g. Existing renewable electricity sources may not always be subsidised or authorised for e-fuel production. Hence, e-fuel plants require newly built renewable electricity sources) (RES3).
Cross-sector	Technological developments in sector A (e.g. automotive, aviation) have resulted in usable technologies in sector B (e.g. maritime) and vice versa (RES5; RES11).	Multiple sectors are demanding e-ammonia (e.g. chemical and fertiliser industries), lowering the incentives for maritime actors to engage in e-ammonia ships (RES17). Sectors with direct applications of different e-fuel types and components (e.g. direct electrification, green hydrogen, different e-fuel types) are more eligible to adopt e-fuels than the maritime sector (RES17; RES21). Inadequate technology standards across different e-fuel consumer sectors result in a dispersed and incoherent approach (e.g. mismatch between road transport and other transport sectors) (RES3). Consumer acceptance and willingness to adopt new e-fuel technologies is slowly growing but still marginal (RES21).

4.5. Policy objectives & measures

Stemming from the drivers and barriers overview, it became evident that there are numerous barriers to adopting e-fuels in the maritime sector. The nature of these different barriers is categorised based on a) socio-technical system interactions by using institutional logics and b) technological sector interactions. The insights gained from the semi-structured interviews and informal expert discussions with e-fuels and maritime industry actors, intermediaries, and research institutes have led to an in-depth understanding of the different types of hindrances that must be overcome to stimulate e-fuels diffusion. This entails respondents highlighting some of the critical shortcomings of existing policies from both an e-fuels and maritime system perspective. By evaluating these policy recommendations concerning the nature and level of the identified socio-technical system interactions in this research, more specific policy objectives and measures to mitigate the socio-technical barriers were defined and summarised in *Table 8*.

Table 8. Policy objectives and measures for addressing socio-technical drivers & barriers to e-fuels diffusion.

Interaction types	Policy measures
Competition	*Dialogue and knowledge sharing* - To mitigate the barriers from competing institutional logics, policymakers should promote dialogue and knowledge sharing between stakeholders to create awareness and understanding of each sector's respective institutional logics. Some examples to facilitate this could be stimulating industry conferences, workshops, and collaborative forums (e.g. expanding ESSF) that enable communication and bridge the knowledge gap. *Practical use cases* - Evade the maritime sector's perceived financial and safety risks when adopting e-fuels by developing pilot projects and demonstrating the viability of business cases. Highlighting concrete evidence and advantages such as cost savings, reduced emissions, improved reputation, and enhanced market access can reduce resistance and scepticism of maritime actors.
Symbiosis	*Integral collaboration* - To facilitate mutual benefits, policymakers should encourage active involvement and collaboration among the key stakeholders of both sectors, including government agencies, industry associations, companies and research institutes. Establishing working groups or task forces to promote discussions and joint initiatives can help to address common challenges. *Long-term prospects* - Develop long-term plans and transition strategies that provide a clear outline and set of milestones for integrating e-fuels into the maritime sector, preferably internationally (e.g. EU or global IMO level). This could be achieved by collaborating with the stakeholders to develop roadmaps highlighting the key barriers and mitigation measures to overcome them over time. Incremental and phased approaches can mitigate implementation risks by slowly building confidence in the transition process.
Integration	*Creating a vision* - Policymakers should work towards creating a shared vision, mutual objectives and a common understanding that aligns the interests of the e-fuels and maritime sectors. This could be achieved by emphasising long-term benefits and the potential advantages arising from collaboration and adopting sustainable practices. For this, it can be important to highlight the economic, environmental and societal benefits of adopting e-fuels to gain buy-in from maritime actors.

