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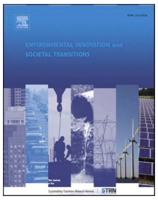

Decarbonizing maritime shipping and aviation: Disruption, regime resistance and breaking through carbon lock-in and path dependency in hard-to-abate transport sectors

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ABSTRACT

Aviation and maritime shipping are hard-to-abate transport sectors that are heavily dependent on fossil fuels. They jointly account for nearly 10 % of global greenhouse gas emissions, while infrastructure and investments are locked into high-carbon pathways for decades. Fuels and technologies to decarbonize include advanced biofuels, electrofuels, hydrogen and electric propulsion. This research aims to analyse the decarbonization strategies for maritime shipping and aviation from a comparative perspective, and analyzing the role of different actors for disruption to break through carbon lock-in and path dependency. The research uses Sweden as a case study and applies qualitative methods, including expert interviews, focus group discussions and site visits. Our research finds that aviation and maritime shipping are slowly changing, albeit with different dynamics. Both sectors show that incumbent regime actors play a major role in shaping transition pathways and disrupting the (quasi)equilibrium, while niche innovation is often developed together by incumbents and niche players.

1. Introduction

The maritime shipping industry and the aviation industry jointly account for just under 10 % of global greenhouse gas (GHG) emissions and about 5 % of CO_2 emissions (IEA, 2023). The maritime shipping industry delivers about 90 % of all globally traded goods (OECD, 2023), while the aviation industry transports more than 4.5 billion passengers every year (World Bank, 2023[1]).

While being important backbones of international trade and people's free movements, maritime shipping and aviation are heavily reliant on fossil fuels (Urban et al., 2024; Harahap et al., 2023b; Christley et al., 2024; Lai et al., 2022a). Nearly all of the fuels used globally in maritime shipping and aviation are petroleum-based products. As hard-to-abate sectors, infrastructure and investments are

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[1] Pre-COVID 19 pandemic levels from 2019. Data from 2022 shows a decline of about 20% compared to 2019, but a steep increase from previous pandemic years 2020 and 2021 (IATA, 2023).

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locked into high-carbon pathways for many years and decades.

This research therefore aims to analyse the following: a) comparative perspectives of decarbonization strategies for maritime shipping and aviation and b) the role of different actors for disruption, reducing regime resistance and breaking through carbon lock-in and path dependency for achieving sustainability transitions in aviation and maritime shipping. The research questions of this paper are therefore as follows: how are the dynamics of sustainability transitions unfolding for decarbonizing maritime shipping and aviation and what is the role of various actors, particularly incumbent actors?

For better understanding the dynamics of sustainability transitions and decarbonization in hard-to-abate sectors such as aviation and maritime shipping, it is important to analyse the socio-technical transitions, the role of various actors, policy perspectives, industrial dynamics as well as study the differences and similarities in decarbonization strategies between these two sectors. Incumbent actors play a special role in decarbonizing maritime shipping and aviation, as these transport sectors are very capital- and infrastructure-intensive, are dominated by large industrial players and require the large-scale adoption of low emission innovation by the social-technical regime. The comparative study focusses on Sweden, a country that has high ambitions and many initiatives for sustainable energy transitions in aviation and maritime shipping. Yet, there are very few publications analyzing these socio-technical transitions in Sweden. This paper therefore aims to fill these knowledge gaps.

The research uses a comparative case study approach, comparing differences and similarities in the aviation and maritime shipping industries (Yin, 2018). The research uses the multi-level perspective (MLP) (Geels, 2002) as a conceptual framework, as well as analyzing path dependency, carbon-lock in (Unruh, 2000, 2002), the role of disruptions for sustainability transitions (Kivimaa et al., 2021) and regime resistance (Geels, 2014). The study uses qualitative methods, drawing on 25 in-depths semi-structured expert interviews, focus group discussions with 33 respondents and participant observations with experts from the aviation and maritime shipping industry between 2020 and 2024. The experts included actors from businesses and business associations, government authorities, as well as research and academia.

The study makes an empirical contribution in providing an analytical comparative perspective of how the maritime shipping and the aviation industries can potentially achieve deep decarbonization. Second, the research has the potential to contribute conceptually by analyzing the role of regime actors in co-developing niche innovations for sustainability transitions in hard-to-abate transport sectors like aviation and maritime shipping. The paper also provides insights into the dynamics of regime resistance and regime support, as well as disruption that has the potential to break through the carbon lock-in and change the path dependency in hard-to-abate transport sectors. This research can thereby contribute to an improved understanding of the dynamics, opportunities and barriers of sustainability transitions in hard-to-abate sectors. While previous literature analysed the role of incumbents for sustainability transitions (Geels and Schot, 2007; Geels et al., 2016), this has not been studied much in relation to hard-to-abate transport sectors like aviation and maritime shipping. These sectors are large-technical systems that require large amounts of infrastructure, investments and the replacement of fossil fuels and fossil-based processes is complex and difficult. Hence this research makes a contribution by applying and refining previous conceptual findings in relation to the case study and the empirical context.

The paper is structured as follows: Section 2 presents the material and methods, Section 3 outlines the theory, Section 4 presents the results, Section 5 includes a discussion of the implications of the research findings and Section 6 presents the conclusion.

2. Material and methods

2.1. Case study material

The research uses a comparative case study approach (Yin, 2017) which compares differences and similarities in the aviation and shipping industries. The expert interviewees and representatives of the reference group discussions represent perspectives primarily from the Nordic countries, particularly Sweden, but also Denmark, Finland and Norway, and wider international and regional issues that are relevant for international aviation management and maritime shipping management. As both aviation and shipping are international and beyond the boundaries of single countries, findings need to be discussed in an international context. The reason why Sweden was the main entry point of this case study, is its ambitious policy to become the world's first fossil-free welfare state (Fossil-free Sweden, 2021), achieving net zero emissions by 2045 (Ministry of Environment and Energy, 2017) and ambitious targets to have a fossil-free aviation industry and a fossil-free shipping industry by 2045. Swedish aviation aims for all domestic flights from Sweden being fossil-free by 2030 and all flights departing from Sweden being fossil-free by 2045 (Fossil-free Sweden, 2023a). Swedish maritime shipping aims for 70 % reduction in GHG from domestic shipping by 2030 compared to 2010 and net zero GHG emissions from domestic shipping by 2045 (Fossil-free Sweden, 2023b). At the same time, Sweden and the Nordics are part of the European Union (EU), which has ambitious policies for decarbonizing both aviation and maritime shipping due to its ReFuel EU Aviation (EU Parliament, 2022) and Fuel EU Maritime policies (EU Parliament, 2023) as part of the Fit for 55 policy package and the EU's aims to have net zero emissions by 2050. The expert interviewees and participants of the focus group discussions mentioned important issues for international aviation and maritime shipping, particularly relating to the goals of the International Maritime Organization (IMO), the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO). Aviation and maritime shipping are both strategically important for Sweden for trade and movement of people. Sweden is a country that is more than 2000 km long, it has as a long coastline, is sparsely populated and the efficiency of the road and train systems are limited by lengthy distances.

Definitions of the Swedish aviation and maritime shipping industry can be found in annex I, part 1.

The next section explains the methods of this study.

2.2. Methods

The study applied qualitative research methods for primary data collection and analysis. This research draws on insights from in-depth semi-structured, open-ended interviews, focus group discussions and participant observations with experts from the aviation and maritime shipping industry and site visits between 2020 and 2024. Key experts from the aviation and maritime shipping industry were interviewed, who were selected based on their leading positions within the regime. This included key experts from incumbent actors such as from major airlines, airports, shipping companies, ports, regulators and fuel producers.

Two workshops were held in January 2020 and September 2021 with experts from the aviation industry, that were the basis for focus group discussions to identify opportunities, barriers and pathways for deep decarbonization of the aviation industry. The workshops included 16–17 experts each time, some experts were attending both workshops while others attended one workshop. In addition, 6 additional interviews were conducted with sustainability managers from leading airlines, sustainability managers at airports, aviation business representatives and researchers that are experts in the transition towards fossil-free aviation. For the maritime shipping industry, the project team interviewed 15 experts from leading shipping firms and business associations, sustainability managers at ports, governmental institutions, and researchers that are experts in the transition towards fossil-free maritime shipping. The project team also interviewed 4 experts from fuel producers in the hydrogen, biofuels and electrofuels industries, who produce fuel both for the aviation and maritime shipping industry. This makes a total of 25 interviews and 33 respondents of focus group discussions (16 in 2020 FGD, 17 in 2021 FGD), hence a total of 58 responses from leading experts in the field. Site visits and participant observations were conducted between 2020 and 2024, including to an airport that has an electric flight school and is aiming to produce green hydrogen for aircrafts and a maritime shipping debate with policy-makers at the Swedish Parliament (Riksdagen).