Spill-over	*Education* **-** To build up sufficient and an eligible labour force concerning e-fuel technologies, policymakers should invest in developing educative programmes and partner with research institutes to provide expertise and support for implementing such sustainable solutions. Similar educative training programmes are necessary to enable the maritime sector to understand and effectively adopt e-fuels.
Intra-sector	*Certification & standards* – Clear regulatory policies are needed to prevent the current ambiguity surrounding the certification, requirements, and standards of e-fuel technologies. *Research & Development* – By providing funding for research and development (R&D), the Technological Readiness Levels (TRLs) of e-fuel technologies can be improved, making them more efficient, bankable and scalable. *Demonstration projects* – Facilitating demonstration projects to showcase the feasibility and scalability of e-fuel technologies can help to attract more private investments to develop and refine e-fuel production and utilisation. *Equalise fuel supply financials* – Arranging tax benefits, low-interest loans, subsidies or grants for e-fuels could make them more competitive with conventional fuels.
Inter-sector	*Public-Private Partnerships* – Stimulating public-private partnerships (PPP) between the involved actors along the e-fuels value chain can help to bridge knowledge gaps, promote technology transfer and facilitate innovation in the e-fuels sector. This involves the arrangement of joint initiatives and knowledge-sharing platforms. *Infrastructural investments* – Governments should prioritise investments in the e-fuel infrastructure, including production facilities, storage facilities, and distribution networks, as this prevents the formation of bottlenecks along the value chain (e.g. insufficient green hydrogen due to shortage of electrolyser capacity resulting in minimal development of the hydrogen derivatives such as e-methanol, e-LNG, e-ammonia, et cetera, or difficulties in transportation of e-fuels as no large scale distribution systems are developed yet). *Integrated policy frameworks* – The policies focused on specific levels of the e-fuels value chain need to be coordinated with the other value chain segments (e.g. mismatching policies at the level of renewable energy supply and e-fuel production plants have repercussions in further downstream value chain segments). Hence, policymakers need to consider the interrelatedness of sectors and discuss the technological interactions with industry stakeholders through creating task forces or committees. While doing so, these measures should be simple with clear definitions to prevent overly complicated and bureaucratic policy frameworks.
Cross-sector	*Carbon pricing & market mechanisms* – Implementing and intensifying carbon pricing mechanisms such as carbon taxes or cap-and-trade systems (e.g. EU ETS – Emission Trading System) creates economic incentives for adopting low-carbon fuels like e-fuels. Such measures encourage emission reductions, stimulate market demand, and provide a more predictable environment for (longer-term) investments. Carbon pricing mechanisms need international alignment considering the global nature of the maritime sector.

Aligning sectoral regulations & standards – Regulations and standards in e-fuel consumer sectors must be coordinated to stimulate overall e-fuel development and use (e.g. similar policies in the different transportation sectors can facilitate mutual benefits by standardisation).

Green corridors – Incentivising the development of green corridors can strengthen the connections between the e-fuels and maritime sectors, providing a holistic approach by incorporating the relevant stakeholders in the process. Mediating organisations coordinating green corridor programmes should be supported by making necessary resources available (e.g. funding, academic & industry knowledge, labour force).

Knowledge diffusion – Creating knowledge platforms, technical training programmes, and educational initiatives can enhance the necessary understanding and skills for e-fuels development and deployment in various sectors. Increased awareness can foster cross-sector collaborations and build human capital, which may stimulate the transition towards e-fuels.

Synthetic fuel deployment - Besides directly stimulating e-fuels with policy measures, stimulating the use of synthetic fuels that are not (entirely) produced from renewables may improve market formation. While initial emissions may be higher, this greatly incentivises further developments for e-fuels and reduces long-term uncertainty.

In addition to the suggested policy measures that form a straightforward approach to meet the regulatory barriers, there are also some aspects the e-fuels and maritime sectors should consider. These two focal sectors must understand that the (in)formal norms and values of the e-fuels and maritime sectors are fundamentally different. Existing practices need to make room for new ones whereby the interests of both sectors are accounted for. For instance, the maritime sector has to acknowledge that 3-month fuel contracts are simply too short for the e-fuels sector, and the e-fuels sector has to acknowledge that their requests for 10-15 year offtake contracts can be unattainable for the maritime sector. Whereas policies may guide in meeting the regulatory boundaries, the diffusion of e-fuels into the maritime sector also depends on the responsibility of the involved actors. Therefore, e-fuels and maritime actors need to find compromises which are deemed acceptable by these two sectors and the governing actors.