The respondents were selected to represent a wide range of perspectives on the aviation and maritime shipping industry and non-fossil jet and shipping fuels, covering the latest insights from industry, policy and academia. The interviews and the second focus group discussion were recorded, transcribed and analysed using Nvivo. The first focus group discussion had a more explorative format and notes were taken of the discussions. The interview data was analysed according to a conceptual framework based on theories from socio-technical transitions for sustainability and industrial dynamics (see Section 3 below for details).

The main analytical themes are linked to the MLP and the role of incumbents for the regime, the socio-technical landscape and the socio-technical niche (Geels, 2002), disruption of the regime influenced by dimensions including (1) technology, (2) markets and business models, (3) regulations, policies and formal institutions, (4) actors and networks, and (5) behavior and cultural practices (Kivimaa et al., 2021) and issues related to path dependency and carbon-lock in (Unruh, 2000, 2002).

The coding pattern used in Nvivo for analysing sustainable energy transitions in aviation and maritime shipping can be found in Annex II. The primary data was supplemented with secondary data on energy and emissions from maritime shipping, aviation and data relevant to port and airport operations. See Tables 1 and 2 for an overview of the respondents.

The next section discusses the theoretical framing of this research.

Table 1
List of respondents from the interviews. Respondents who were both interviewed and participated in one or both workshops are marked as *.

Number #	*Interviews* Title	Organisation	Date
1	Sustainability manager*	National airport association	January 2020
2	Sustainability manager*	Regional airport association	March 2021
3	Project manager and business consultant*	Aviation-related business and network	March 2021
4	Sustainability manager*	International airline	May 2021
5	Sustainability manager*	Domestic airline	January 2022
6	CEO*	Aviation-related business	January 2022
7	Researcher	Aerospace and maritime research institution 1	September 2022
8	Researcher	Aerospace and maritime research institution 2	October 2022
9	Researcher	Maritime research institution 1	October 2022
10	Researcher	Maritime research institution 2	October 2022
11	Researcher	Maritime research institution 3	October 2022
12	Sustainability manager	Maritime shipping business association	October 2022
13	Team leader	Maritime Administration	October 2022
14	Sustainability manager	International shipping company	October 2022
15	Owner operator	Regional shipping company	October 2022
16	Project manager	Energy authority	October 2022
17	Sustainability manager	Small port 1	November 2022
18	Sustainability manager	Small port 2	November 2022
19	Sustainability manager	Large port 1	November 2022
20	Business development manager	Large port 2	November 2022
21	Power system expert	Grid operator	January 2023
22	CEO	Fuel producer association 1	April 2023
23	CEO	Fuel producer 1	April 2023
24	Head of marine fuels	Fuel producer 2	April 2023
25	Director	Fuel producer association 2	May 2023

Table 2
List of respondents from the two focus group discussions. Respondents who were both interviewed and participated in one or both workshops are marked as *.

Number #	*Focus Group Discussion 1* Title	Organisation	Date
1	Sustainability manager*	National airport association	January 2020
2	Sustainability manager*	Domestic airline	January 2020
3	Project manager*	Aviation network and research organisation	January 2020
4	Aviation expert*	Transport authority	January 2020
5	Head of business development*	Fuel supplier biofuels	January 2020
6	Business development	Fuel supplier biofuels	January 2020
7	Project manager	Energy authority	January 2020
8	Sustainability manager	National airport association	January 2020
9	Fuel manager	Fuel supplier biofuels and fossil fuels	January 2020
10	Researcher	Aviation center	January 2020
11	Researcher	University	January 2020
12	Researcher 1	Technical university	January 2020
13	Researcher 2	Technical university	January 2020
14	Researcher 3	Technical university	January 2020
15	Researcher 4	Technical university	January 2020
16	Researcher 5	Technical university	January 2020

Number #	*Focus Group Discussion 2* Title	Organisation	Date
1	Sustainability manager*	International airline	September 2021
2	CEO	Regional airport	September 2021
3	Project leader	Fuel supplier hydrogen	September 2021
4	Project manager and business consultant*	Aviation-related business and network	September 2021
5	Strategy manager	National airport association	September 2021
6	Sustainability manager*	National airport association	September 2021
7	Aviation expert*	Transport authority	September 2021
8	CEO*	Aviation-related business	September 2021
9	Team leader	Aerospace business association	September 2021
10	Consultant	Aviation consultancy	September 2021
11	Aviation expert	Transport business association	September 2021
12	Head of business development	Fuel supplier biofuels	September 2021
13	Head of business development	Fuel supplier biofuels	September 2021
14	Environmental expert	International consultancy	September 2021
15	Researcher 1	Technical university	September 2021
16	Researcher 2	Technical university	September 2021
17	Researcher 3	Technical university	September 2021

3. Literature review and theory

3.1. Literature review

A growing body of literature analyses the techno-economic opportunities and limitations for sustainable energy transitions in maritime shipping and aviation. One of the earliest research papers in this field was by Bows-Larkin (2015) who emphasized the intersection of aviation, shipping, and climate change policy.

For maritime shipping, Taljegard et al. (2014) modelled the cost-effectiveness of marine fuels in a carbon-constrained world. Hansson et al. (2019) conducted a multi-criteria analysis to evaluate the adoption of alternative marine fuels. Their findings presented a nuanced perspective by considering various criteria, such as economic viability, environmental impact and stakeholder preferences. Korberg et al. (2021) conducted a techno-economic assessment of advanced fuels and propulsion systems for decarbonizing maritime shipping.

Grahn et al. (2022) reviewed electrofuel feasibility for maritime shipping with a focus on cost and environmental impact. Their findings considered both the costs associated with electrofuel production and delved into the environmental impacts, emphasizing the importance of a holistic approach in assessing the sustainability of these fuels.

Kanchiralla et al. (2022) conducted a lifecycle assessment (LCA) and a cost analysis for decarbonized marine fuels. Beyond costs, the study considered environmental implications throughout the entire lifecycle, providing a more nuanced understanding of the overall sustainability of various fuel options.

Harahap et al. (2023a) analysed renewable marine fuel production, with a focus on pathways, policies and transition dynamics. Their analysis encompassed various pathways for fuel production, including biofuels and electrofuels, evaluating the technical and economic feasibility of each.

Urban et al. (2024) analysed the role of sector coupling between maritime shipping and other sectors, particularly for the production of renewable maritime fuels. They conclude that sector coupling between maritime shipping, the energy sector, agriculture, forestry and food producing sectors are increasingly emerging for renewable maritime fuel production.

Mäkitie et al. (2022) investigated the adoption of alternative fuels for maritime shipping in Norway, shedding light on the specific challenges and opportunities within this geographical context. Bach et al. (2021) also focused on Norwegian shipping, however analyzing the prospects for biofuels. The research highlighted the need for a coordinated effort among stakeholders, including industry players, policymakers, and investors, to drive the successful integration of biofuels into the maritime sector. Bergek et al. (2021) analysed the role of regime segmentation for decarbonizing maritime shipping. The study identified distinct regimes within the industry and explored how segmentation could either facilitate or hinder the transition process.

For aviation, Lai et al. (2022a) analysed the opportunities and challenges for mitigating the climate impact of aviation, whereas Lai et al. (2022b) combined LCA with socio-technical systems analysis to evaluate the environmental impacts of sustainable aviation fuels (SAF).

De Jong et al. (2017) carried out an LCA with a focus on GHG emissions for renewable jet fuel production. Noh et al. (2016) analysed policy perspectives related to biofuels for aviation, while Wang et al. (2019) focused on the challenges and opportunities for biofuels for aviation. Winchester et al. (2015) investigated the impact of advanced biofuels for the US aviation sector. This research shares a common focus on the policy aspects of biofuel adoption in aviation, discussing the role of incentives, rules, and mechanisms to promote biofuel use.

Baroutaji et al. (2019) investigated the opportunities for hydrogen and fuel cell technology for aviation, analysing technical aspects of integrating hydrogen fuel cells into aircraft, considering factors such as efficiency, weight, and safety.

Gnadt et al. (2019) and Schäfer et al. (2019) evaluated the techno-economic and environmental implications of electric aircrafts. These studies provided a comprehensive analysis of the potential benefits and challenges associated with electric propulsion in aviation.