While corporate responsibility and an adequate policy framework providing regulatory boundaries are critical aspects to consider, the importance of mediating actors cannot go unnoticed. What became evident from this research is that boundary spanners and system entanglers are currently addressing numerous barriers and pursuing several of the policy suggestions mentioned above. This relates to forming connections between different value chain segments and sectors, conducting critical research to improve technologies, and highlighting probable e-fuel development and integration directions. As these actors operate at the interface of multiple sectors, they are exceptionally aware of each respective sector's barriers. Therefore, policymakers should embrace the insights of boundary spanners and system entanglers as they often pinpoint the deeply-rooted challenges which need to be addressed with policy interventions.

5. Discussion

This thesis proposed a novel approach to better understand and analyse multi-system dynamics. With the combination of several theoretical frameworks, new theoretical insights were acquired regarding the interactions of multiple systems and provided practical insights by revealing different natures and levels of the drivers and barriers to technology diffusion. As a result, a few implications could be derived from this research.

First, by using the concepts of institutional logics, sector interactions, and boundary spanners and system entanglers, this research provided a holistic perspective of multi-system dynamics by considering institutional and technological relationships and the mediating roles of actors at the interface of multiple systems. As these theoretical frameworks highlight the connection of multiple systems, this research approach allowed for a more targeted manner to uncover and interpret multi-system interactions, which can be more challenging to achieve with other transition study frameworks as there is no conventional framework available to analyse multi-system dynamics properly (Rosenbloom, 2020). This provided a clear guideline for defining appropriate policy objectives and measures to overcome the barriers of e-fuel diffusion into the maritime sector. Hence, combining multiple frameworks is one of this research's unique and profound contributions to the multi-system transition studies literature.

Second, this research has emphasised the role of actors in shaping and driving the diffusion process by recognising that various actors from different systems interact and negotiate, shaping the pace and direction of technological change. For instance, the institutional logics approach considers specific institutional contexts and acknowledges that different sectors have unique institutions that guide actor behaviour, affecting the dynamics and outcomes of technological change and diffusion. Moreover, following the rationales of boundary spanners and system entanglers has allowed us to identify unique leverage points for interventions or change related to the e-fuels and maritime systems. Incorporating this aspect of boundary spanners and system entanglers is critical to better understanding how different systems are correlated and can be connected through the activities of actors at the interface of multiple systems (Andersen & Geels, 2023; Hassink et al., 2018; van der Vleuten, 2019). The key drivers and barriers that affect multi-system dynamics could be identified by recognising their interpretations, resulting in a better-substantiated approach for intervention strategies that mitigate the negative consequences and foster the desired outcomes. Accordingly, this research approach has provided insights into power dynamics, social pressures, and how power is exercised, negotiated or challenged within and between systems. By grasping these intricate dynamics, the inherent sociological drivers and barriers can be targeted to ease the transition process.

Third, the intra-sector, inter-sector, and cross-sector interactions framework illustrated how technology interactions and dynamics appeared between different levels of the value chain. This has enabled a more nuanced examination of the technological interrelatedness that shapes and influences the transition process. For example, specific bottlenecks or critical components of the value chain were identified, which should be cautiously addressed and monitored to stimulate the development of the e-fuels sector. This suggests that including the sector interactions framework is valuable for better understanding the causal relationships between different sectors. Combining institutional logics, sector interactions, and boundary spanners and system entanglers frameworks has resulted in an elaborate approach for analysing the nature and level of multi-system interactions that affect the diffusion of innovations.