Kim et al. (2019) and O'Connell et al. (2019) also analysed the transition to aviation biofuels. Kim et al. (2019) employed a socio-technical lens, emphasizing the need for collaborative efforts among various actors in accelerating the transition to aviation biofuels while O'Connell et al. (2019) considered factors such as feedstock availability, production processes and policy frameworks

Trinh et al. (2021) investigated the policy impacts of renewable jet fuels, including feedstock availability and policy options for scaling-up the production and use of sustainable aviation fuels (SAF). Hoelzen et al. (2022) analysed the prospects for hydrogen-powered aviation and infrastructure perspectives, providing a comprehensive analysis of the technical feasibility of hydrogen as an aviation fuel, considering factors such as energy density, storage, and safety.

Christley et al. (2024) analysed the role of expectations in shaping sustainable energy transitions for aviation. They highlight the role that industry actors play for driving forward sustainability transitions in aviation, including for advanced biofuels, electric aircrafts and hydrogen fuels.

Some of the previous research is primarily on techno-economic assessments related to new fuels and technology, particularly biofuels, electrofuels, hydrogen and electric propulsion. Some studies focus on policy perspectives and transition dynamics, yet within a rather narrow framing that is focused on specific fuels/technologies or that only focusses on (parts) of maritime shipping or aviation.

A comparative analysis between the aviation and maritime shipping sectors tends to be missing, despite many similarities between the two sectors and similar use of fuels for decarbonization. This is where this paper adds value and new knowledge, by providing a comparative perspective for both aviation and maritime shipping, and discussing a wide range of different fuels and technologies for sustainability transitions.

Similarly, socio-technical transitions perspectives for hard-to-abate sectors are often less well explored. Previous research on lock-in mechanisms in transition processes analysed energy transitions in road transport (Klitkou et al., 2015), while other research explored the coupling of various sectors, such as analyzing the inter-sectoral dynamics for sustainability transitions (Dahl Andersen et al., 2020) and analyzing multi-system dynamics for net zero transitions (Dahl Andersen and Geels, 2023). This research adds value by exploring the socio-technical transitions perspectives for hard-to-abate sectors like maritime shipping and aviation.

The next section outlines the case study material.

3.2. Theory

The maritime shipping industry and the aviation industry are conceptualized as socio-technical systems undergoing sustainability transitions (Köhler et al., 2019), where networks of technologies, actors and institutions are embedded in infrastructural, political, economic, geographical and socio-cultural aspects (Markard et al., 2012). The maritime shipping industry and the aviation industry are currently undergoing socio-technical changes towards decarbonization that are a result of landscape pressures due to climate change.

3.2.1. Carbon lock-in, path dependency and disruption

The development, adoption and diffusion of low carbon technologies is a complex, non-linear process that may be inhibited by carbon lock-in and path dependency (Unruh, 2000, 2002). Sustainability transitions in aviation and maritime shipping therefore involve disruption of the current (quasi-)equilibrium and leading to transformational changes in multiple dimensions. Disruption can facilitate or even accelerate sustainability transitions (Kivimaa et al., 2021), through various dimensions including (1) technology, (2) markets and business models, (3) regulations, policies and formal institutions, (4) actors and networks, and (5) behavior and cultural practices. The dimensions constitute the principle mechanisms for change in transition theories.

An improved understanding of the dynamics of disruptive innovation, regime resistance, carbon lock-in and path dependency are essential for analyzing the industrial dynamics and transition pathways from fossil-based shipping and aviation towards an increased use of renewable fuels. Disruptive innovation emerges when there are new technologies in existing markets (Henderson and Clark, 1990). In the field of transition studies, scholars have also been studying how niche innovations –including disruptive innovations- emerge, grow, survive or decline over time (Raven et al., 2016). In the maritime shipping and aviation sectors, the majority of fuels are fossil-based, whereas new fuels like advanced biofuels, electrofuels and hydrogen, as well as electric propulsion, are emerging at the niche level. These new fuels and technologies emerge as various technological trajectories (Dosi, 1982) which are supported by different key actors in aviation and maritime shipping simultaneously. These new fuels and technologies also require a systems' change in some cases, with new production, distribution, fueling, storage and charging facilities required in ports, airports, refineries and bunkering facilities, new supply chains, as well as a change in the design and construction of vessels and aircrafts. These new fuels and technologies can potentially break through the carbon-lock in and the fossil fuel path dependency (Unruh, 2000, 2002), thereby destabilizing and altering the dominant regime and potentially leading to new technological trajectories. Disruptive innovation can potentially disrupt the market, push incumbent firms out of their market leadership, and create space for new niche technologies and emerging companies. Breaking through the carbon lock-in towards sustainability transitions has environmental and social advantages as well as economic and business advantages to avoid stranded assets and financial risks (Unruh, 2019). Earlier research however finds that incumbents in existing fossil fuel regimes often negate the benefit of alternative fuels. Incumbents often argue that policy-makers and scientists are unrealistic in their visions for sustainability transitions (Geels, 2014).

3.2.2. *The role of incumbent actors*

Incumbent actors, such as established companies and industries, have significant influence in socio-technical regime transitions toward sustainability. They often play a dual role, both as drivers and recipients of transition processes. Incumbents play pivotal roles in determining the direction and pace of transitions. Their actions and strategies—whether they resist change, adapt to new technologies, or actively drive innovation—affect the unfolding of these pathways. Incumbent actors' responses to external pressures and their engagement with emerging technologies and policy frameworks significantly influence the trajectories of low-carbon electricity transitions (Trencher et al., 2021; Kungl and Geels (2018); Geels et al., 2016; Geels and Schot, 2007).

For instance, in the energy sector, incumbents have faced destabilization due to the rise of renewable energies (Kungl and Geels, 2018). Smink et al. (2015) emphasize that incumbents' institutional strategies can either foster or hinder sustainable innovation. Additionally, van Mossel et al. (2018) and Hoerisch (2018) point out that incumbents possess dynamic capabilities and can actively contribute to transitions through adaptive strategies and innovations. Incumbents' responses to regulatory changes significantly impact the pace and direction of sustainability transitions (Stalmokaite and Yliskylä-Peuralahti, 2019 and Kattirtzi et al., 2021). The study by Nurdiawati and Urban (2022) emphasized the pivotal role of incumbent actors in advancing technologies like advanced biofuels, green hydrogen and carbon capture and storage (CCS) for decarbonizing the oil refinery sector.

3.2.3. *The multi-level perspective (MLP) and sustainability transitions*

This research draws on the MLP for sustainability transitions (Geels, 2002). Geels and Schot (2007) conceptualized four different types of transition pathways for sustainability transitions, namely (1) the transformation pathway (2) the reconfiguration pathway (3) the technological substitution pathway and (4) the de-alignment and re-alignment pathway. The typology considers various factors, including technological innovation, policy frameworks, and the roles of different actors within the transitions. Geels et al. (2016) later refined the theories by adapting the framework to the specific context of low-carbon electricity transitions, incorporating a temporal dimension and providing a more detailed contextualization of the transition pathways.

The MLP (Geels, 2002; Geels et al., 2016) is used in this research as a conceptual framework to analyse innovation processes and their impact on socio-technical transitions within hard-to-abate industries. Hard-to-abate sectors, including maritime shipping industry and aviation industry, are currently under transformation pressure to reduce their emissions, transition from fossil fuels to cleaner, renewable fuels and thereby transform the dominant socio-technical regime towards deep decarbonization (Geels et al., 2017). The MLP is therefore a highly relevant framework for understanding these dynamics and the interactions at the different levels of niche, regime, and landscape.

To apply the socio-technical regime concept, we focused on the maritime shipping and the aviation industry and its current fossil-fuel dominated fleets of ships and aircrafts, related port and airport infrastructure, fuel producers and financiers. To apply the niche concept, we analysed initiatives towards sustainable energy transitions and electrification, which have the potential to transform the established regimes for aviation and maritime shipping. For the socio-technical landscape concept, we considered national and international policies and targets to reduce GHG emissions as well as societal pressures related to climate change. We integrate the niche, regime and landscape levels of the MLP (Geels, 2002) with Kivimaa et al. (2021) systems' that are transformed by disruptive innovation as well as investigating aspects of regime resistance (Geels, 2014) and regime support.

Hard-to-abate sectors, such as heavy industry and maritime and air transport, face huge challenges related to decarbonization as they have high emissions, changes are very costly and require large-scale investment, policy, business models and value chains have to change, while technological solutions are still under development (e.g. large electric aircrafts, hydrogen-driven ships).

The next section presents the results of the study.