Lastly, recent meetings of the Marine Environment Protection Committee (MEPC 80) at the beginning of July 2023 have resulted in the IMO adopting a revised GHG reduction strategy for mitigating global shipping emissions (IMO, 2023). Some of the key policies include more specific guidelines for the life cycle GHG intensity of marine fuels (i.e. well-to-tank and well-to-wake emissions), carbon pricing mechanisms, and the indicative checkpoints and sub-targets for GHG emissions by 2030 and 2040

(MEPC, 2023). In this regard, some of the policy suggestions as illustrated in *4.5. Policy objectives & measures* have been (partially) implemented, such as creating long-term prospects, creating a vision, certification & standards, and carbon pricing & market mechanisms. Nevertheless, the adopted measures by the IMO are still ambiguous and non-binding (e.g. '20% GHG emission reductions by 2030, *striving for 30%*' or 'net-zero GHG emissions *by or around, i.e. close to 2050*'), but more importantly, experts have highlighted that this policy package falls short for achieving the emission reduction targets as agreed upon in the Paris Agreement (Comer & Carvalho, 2023). Considering the IMO's inadequate adoption of policy measures, this research provides an elaborate list of potential policy measures to stimulate e-fuels diffusion into the maritime sector and reduce maritime GHG emissions (see *Table 8*).

However, it has to be acknowledged that this research approach also has its limitations. First, combining the different theories has resulted in a complex theoretical framework. Concerning the extensive theoretical framework (i.e. institutional logics, multi-system interactions, boundary-spanning and system-entangling activities), it is difficult to discuss all used theoretical concepts within the timespan of semi-structured interviews or informal expert discussions is challenging. This has led to excluding some topics during the interviews and discussions and primarily focusing on topics within a specific respondent's expertise and knowledge base. As a result, of the roughly twenty interview guide questions (see *Appendix II – Interview guide*), only three-fourths of them have been discussed on average. In addition, the robustness of the findings, such as identifying institutional logics or the role and activities of boundary spanners and system entanglers, could have been improved if more additional data sources (e.g. newspaper articles, reports, publications) were used. For example, the boundary-spanning and system-entangling role of governments poses an interesting aspect to be considered but could not be fully grasped by limited access to respondents of national or international governments (e.g. European Commission, International Maritime Organisation). Moreover, it has to be noted that the findings from the semi-structured interviews and informal expert discussions may be subject to the different actors' perspectives, interpretations and interests. This potential subjectivity is a factor that has to be acknowledged regarding the interpretations of the results. Concerning the vastness of the maritime sector and growing attention towards e-fuels, being primarily dependent on the insights of 33 respondents can, therefore, be seen as a limitation to the reliability of this research.

Second, the framework's complexity can make it difficult to fully grasp, analyse and interpret the direct correlations between the different theoretical concepts. This requires a deep understanding of the theoretical concepts, how to make sense of numerous interrelated factors, and how to derive valuable findings from data sources but this leaves room for interpretation and potential subjectivity. Additional complexities arise from the ambiguity of definitions, such as the intra-sector, inter-sector, and cross-sector interactions which can be partly overlapping. Consequently, categorising the different multi-system interactions can be complicated using this approach.

Lastly, the applicability of this framework can be challenging in some cases. For instance, analysing the institutional logics is better suited for more mature and established systems as this allows researchers to examine the discourse related to changing dominant field logics over time, thereby resembling a socio-technical transition (Fuenfschilling & Truffer, 2014). In the case of applying this theory to highly volatile and indefinite niches such as e-fuels, there is likely no clear field logic that describes the most prominent (in)formal rules, norms, and values. Despite helping understand what differing logics are present within a niche, it can be challenging to determine to what extent the combined set of institutional logics is aligned with the institutions of other (more mature) systems.

Considering some of the previous factors, recommendations can be made for further research to enhance the quality and usefulness of this theoretical framework. For instance, whereas the competition, symbiosis, integration, and spill-over interactions defined the *nature* of the different institutional (socio) interactions and the intra-sector, inter-sector and cross-sector interactions illustrated at what *level* technological (technical) interactions take place, future research can investigate the synthesis of these socio-technical interactions into one holistic approach (i.e. defining the nature of interactions at different levels for both socio and technical aspects). Additionally, follow-up studies can examine the viability of using or adding other qualitative research methods, such as content analysis of newspaper articles, reports, and publications, to improve the understanding of multi-system dynamics. Moreover, further research can explore the additionality of quantitative data in quantifying and visualising the multi-system dynamics. Such quantitative analyses may indicate the changing discourse related to the diffusion of innovations, provide a more longitudinal development perspective, or indicate the key networks of related systemic components, actors, and institutions. Therefore, different data sources and analysis approaches can improve the framework's applicability by exploring the multi-system dynamics in different contexts.

6. Conclusion

To extend transition study literature and contribute towards sustainable development goals, this thesis research has examined the effects of multi-system dynamics in an empirical case study by addressing the following research question: *"How do multi-system dynamics affect the diffusion of e-fuels into the maritime sector?"* Building upon the theoretical concepts of institutions, sector interactions, and boundary spanners and system entanglers, a novel framework has been developed to analyse the effects of multi-system dynamics on the diffusion of innovations.

Based on the analysis, it became evident that using these different theoretical concepts has allowed us to distinguish both sociological and technological drivers and barriers stemming from multi-system interactions that influence the adoption rate of e-fuels in the maritime sector (see *Table 7*). For example, institutional differences such as long versus short-term strategic orientation or different stances towards collaborative efforts result in clear sociological barriers between e-fuels and maritime actors. Moreover, the competing and symbiotic relationships of technologies within the e-fuels sector (intra-sector), the interrelatedness with up and downstream value chain sector technologies (inter-sector), and the competing interests of e-fuel (components) by numerous end-user sectors (cross-sector) illustrates the multi-faceted types of technological interactions and, thereby, the embeddedness of the e-fuels system. At last, the boundary-spanning and system-entangling activities of NGOs, industry associations, research institutes, governments, and e-fuels and maritime actors have led to a deeper understanding of the socio-technical differences between the e-fuels and maritime systems and highlighted some potential directions for creating policy interventions. Altogether, this framework has formed the basis for determining specific policy objectives and measures to mitigate such socio-technical barriers and stimulate the drivers to foster e-fuels diffusion while considering the broader scope of multi-system dynamics (see *Table 8*).

While this thesis illustrated a suitable approach to analyse multi-system dynamics, scholars can explore different research methods to improve the practicality of this framework or shed light on multi-system dynamics using different research designs (e.g. content analysis, quantitative research approaches, or longitudinal research designs). In this regard, this framework provides fruitful ground for further empirical research on multi-system dynamics in different environments and contexts.

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Appendix I – E-fuel types for the maritime sector

This study considers three different types of e-fuels (i.e. 4th generation biofuels): carbon-based e-fuels, green hydrogen, and nitrogen-based e-fuels. Other common denotations of e-fuels in policy terms are Renewable Fuels of Non-Biological Origin (RFNBO) and Recycled Carbon Fuels (RCFs), based on biogenic CO_2 for example. In the maritime sector, there are a few promising e-fuels for each of these three types. Considering carbon-based e-fuels, e-LNG and e-methanol are seen as the most viable (Lindstad et al., 2021; Song et al., 2022). Regarding e-hydrogen, these are primarily highly compressed hydrogen or liquified hydrogen to alleviate the downsides of the low volumetric energy density. For nitrogen-based e-fuels, e-ammonia is one of the most viable e-fuels for the maritime sector (Gore et al., 2022; Lindstad et al., 2021; Song et al., 2022). Some of the key (dis)advantages of the different e-fuels are shown in *Table 9*.

Table 9. Overview of the (dis)advantages of various fuel types in the maritime sector.