4. Results

4.1. *Decarbonization options for maritime shipping and aviation*

4.1.1. *Aviation*

The IATA has the global target that its member airlines will be achieving net-zero carbon emissions from their operations by 2050, primarily through the use of SAF (IATA, 2021). This target applies to IATA's 300 airlines in over 120 countries. UN agency ICAO has also the goal to achieve net-zero carbon emissions by 2050 and has 193 members states (ICAO, 2023).

Our interviews and focus group discussions find that in the past, the aviation sector has reduced its energy and carbon intensity by incremental innovation in energy efficiency through engine improvements, material improvements and enhanced operations management. Each new aircraft generation minimizes CO_2 emissions by about 30 %. Yet, respondents argue that this is not enough to mitigate climate change and to achieve decarbonization of aviation, instead more radical innovation is required such as replacing fossil fuels by renewable energy and renewable-based electricity, using sustainable aviation fuels (SAF), electric aviation and hydrogen (Lai et al., 2022). These options are briefly elaborated below, and in more detail in Annex I part 2:

- SAF,
- Electric propulsion
- Green hydrogen

Table 4 in Annex I, part 3, summarises the different alternative aviation fuels.

4.1.2. Shipping

The International Maritime Organization (IMO) has the following emission targets for international maritime shipping:

- Cutting the total annual GHG emissions by 20–30 % by 2030 and 70–80 % by 2040 compared to 2008.
- Peaking GHG emissions as soon as possible from international shipping
- Reaching net zero GHG emissions by about 2050 (IMO, 2023).

Non-international shipping is not included in these targets. Maritime shipping will be included in the EU ETS from 2024.

Our interviewees explained that in the past, operational measures improved energy and carbon efficiency both for fleet management (e.g. vessel design, speed optimization, logistics management) and port management (e.g. onshore power, decarbonization of port operations). However, as in aviation, the efficiency improvements are not sufficient for mitigating climate change and decarbonizing the maritime shipping sector. Instead, according to our interview respondents, fossil fuels have to be replaced with alternative renewable marine fuels in the medium- and long-term, while larger ports will most likely need to play a more active role in providing alternative marine fuels and becoming energy hubs.

Similarly to aviation, advanced biofuels, electrofuels, hydrogen and electric propulsion play a major role in decarbonizing the maritime shipping sector. However the decarbonization options are more complex for the maritime shipping sector than for aviation, as a larger variety of functions and segmentation along the shipping value chain occur (Bergek et al., 2021). Table 3 in annex I outlines the different segments of the maritime shipping industry. The largest distinction between the different shipping segments can be made between containers and other solid cargo carriers; tankers and passenger ships. According to the expert interviews, the accountability of other types of ships and boats (e.g. fishing vessels) is generally low as they can vary heavily in size and very large fishing fleets may be operating on the high seas for very long periods of time without reaching ports.

Key options for decarbonizing the maritime shipping sector are as follows and in more detail in annex I part 2:

- Liquid natural gas (LNG)
- Green hydrogen
- Advanced biofuels, such as Hydrogenated Vegetable Oil (HVO), bio-methane and bio-methanol
- Methanol
- Ammonia
- Battery-electric propulsion
- Wind-based and solar-based propulsion

Table 5 in Annex I (part 3) below summarises the different alternative marine fuels.

4.2. Role of the socio-technical regime versus role of the niche in driving forward sustainability transitions in aviation and maritime shipping

This research analysed the role of disruptive innovation, carbon lock-in and path dependency, regime resistance, laggards and first movers, as well as the role of the incumbents at the regime level versus the role of niche players. These aspects are important for analyzing the industrial dynamics and transition pathways from fossil-based aviation and shipping towards an increasing use of sustainable marine fuels and sustainable aviation fuels.

4.2.1. Disruptive innovation to break through the carbon lock-in and path dependency

Disruptive innovation is likely to emerge for the aviation and maritime shipping sector as new technologies are currently under R&D that will be introduced to existing markets (Henderson and Clark, 1990). New fuels like advanced biofuels, electrofuels, hydrogen and electric propulsion, are emerging at the niche level. These new technologies and fuels will require a systems change for new fuel production facilities, transportation and distribution facilities, new supply chains, new infrastructure (e.g. electric charging stations) as well as a change in the design and construction of vessels and aircrafts. Other niche innovation like wind-powered vessels and electric ferries for coastal near-shore shipping have potential to disrupt the current fossil-based path dependency. Fossil fuels and fossil infrastructure is therefore likely to be disrupted, hence there is a chance for breaking through the carbon-lock in and altering path dependency (Unruh, 2000; Unruh, 2002). This could potentially destabilize and change the current regime, hence leading to new technological trajectories. This has the potential to disrupt the financial viability of fossil-dominated systems, as one interviewees reports:

> "When the new technology will get introduced, the supply and demand of traditional kerosene will be reduced and the price [of kerosene] will go up." (Head of sustainability, international airline, September 2021).

Yet, at the moment alternative aviation and maritime fuels are still more expensive than conventional jet fuel and conventional shipping fuel.

> "[Advanced biofuels for shipping are] two times more expensive, more or less. That was a premium because only sustainable certified feedstock waste and residual feedstock are used and they are already more expensive at the feedstock versus crude oil." (Head of marine fuels, fuel producer 2, April 2023).

SAF is currently 4–5 times more expensive than conventional jet fuel, hence renewable marine fuels are about half the price of SAF in aviation.

> "25 years from now, biofuels and electrofuels will really be the key because you can use the existing infrastructure. Most of the gains regarding the emissions will come from the replacement of the existing fuel. (Project manager and aviation business consultant, September 2021).

There is a risk of stranded assets, both in case companies keep on relying on their high-carbon infrastructure and in case that they invest into the "wrong" technological trajectories which then do not become dominant. One interview explains it as follows:

> "You need to make sure you make use of your assets because if you don't, they become stranded assets. We need to be smart because we can't invest in a lot of new infrastructure just to provide a new energy solution. We need to use the infrastructure that's already in place, and what we see is that we do have a lot of that infrastructure already basically to solve the energy transition" (Sustainability manager, large port, November 2022).

4.2.2. Role of the incumbents at the regime level and role of smaller actors at the niche level

The incumbents in the aviation and maritime shipping industry play a major role for investing in and contributing to the development of new types of vessels and aircrafts, investing in alternative fuel production and supporting the development of infrastructure and supply chains for sustainable energy transitions in these two sectors. Smaller actors play a role for developing cutting-edge innovative technology, such as electric aircrafts or electric boats. However it is often in collaborations with the incumbent actor such as airlines, shipping companies, aircraft manufacturers, shipbuilders, airports, ports and fuel developers that smaller players are able to scale-up and break through from the niche level to the regime level. This is being exemplified by the following quote:

> "The demand needs to be there so that producer can actually start building or investing because it takes roughly (…) three to five years to build a plant or increase capacity or convert your existing fossil refinery to a bio plant. (…) The players are around, the oil companies and so on are ready to invest, and also new start-ups are ready to invest in this [SAF] if they feel they will be confident on the demand in the future. (…) So I think it's fully possible [to decarbonize the aviation industry]. We believe and we are increasing our production. We've got to make it 15 times more than now in just two years. So we strongly believe in SAF and fossil free aviation" (SAF fuel producer, September 2021).

Some interviewees point out the role of different players along the value chain as well as the segmentation of the shipping industries. Both aviation and maritime shipping are large technical systems (Hughes, 1987), which require large investments, huge infrastructure, have high entry barriers and are dominated often by a few large actors. Innovation here happens mainly at the regime level, although some niche level innovation occurs too (e.g. Heart Aerospace's development of a hybrid electric 30 seater for short-haul flights or Candela's development of electric boats for coastal commuting in urban areas). Yet, the largest-scale transitions from fossil fuel to renewable fuels are happening by incumbent actors that are very visible along the value chain and that have strong customer exposure.

> One expert interviewee explains: "Some sectors that are not interested at all are less consumer-facing. And then you would have the H&Ms and IKEAs of this world that know that to decarbonise their products, they need to reduce their Scope 3 emissions, which are huge. (…) Their very large scope 3 emissions are our scope 1 emissions. And so, if we reduce that, we actually help them decarbonise the supply chain." (Sustainability manager, international shipping company, October 2022).
>
> Yet, another interviewee remarks that "It's important to bring in also the smaller companies, which are very innovative. It's a tendency that everything should happen with the big companies, the big multinational ones, and that they are important for the scale of it. But on the innovation side, they normally don't have the innovation brains, those you will find in the smaller companies" (CEO, fuel producer association, April 2023).