Fuel type	Advantages	Disadvantages
Carbon-based e-fuels (e.g. e-LNG, e-methanol, synthetic e-diesel, dimethyl ether (DME), et cetera)	Existing propulsion systems are compatible or could rather easily be retrofitted. There are existing markets that could directly consume these types of e-fuels. On average, one of the highest energy densities of e-fuel types that are suitable for the maritime sector (Placek, 2022).	Combustion still encompasses carbon emissions. Requires carbon capture and carbon reforming technologies in addition to green hydrogen production. On average, lower energy density than conventional Marine Diesel Oil (Placek, 2022).
Green hydrogen (e.g. gaseous, liquid, LOHC)	Does not require additional feedstock molecules besides water. No carbon or other GHG emissions, only pure water (H_2O).	Requires new engine types. Low energy density, even in various forms (e.g. liquid at -252C 9.55 MJ/L, 700 bar 6.8 MJ/L, 350 bar 3.4 MJ/L) compared to Marine Diesel Oil (36 MJ/L) (Placek, 2022). Requires liquefaction or compression that consumes significant amounts of energy.
Nitrogen-based e-fuels (e.g. e-ammonia, Hydrazine, et cetera)	There is an existing market for these substances (e.g. ammonia in the chemical industry and agricultural fertilizers). Higher energy density than plain hydrogen. No carbon emissions.	Requires new types of engines. New associated risks due to toxicity. A low energy density of 12.8 MJ/L at -35C compared to Marine Diesel Oil (36 MJ/L) (Placek, 2022).

Appendix II – Interview guide

Introduction

Master's & thesis topic introduction, ask for permission to record [consent → start recording].

Introductory questions

1. Can you briefly introduce yourself?
2. Can you tell me something about your affiliation with e-fuels/maritime sector(s) or in what ways you are involved in them?

Questions

Institutional logics

1. Can you tell me a bit more about your organisation and its role in the e-fuels/maritime sector(s)?
2. How does your organisation see the role of e-fuels in the maritime sector?
3. What type of technologies does your organisation employ in the e-fuels/maritime sector?
4. Can you illustrate some factors that your organisation considers in the decision-making process of developing/using e-fuels (in the maritime sector)?
5. What are the main goals and motives of your organisation for the e-fuels/maritime sector?
6. Who defines these objectives and encourages you to pursue them?
7. What does your organisation value the most when approaching its targets regarding the e-fuels/maritime sector?
8. Can you elaborate on any challenges or opportunities that arise from the integration of e-fuels into the maritime sector and how does your organisation approach this?

Multi-system dynamics

1. How do you see the relationship between the e-fuels and maritime sectors evolving in the following decades?
2. How do you see the relationships between organisations with the e-fuels and maritime sectors? Are they cooperative, do they complement each other or is there competition among each other?
    a. How do you see this affecting the development of e-fuels/the maritime sector?
3. Can you indicate any specific partnerships or initiatives that have been formed between actors of the e-fuels and maritime sectors?
    a. How was this relationship and how was knowledge shared?
    b. Who do you see as the main actors that are creating and maintaining these relationships/interactions between the two sectors?
    c. Can you discuss any notable challenges that actors have encountered when working together?
4. Maritime: Various technologies are available for making the maritime industry more efficient/sustainable, how does this affect the application/use of e-fuels in the maritime sector?
5. E-fuels: There is a wide variety of sectors that could use e-fuels, to what extent is the maritime sector preferable or what are the considerations in this debate?
6. To what extent are there relations with other related sectors?
    a. What potential issues/side effects do you see arise from this? Why/how?
7. What do you perceive as the key technologies for e-fuels use in the maritime sector, and what challenges are associated with them?
8. How does your organisation see the role of policy and regulations in promoting the integration of e-fuels in the maritime sector?
    a. How does your organisation approach this and does it connect with policymakers?
9. In what way do you see that different actors in the e-fuels or maritime sectors influence policy or decision-making processes regarding the integration of e-fuels in the maritime sector?
    a. Who are the most prominent actors from your perspective?

Closing questions

1. Do you have any additional questions from your side?
2. Any remarks that you think of that might be relevant but which we did not address?
3. Do you want to review the interview transcripts to indicate changes or make revisions?
4. Do you want to receive the final thesis once completed?

Thank you for participating in this thesis research, it is well appreciated.