An interesting aspect is also the role of municipalities in daring to develop a vision for the future that involves fossil-free aviation, as our site visits to airports showed. One example is Skellefteå airport, which is owned by the municipality. The municipality has been active in developing a vision, then investing public funds to pursue this vision and as a consequence private investment has followed. The municipality invested in electric charging infrastructure for aircrafts, after which a private flight school decided to use the airport for training purposes. Similarly with hydrogen production for aircafts, where the municipality has developed a joint venture with private companies. The municipality also has close collaboration with the local power utility Skellefteå Kraft, which is publically owned. The utility company is mainly powered by hydropower and also has deals to supply the Northvolt battery factory with low carbon electricity. In this case Skellefteå municipality is engaging both with incumbent actors and with niche players.[2]

4.3. Regime resistance vs regime support

Our qualitative research results show a difference between parts of the aviation industry and parts of the maritime shipping industry regarding the level of regime resistance that occurs towards sustainable energy transitions. Our interviews and focus group discussions reveal that in the aviation sector, there is more wide-spread regime support for achieving fossil-free aviation across Europe, amongst the entire value chain, from aircraft manufacturers, fuel producers, airlines and airport operators. This is for example the case in Sweden, which has the goal to completely decarbonize aviation by 2045, as well as wide-spread support for this vision in the Nordics and the wider EU, for example due to the ReFuel EU Aviation policy. The EU policy aims for a share of 85 % sustainable aviation fuels by 2050 (EU Parliament, 2022).

In Sweden, incumbents, such as major airlines, airports, aircraft manufacturers and fuel producers are actively working towards this transition, alongside smaller start-ups and scale-ups such as electric aircraft manufacturers. The major incumbents at the regime level are therefore actively working together with smaller actors to achieve the joint vision of fossil-free aviation. Hence in relation to aviation, the observation can be made that there is a lack of regime resistance by major aviation actors, at least in Sweden, according to our interviews, focus group discussions and field visits. However there still seems to be a lack of awareness by the public that SAF is available for purchase on flights and the willingness to pay is rather low (Dowds, 2023).

On the other side in the maritime shipping sector more regime resistance can be observed by some actors, especially those that are close to the fossil-fuel dominated socio-technical regime, such as oil tankers, according to our interviewes with shipping associations, shipping companies, fuel producers and academic experts.[3] There are some front-runners and some laggards, with some large international companies being front-runners and making large investments in alternative maritime shipping fuels (e.g. Maersk with methanol), while others are showing clear signs of regime resistance by delaying action and not investing in new cleaner technology. Investing in LNG-powered vessels is further prolonging the carbon-lock in and path dependency as fossil fuels are favoured over renewable maritime fuels. Our qualitative research findings shows that there is a much larger variety of approaches towards mitigating emissions from the maritime shipping industry, partly due to the fragmentation and complexity related to segmentation in the shipping industry, partly due to a lack of external pressure. For example, some interviewees from shipping companies and shipping associations pointed out that maritime shipping companies with customers that demand greening of supply chains or greener travelling options are much more likely to change than those who are dealing with “dirty businesses” that have lower accountability and lower visibility. As an example, oil tankers feel far less pressured to switch to renewable maritime fuels than local ferries that have local customers or container companies that have global retailers requesting greener fuels along their value chain. Some interviewees argued that some actors are displaying more subtle signs of regime resistance by a) arguing that the emissions of maritime shipping are low compared to other sectors (e.g. energy production), b) that the share of emissions will further reduce in the future due to a decline of global transports of fossil fuel and c) that the emissions from maritime shipping are likely to decline in the future due to a reduction in global supply chains as production will become more localized and less fossil-based. Some of our interviewees from the maritime shipping industry and academia highlighted that inaction and simply waiting out the problem was a strategy for regime resistance. Yet, as international policy pushes for decarbonization and some globally leading shipping companies are investing in new vessels that can run on renewable liquid fuels, such as biomethanol and e-methanol, there is a risk that the maritime shipping industry will experience some disruption the coming years and decades which is also likely to affect the laggards in the sector.

Our research concludes that aviation and shipping segments affected by visible external pressure tend to be at the forefront of decarbonization, whereas shipping segments that are less visible rather tend to be laggards (e.g. oil tankers). Hence, the decarbonization efforts of aviation and maritime shipping companies are partly driven by consumers (including along the supply chain), in addition to policies and legislations, as well as economic incentives.

4.4. The role of policy

To overcome the regime resistance, policy and financial instruments as well as political support is required at the national, regional and international level. The international climate targets by IMO, ICAO and IATA, as well as the EU Fit for 55 policy package that includes the ReFuel EU Aviation and Fuel EU Maritime policies provide strong frameworks for change and reduce uncertainty for investors and innovators. National goals such as those in Sweden and other EU countries are at least as ambitious as those regional and

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[2] To our knowledge the case of Skellefteå airport is an emerging trend of public-private partnerships between airports and ports for renewable fuel production, yet this is a relatively new phenomenon and does not yet follow a larger pattern across Sweden.

[3] Previous research from Norway shows that there may be strong support for sustainable energy transitions at the national and local level, with many ferries operating on clean electricity (Mäkitie et al, 2022; Bach et al, 2021; Bergek et al, 2021). The findings of these studies are therefore geographically specific and may differ from (parts of) Sweden.

international goals. Together they create strong policy and legislative frameworks for deep decarbonization for aviation and maritime shipping.

> As one interviewee explains: "We should be grateful for the EU politicians. They've been very strong in delivering clear messages that we need to work with hydrogen [and other sustainable fuels]" (CEO, fuel producer association, April 2023). Another interviewee reports: "One political driver comes from the European Union, the Green Deal, the Fit for 55 and the inclusion of shipping into the European Emissions Trading Scheme. (...) The price on carbon is going to change the dynamics in the freight market for all the ships that call in EU ports, which (…) is a very important shipping market." (Researcher, maritime research institution 1, October 2022)

Once the price of CO_2 under the EU ETS will be higher, it will be too expensive to pollute and then even the change-resistant laggards at the regime level are likely to switch towards renewable maritime fuels. The experts we interviewed assume that the financial threshold level could be reached when one ton of CO_2 costs about 150 Euros (compared to about 60–100 Euros per ton during the last two years), according to several experts. In that case the business models of those shipping companies have to change, to avoid excessive financial penalties.[4] Three interviewees report the following:

> "There is a big price gap between the green fuels and the conventional fossil fuels. (…) Looking at the historical development of fuel prices and its impact on energy efficiency, you have to have a very high price of carbon." (Researcher, maritime research institution 1, October 2022)
>
> "If you're looking at putting a carbon price, if you started at 50 - 60 dollars and then move it up to 150 dollars (…) you're looking at a lot of cash." (Sustainability manager, international shipping company, October 2022).

There is also the risk of carbon leakage from countries that are demanding tighter emissions regulations to countries that have lower requirements, e.g. when refueling in other countries. This can be reduced by having regional or even international legislations at the IMO and ICAO levels. In 2023 the EU introduced its carbon border adjustment mechanisms for imports to the EU from countries with lower emission control requirements, which are aligned to the EU ETS costs of carbon.

4.5. *Differences and similarities for decarbonizing maritime shipping and aviation*

Table 6 shows the findings related to the differences and similarities for decarbonizing the maritime shipping and aviation sectors.

Our interviews, focus group discussions and site visits show that a similarity between maritime shipping and aviation is that they are likely to use similar decarbonized fuels and technology, mainly advanced biofuels, electrofuels, hydrogen and electricity. Hence both hard-to-abate sectors will require a large up-scaling of alternative fuel production, as well as infrastructure for production, transportation, distribution and storage close to airports, ports and fuel bunkering sites. However there is a larger variety of different technological trajectories in the maritime shipping industry, partly due to segmentation.

Airports and ports are likely to become energy hubs that act as centers for fuel production, transportation, distribution and storage for a variety of alternative renewable fuels. This will require large-scale investments and needs to go far beyond the current alternative fuel production capacities.[5]

Our interviews, focus group discussions and site visits show that differences are that the aviation industry is very visible to public scrutiny, as they deal mainly with passenger transport and are accessible for a large part of the global population. The maritime shipping industry is more conservative, more hidden from the public eye as they mainly deal with cargo. The interviewees report that maritime shipping has less tightly regulated legislation, especially at the international level, there is a low requirement for fuel quality and the segments within maritime shipping are very fragmented. On the other side, aviation is more tightly regulated with regards to safety, fuel quality and emission control, including at the international and regional level. The interviewees also highlight that this increases the costs of the fuels for aviation much more than the costs of shipping fuels, which are inexpensive fuels and of lower quality compared to aviation.

An example of international regulation for aviation is the inclusion of aviation in the EU ETS since 2012, whereas maritime shipping is only included in the ETS from 2024, and there are loopholes (for example for smaller vessels). At the international level, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) by the International Civic Aviation Organization (ICAO) is in the pilot phase since 2021, with 115 states having joined voluntarily, while participating may be compulsory during later stages (e.g. from 2027 onwards). The aim of CORSIA is to have a harmonized, international system in place for emission reductions and offsetting. Such harmonized, international approaches to reduce emissions do not exist yet for maritime shipping. However at the EU level both the Fuel EU Maritime and the ReFuel EU Aviation initiatives under the EU's Fit for 55 policy package are actively applying pressure at the landscape level that is changing the regime towards sustainability transitions in aviation and maritime shipping.

> Regarding the differences between the aviation and the maritime shipping sector, one interviewee reports it as follows: "Historically, (…) the shipping sector has a rumor of being relatively conservative so that they for very long time disregarded the need to make any efforts in their sector. It is fantastic that the IMO have had the courage to put the international goal for

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[4] Modelling results show that for Sweden, biomethanol and hydrogen-based marine fuels are cost-effective at a carbon price beyond 100 €/tCO2 and 200 €/tCO2 respectively (Harahap et al, 2023).

[5] This resonates with earlier findings, e.g. by Alamoush et al, 2022 and Bjerkan et al, 2021; Kivits et al, 2010.

Table 6
Summary of comparative elements between the international aviation and maritime shipping sectors.

Aspect	Aviation	Maritime
Primary function	Leisure, business travel (passengers)	Trade (goods)
Industry structure	Dominated by a few major players (aircraft manufacturers and airlines segments)	Fragmented, consists of a large number of shipbuilders, shipowners, operators, end users
Alternative fuels	Sustainable aviation fuels, including hydrogen-based fuels; electric propulsion More tightly regulated with regard to safety, fuel quality and emission control	LNG, biofuels, hydrogen-based fuels, wind propulsion, nuclear, and electric propulsion. It can be influenced by type of ships, length of voyages, and region of operation. Low requirement for marine fuel quality
Global policy landscape	Global market system for emissions trading exist (CORSIA)	IMO 2050′s targets
Public perception	Necessary, more visible to public scrutiny	Distant; importance not widely recognized. Visibility varies influenced by positions in the overall value chain and market dynamics
Infrastructure	More standardized infrastructure and facilities driven by international regulations	Port is less homogeneous due to vessel types, cargo handling requirements, local factors, and regulatory variations.

> emission reductions.” (Researcher, Maritime research institution 2, October 2022). Another interviewee reports: “(…) In aviation there are regulations in place, there are mandates. (…) It creates demand. (…) Aviation is moving faster on decarbonization. The legislation is there. Marine is coming behind. So now with Fuel EU Maritime, the situation will be changing. For marine, the demand is only forming (…). So the industry is clearly in the transition.” (Head of marine fuels, fuel producer, April 2023).

Another difference between maritime shipping and aviation is the segmentation dynamics in the maritime shipping sector. In aviation, new fuels and technologies are mainly required for two different segments: short-haul flights and long-haul flights. At the moment, both segments can be fueled by SAF (both advanced biofuels and electrofuels) as drop-in fuels. In addition, short-haul flights are likely to be operated by electric aircrafts or hybrid-electric aircrafts (e.g. up to about 400–800 km from about 2028 onwards), whereas long-haul flights are likely to be operating on SAF and later hydrogen (from about 2035 onwards). The segmentation dynamics are more complex in maritime shipping, depending on type and size of ships, length of voyages, region of operation. Short-distance segments can also be electric (e.g. some ferries), while long-range shipping segments (containers, bulk carriers etc.) are likely to be using renewable liquid fuels. Yet, fuels are less standardized in maritime shipping than in aviation and need to fulfill lower standards for safety and accreditation. A plethora of different fuels can therefore be used, which are likely to co-exist alongside each other. As interviewees report, different shipping companies may be choosing different technological trajectories at different time scales. At the time of some of the interviews in autumn 2022, the world’s largest container shipping companies initially chose different strategies: Danish-based Maersk invested in dual-fuel methanol-driven vessels (25 new methanol-driven vessels out of a total fleet of about 700 ships by 2025), whereas Swiss-based competitor MSC invested in LNG vessels (10 new LNG-driven vessels out of a total fleet of about 700 ships by 2025/26, including bio-LNG and e-LNG). One interviewee commented on this development as follows:

> “This means if these two shipping companies operate on the same shipping routes, if they now invest, we’re starting to invest in different fuels for their ships. You will need to have a double infrastructure in the port side for these two different fuels” (Sustainability manager, maritime shipping business association, October 2022).

However less than a year later, in mid-2023, it was reported that MSC, as well as other large shipping companies, also started investing in methanol-powered vessels (The Maritime Executive, 2023; Container News, 2023). The speed of the transitions is increasing fast as in November 2023, Maersk announced a deal with Chinese Goldwind to supply 500 kt of green methanol each year from 2026, including both bio-methanol and e-methanol (Maersk, 2023). The shipping company also increased its order of methanol-powered vessels to 40 (status spring 2024). By mid-2024, the top 10 major container shipping lines had announced to either build or retrofit vessels that can be powered by methanol.

> One interviewee concludes that “the dynamics in the three major shipping segments (container ships, tankers and dry bulk ships) are very different. The container lines and container business is very concentrated so that the big five have a market share that covers 80 percent of the market” (Researcher, Maritime research institution 3, October 2022). For tankers and dry bulk carriers there are hundreds of shipping companies offering comparable services. Entry barriers are lower, enabling easier entry and exit of the market. For the container ships the entry barriers are high and the leading container lines have been in operation for decades. The container lines have to adopt a long-term perspective that also addresses decarbonization, whereas this is less often being adopted by the smaller tanker and dry bulk companies. However a change can be seen for smaller shipping companies that are family-owned or publicly listed and hence “being subject to some pressures from their shareholders or possibly from the shipping banks as well.” (Researcher, Maritime research institution 3, October 2022).

The role of maritime shipping banks and financiers is critical in shaping sustainability transitions as highlighted by other studies.

Shipping finance is rather concentrated, contrary to ships' ownership and ports, which also adds pressure to shipping companies, as they need to be able to obtain financing for their vessels. Similarly for aviation, investors and financial institutions are becoming more aware of the climate impact and require cleaner solutions (Geddes and Schmidt, 2020; Naidoo, 2020; Fricaudet et al., 2023).

The next section discusses the implications of the research findings.

5. Discussion

Figs. 1 and 2 indicate the elements influencing sustainability transitions in the maritime shipping and aviation sectors.

The findings of this research indicate how there are similarities and differences between aviation and maritime shipping related to decarbonization. Overall, the aviation industry and the maritime shipping industry as socio-technical systems are difficult to transform. Main challenges are high costs of alternative fuels, limited production of alternative fuels, slow uptake by incumbents and customers, long lifetimes linked to infrastructure and technology development, limited international policy instruments and sustainability concerns about some fuels. Similar fuels are being used, with a focus on advanced biofuels, electrofuels, hydrogen and electrification. A variety of fuels are likely to be used simultaneously in the maritime shipping sector, for various segments of the shipping industry and in various regions. For aviation several fuels are likely to co-exist as well, with SAF from advanced biofuels being already available as a drop-in fuel today for both short- and long-haul, whereas electric aviation may play a role for short-haul flights from about 2028 or later, while hydrogen will most likely only enter the commercial market from 2035 or later.

Both sectors are large technical systems that have mostly high entry barriers for entering the market, requiring huge investments, large infrastructure, many actors and international linkages. Policy plays an important role in creating landscape pressure to destabilise the current fossil-dominated regime and for niche-level technology to break through at the regime level. Interestingly, while some niche players are taking a central role in developing niche-level innovation (e.g. electric airplanes developed by Swedish start-up Heart Aerospace, with Air Canada and Saab as shareholders), it is also large international regime players that are driving forward innovations. For example, this is the case with Airbus developing hydrogen-based planes, airlines that are ordering electric planes (e.g. Air Canada, Braathens Regional Airlines BRA, Icelandair, Mesa Air Group, New Zealand's Sounds Air, Scandinavian Airlines SAS, United Airlines and aircraft lessor Rockton), as well as airlines adopting the up-take and even the production of SAF (e.g. electrofuels production as a joint venture between SAS, Vattenfall, Shell and Lanzatech), airports and ports becoming hubs for sustainable fuel production and electric charging infrastructure, and international shipping companies investing in methanol-powered vessels (e.g. Maersk).