Appendix III – Coding scheme

Institutional logics

Table 10. Identification of institutional logics based on Fuenfschilling & Truffer (2014), Thornton & Ocasio (2008) and Wesseling et al. (2022)

Category	Indicators
Basis of strategy	This describes how the organisation aims to achieve its goals and preserves its organisational values.
Efficiency focus	Efficiency focus is adapted from Wesseling et al. (2022) and in this thesis also relates to the logic of investment and basis of attention described by Thornton & Ocasio (2008). The categories of values, mission and basis of strategy are partly related as this forms the basis that drives the efficiency focus of organisations.
Expertise	This addresses the knowledge and cognitive contributions of an organisation. Some examples of this could be the knowledge of technical system requirements for propulsion systems, an educative and informing role, the creation of business cases and the boundary spanning between different actors.
Funding	This highlights where the financial resources originate from to fund investments.
Informal control mechanisms	The informal rules, norms and values embedded in the social actors that influences the behaviour of the actors surrounding them. Examples could be pressures originating from co-workers and communities.
Mission	The mission encompasses the main goals and objectives of the organisation. Examples of this are developing new knowledge, processes and technologies, increasing profits, and improving sustainability.
Sector logic	Family-logic, community-logic, religion-logic, profession-logic, state-logic, corporate-logic, market-logic. A more elaborate description is provided underneath this table.
Sources of authority	Sources of authority refer to the actors or individuals that can exert power and possess the ability to make (organisational) decisions. In this research, the category of *governance mechanisms*, as by Thornton & Ocasio (2008), is also incorporated in this concept considering the partial overlap and relatedness to the sources of authority conceptualisation. Sources of authority is also referred to as *organisational form* in the work of Fuenfschilling & Truffer (2014).
Technologies	This highlights the main technologies an organisation employs, develops or advocates for.
Values	The values refer to the topics organisations prioritise and attach great importance to in their daily operations. Some examples may include, but are not limited to, safety, welfare, efficiency, profitability, and equity.
View on business	The definition of short-term or long-term decision making and setting objectives.

Sector logics

Below, the seven ideal-type sector logics and their main ways of indicating them are described based on the theoretical definitions of Thornton (2004), Thornton & Ocasio (2008) and Thornton et al. (2012).

Community-logic

Community-logic emphasises the importance of collective action, shared values and social connections between actors. Some examples of actors that represent the community logic can be non-profit organisations, social movements or local communities. Aspects which could lead to identifying this sector logic can be:

1. Highlighting shared values, social connections between actors and refferrals to specific communities.
2. Emphasising the importance of collective action and working towards a shared goal.
3. Striving for wellfare and well-being for a broader community rather than for individuals.
4. A sense of social responsibility and the belief to create a positive impact for the community.
5. The feeling of shared ownership and responsibilities among its members.

Corporate-logic

The corporate-logic characterises the focus on efficiency, productivity, and profitability. The corporate logic may resemble corporations, business organisations, firms and companies. Some indicators for identifying this sector logic may include:

1. Mentioning aspects such as a focus on efficiency, productivity, and/or profitability.
2. Emphasising competition in the market, growth and staying ahead of the competitors.
3. The prioritisation of profit maximisation, cost reductions and increasing value for shareholders.
4. Taking smart, data-driven decisions and taking calculated risks.
5. A feeling of responsibility towards shareholders, employees, and customers.

Family-logic

The family-logic highlights a ‘family-like’ environment and the strong personal relationships between actors. Family oriented organisations are often close-knit whereby loyalty and trust are valued. Examples where this logic can often be found can be small businesses, family-owned companies, and social networks which may be identified by:

1. Referrals to close personal relationships among individuals and a family-like atmosphere.
2. Emphasis on maintaining strong relationships to foster trust and loyalty.
3. A feeling of coherence and shared responsibility among members.
4. Trying to avoid internal conflicts and preserve harmony among the people involved.
5. Focus on collective efforts and supporting each other.

Market-logic

Considering the market-logic, there is an emphasis on the importance of supply-demand and market forces that determine the outcomes. This is often resembled in market-oriented organisations and fields such as finance and economics. The market-logic can be identified by, for example:

1. References to the importance of supply-demand dynamics and market forces.
2. Highlighting the role of prices, competition and consumer choices in guiding decision-making.
3. Striving for market efficiency and staying ahead of market trends.
4. Importance of making market informed and market-driven decisions.
5. Perceived responsibility towards shareholders, employees, and customers.