This research therefore concludes that incumbent regime actors play an important role in co-producing niche innovations for sustainability transitions, together with niche players. This is a conceptually valuable finding, as most research on sustainability transitions in the past focused on the role of niche players in developing innovation that can transform the regime level, whereas the internal dynamics at the regime level and the co-production of innovation between niche players and incumbents has received less attention.

From a conceptual perspective this results in an amended MLP with more niche innovations emerging from within or in

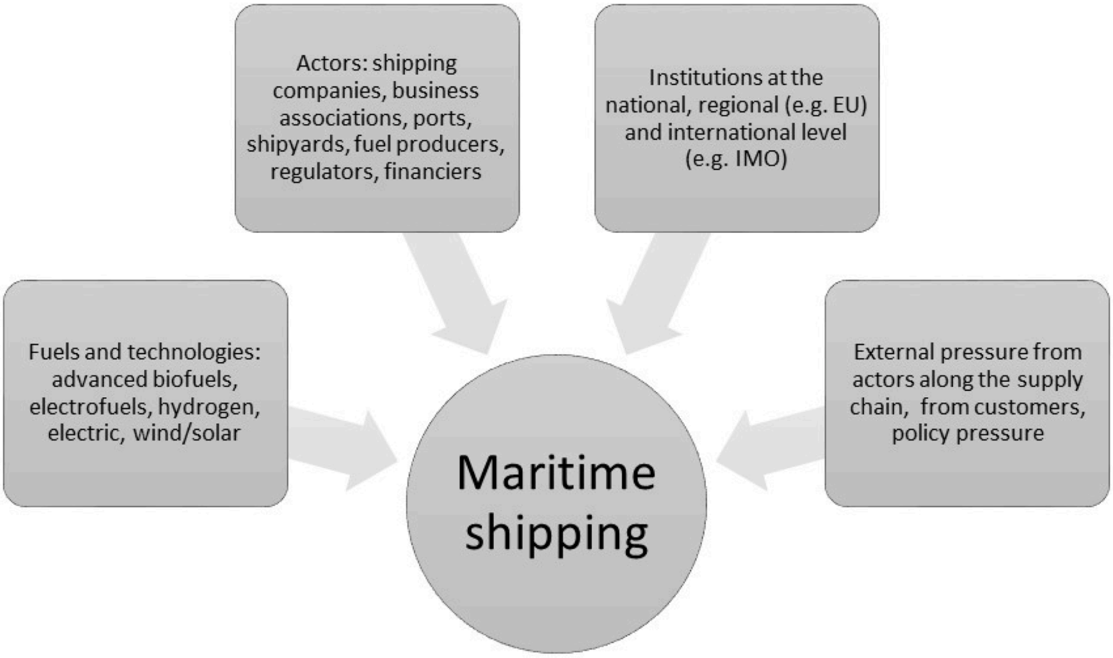

Fig. 1. Elements influencing sustainability transitions and decarbonization efforts in the maritime shipping sector.

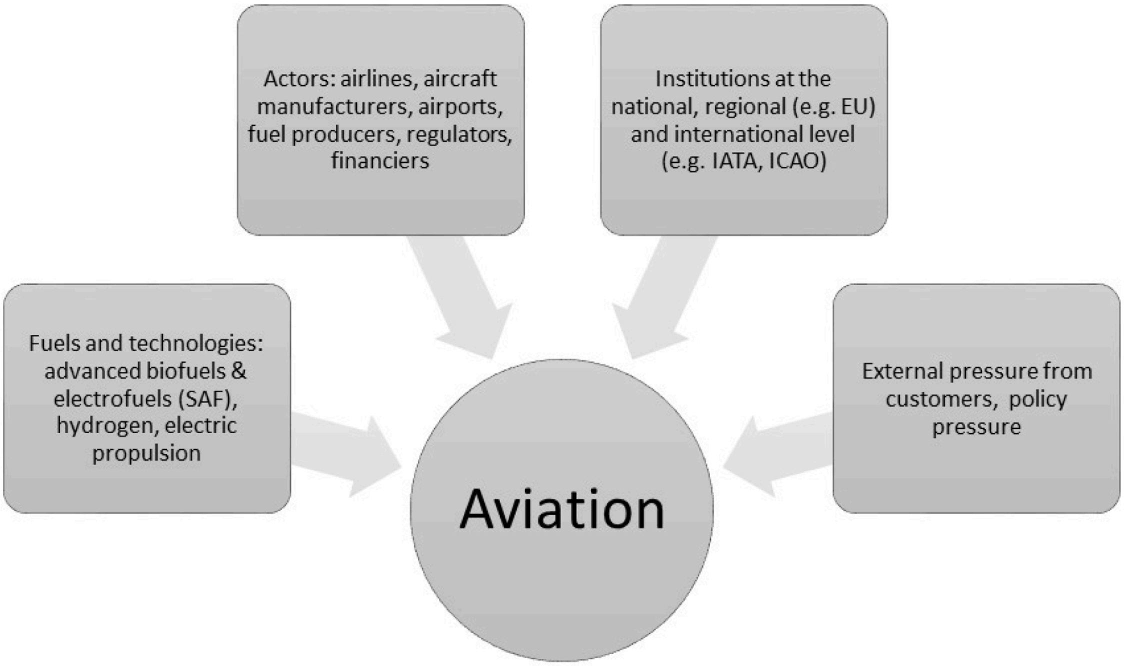

Fig. 2. Elements influencing sustainability transitions and decarbonization efforts in the aviation sector.

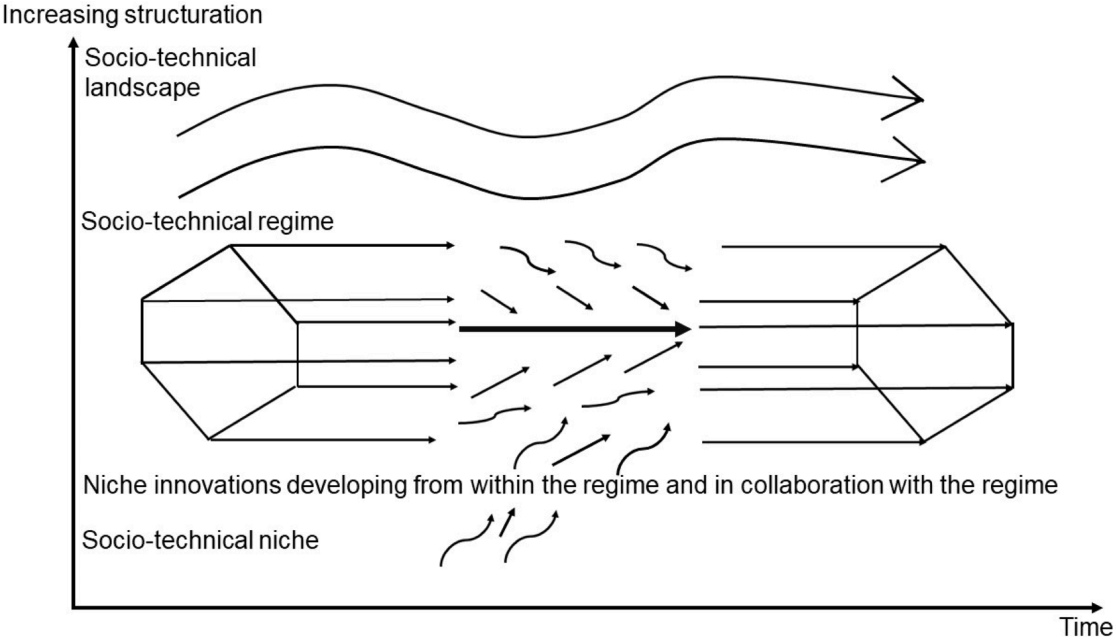

Fig. 3. Amended MLP, based on Geels (2002) and Geels and Schot (2007), with increasing number of niche innovation developing from within and in collaboration with the regime, as observed for decarbonization of aviation and maritime shipping. Please note that the niche level is still important and that some innovations are still developing in protected spaces within the niche, however some of the major innovation is also developing within the regime, or in collaboration between incumbent regime actors and niche actors.

collaboration with the socio-technical regime, particularly incumbent industries, as Fig. 3 indicates.

Slowly but steadily the regime is changing, with a larger demand and market creation for alternative fuels and technologies, as well as more players adopting niche technologies that have the potential to be disruptive. At the same time, there are laggards among important regime actors that are unwilling to move towards different technological trajectories, for various reasons of socio-economic, policy-related and technological nature including high upfront investment costs, lower costs of fossil fuels, low penalties for polluting, lack of international policy instruments and legal requirements, conservative culture and traditions that are based on decades of carbon lock-in and fossil dependency.