Profession-logic

The profession-logic relates to the importance of expertise, specialised knowledge, and ethical standards and is often found in professional organisations such as medical, legal or engineering associations. The profession-logic may be identified by:

1. Emphasising the importance of expertise, specialised knowledge and training.
2. Focus on maintaining a good reputation, as well as abiding ethical standards and professional conduct.
3. Striving to provide clients or consumers with high-quality services or products.
4. Highlighting the importance of ongoing education and professional development.
5. Feeling of shared responsibility and accountability among members of the organisation.

Religion-logic

Actors following the religion-logic prioritise faith, spirituality, and moral values. This sector-logic is often prominent in religious organisations, such as churches, mosques, and synagogues, but can also be present in secular organisations emphasise ethics and moral values. Indicators for the religion-logic can be:

1. Mentioning religious and spiritual practices or beliefs.
2. Focus on ethics and moral principles.
3. Prominence of spirituality and relation towards individual growth and development.
4. The belief to serving a higher purpose or mission.
5. A set of shared values and principles among the members of the community.

State-logic

The state-logic underlines the importance of the government and abiding the rules and regulations that define the boundaries. This sector logic is often found in public, government or global organisations such as government agencies or multi-national corporations. Indicators for identifying the state-logic may include:

1. Highlighting the importance of governments and abiding rules and regulations.
2. Organisational focus on structure, stability and hierarchy.
3. Ensure smooth operational processes of the organisation by maintaining order.
4. Focus on contributing to societal objectives.
5. Perceiving the responsibility to follow the set of rules and regulations.

Multi-system dynamics

Table 11. Multi-system interactions based on Andersen & Markard (2020) and Raven & Verbong (2010).

Interaction pattern	Indicators
Competition	The competing interests between different systems through differing sector logics, values, technology preference, missions, and efficiency focus. This may positively affect e-fuel use (e.g. spur development and thereby improve technological and economic competitiveness) but could also hamper development (e.g. increasing uncertainty of potential outcome).
Symbiosis	The joint efforts, collaboratives and initiatives aimed at achieving the objectives of multiple systems whereby the organisational missions, expertise and technologies may benefit from the partnerships.
Integration	Changes in the markets and industries by the merger or separation of organisations create or dismantle shared institutions between systems. This could extend expertise through knowledge assimilation and may positively or negatively affect dominant sector logics, values, missions, sources of authority, strategy and efficiency focus of organisations depending on the prior alignment of these categories.
Spill-over	The transfer of institutions between multiple systems which may spill-over values, expertise, missions, the basis of strategy and efficiency focus between sectors.
Intra-sector	The used or preferred technologies and the interactions between technologies within a specific sector or value chain segment.
Inter-sector	The hierarchical dependence and relationships of technologies with up or downstream sectors or value chain segments.
Cross-sector	The interface that highlights the technological potential and applicability in multiple sectors.

Boundary spanners and System entanglers

Table 12. The identification of boundary spanners and system entanglers based on Van der Vleuten (2019) and Zietsma & Lawrence (2010).

Actor type	Indicators
Boundary spanner	Boundary spanners are performing institutional work at various levels in an organisational field. This relates to bridging different domains, creating connections between different actor groups, manage the tensions between them, mobilise resources from different sources, and challenge and reconstruct new boundaries within the institutional landscape. Some examples are stimulating cross-sector collaborations and partnerships, facilitate knowledge exchange at the level of organisational networks, or advocacy and lobbying to influence policy-making processes.
System entangler	Actors who are active in creating convergence between previously lesser aligned systems, as well as creating divergence between multiple systems which are currently more closely tied to each other. For instance, convergence can be created by fostering collaborations across systems, aligning the goals, strategies and practices of organisations, and try to reduce diversity and variation by providing a general direction or set of principles. Divergence, however, may encompass advocating for diverse emerging disrupting innovations and niches, challenging the existing institutional field by indicating flaws and limitations and promoting institutional change.