Similar to the technical changes in the aviation and maritime shipping industry, disruptive technological changes have been observed in other industries, for example telecommunications and digital imagery. Two prominent historic examples of disruption and decline are Nokia and Kodak. 1) Nokia, once the world's largest mobile phone company did not see the rise of smartphones as worth investing in (Vuori and Huy, 2016; Bouwman et al., 2014) and 2) Kodak, once the world's leading photo company did not consider digital cameras to be relevant for the industry (Ho and Chen, 2018; Lucas and Goh, 2009). Both companies declined rapidly as a result of not understanding the importance of investing in new, disruptive innovation that completely changed the market and the technology within only a few years. Both cases show how leading incumbent industries can ignore emerging technological change, which ultimately leads to their decline and the take-over by more innovative companies that are front-runners in the new technologies (e.g. Apple and Samsung for mobile phones and Fujifilm and Canon for digital photography). We can see similar developments in the maritime shipping industry, where some global logistics companies, such as Maersk, are investing in renewable fuels like methanol and modernizing their shipping fleets with methanol-adaptable vessels, whereas other companies are not investing in renewable maritime fuels yet. Different technological trajectories are instead pursued, such as investment in LNG vessels, which have lower emissions than conventional vessels that are powered by fossil shipping fuels (e.g. diesel) but are nevertheless fossil fuels (Harahap et al., 2023b). Only time will tell which strategy will win in the long-term. However disruption at the dimensions of (1) technology, (2) markets and business models, (3) regulations, policies and formal institutions, (4) actors and networks, and (5) behavior and cultural practices (Kivimaa et al., 2021) are already ongoing and carry with them a huge potential for change.

Regarding transition pathways, the aviation and maritime shipping systems are at the beginning of emerging sustainability transitions. This implies that pathways may change over time as the transitions unfold. The transition pathways for aviation and maritime shipping are not homogenous per sector, but instead different technologies and different fuels follow different pathways.

Advanced biofuels, such as HEFA fuels for aviation and HVO for maritime shipping are already being used as drop-in fuels today, and are following a *technological substitution pathway*. The niche innovations are disruptive to the regime and technological development is advanced when landscape pressure occurs (Nurdiawati and Urban, 2022) *Other biofuels with lower technological readiness levels (TRL)*, such as bio-methanol or bio-methane, are more likely to follow a *transformation pathway*. This means that the niche innovation has not developed substantially yet when landscape pressure occurs, while there are symbiotic relationships with the socio-technical regime due to incumbents driving the transition.

Electrofuels, such as e-methanol and e-ammonia, are following a *transformation pathway*. Niche innovation has not developed substantially yet when landscape pressure occurs, while there are symbiotic relationships with the socio-technical regime due to incumbents driving the transition.

Green hydrogen tends to follow a *transformation pathway*. For aviation, it is likely that the sustainability transition will follow the transformation pathway until at least 2035 or later, while for maritime shipping hydrogen-based shipping may be available earlier and may move towards other transition pathways earlier, e.g. technological substitution.

Electric aviation tends to follow a *transformation pathway*. Niche innovation has not developed substantially yet when landscape pressure occurs, while there are symbiotic relationships with the socio-technical regime.

Electric vessels tend to follow a *reconfiguration pathway*, at least at the small-scale for commuter ferries for short-distance routes. Niche innovations have substantially developed when landscape pressure occurs and they are in cooperation with the regime. For larger vessels electric shipping is following more towards a *transformation pathway*.

The next section concludes the paper.

6. Conclusion

The maritime shipping industry and the aviation industry jointly account for just under 10 % of global greenhouse gas emissions and about 5 % of CO_2 emissions (IEA, 2023). There is a high fossil fuel dependency with nearly all fuels being based on petroleum products. This research therefore aimed to, first, provide comparative perspectives of decarbonization strategies for maritime shipping and aviation, and second, to analyse the role of different actors for disruption, reducing regime resistance and breaking through carbon lock-in and path dependency for achieving sustainability transitions in aviation and maritime shipping. The second research focus also investigated the role of the socio-technical regime versus the role of the niche in driving forward sustainability transitions.

Our research findings indicate the following:

First, our comparative research on the dynamics of sustainability transitions for decarbonizing aviation and maritime shipping finds that both the aviation industry and the maritime shipping industry are slowly changing due to landscape pressure, albeit with different dynamics, different technological trajectories and at different paces. The Paris Agreement laid the basis for international climate targets by the IMO, ICAO and the IATA, as well as the EU Fit for 55 policy package that includes the ReFuel EU Aviation and Fuel EU Maritime policies, coupled with national goals for decarbonization, which are creating strong policy and legislative frameworks for deep decarbonization. Incremental innovation in the form of energy efficiency improvements and operations management are most likely not sufficient, instead disruptive innovation is required with new technologies/fuels (Henderson and Clark, 1990). Several technological trajectories are being pursued simultaneously in both sectors for different segments of the industries, in different regions and for different time frames, with a focus on various types of advanced biofuels, electrofuels, hydrogen and electric propulsion.

Some of these new technologies/fuels also require systems' changes, with new production and distribution facilities required, new infrastructure at (air)ports, new supply chains, changes in the design and construction of vessels/aircrafts, new business models and business alliances. These new fuels and technologies have the potential to break through the carbon-lock in and the path dependency, thereby destabilizing and altering the current regime and potentially leading to new technological trajectories.

Second, our research finds differences and similarities between the aviation industry and the maritime shipping industry. Both sectors show the strong role of the socio-technical regime, with incumbent regime actors playing a major role in shaping the transition pathways and disrupting the (quasi)equilibrium, while niche innovation is often being developed jointly by incumbents and niche players. This includes an awareness for the need to change as well as practical action for change by airports, airlines, aircraft producers, fuel producers, ports, some shipping companies. Differences are that parts of the maritime shipping industry are more reluctant to change, some of them displaying more regime resistance, often as a consequence of being rather invisible to public scrutiny compared to aviation and not needing to have a "green" public image, for example companies operating oil tankers. The shipping industry is more complex, fragmented and some segments are less publically visible, making consensus on decarbonization challenging. Based on our empirical material, we find that the aviation industry on the other hand tends to be more supportive of regime change and is actively nurturing niche technologies, while also having more international policy instruments in place for decarbonization such as CORSIA and EU ETS where aviation has been included since 2012. Clear front-runners in innovation can be identified, as well as laggards.

These results are country specific, as the paper was based on a case study of Sweden. However maritime shipping and aviation are international as aircrafts and ships travel from one country to another calling at various (air)ports. This research therefore has global relevance and can provide lessons for other countries, particularly in the Nordics and the EU, which have similar legislations and decarbonization targets. Recent research on Norway highlights that the maritime shipping industry is actively leading innovation for sustainability transitions (Mäkitie et al., 2022; Bach et al., 2021; Bergek et al., 2021). Recent research on the EU and the USA highlights that the aviation industry is actively pursuing sustainable energy transitions (Babuda et al., 2024).

The implications of this research are the following: First, the study provides a comparative perspective and an overview of how the maritime shipping and the aviation industries can potentially achieve deep decarbonization, providing evidence for sustainable energy transitions in hard-to-bate sectors. Second, the research has the potential to contribute conceptually by analyzing the role of regime actors in co-developing niche innovations for sustainability transitions in hard-to-abate transport sectors. This has conceptual implications for applying the MLP, as niche innovation tends to increasingly come from within the socio-technical regime, particularly from incumbent industry players and from joint initiatives between incumbents and smaller niche players. This has the potential to create disruptive innovation, such as electric and hydrogen-based aviation as well as methanol-powered vessels, which can break the carbon lock-in and the path dependency of the fossil-dominated regime. Previous research discussed the role of incumbents both conceptually and empirically (Geels et al., 2016; Geels and Schot, 2007), however this research focused on the dynamics in hard-to-abate transport sectors like aviation and maritime shipping and thereby contributes further insights.

While this research studied the early stages of the transition to fossil-free aviation and maritime shipping, future research is needed over time to analyse how these sustainability transitions will unfold within the next couple of decades. Further research is also needed from a regionally comparative perspective, for example to study the transitions dynamics in the hard-to-abate transport sectors in various other European countries and in other world regions.

CRediT authorship contribution statement

Frauke Urban: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Anissa Nurdiawati:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Fumi Harahap:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Kateryna Morozovska:** Writing – review & editing, Validation, Investigation, Formal analysis.

Declaration of competing interest

No conflict of interests.

Data availability

The authors do not have permission to share data.

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Appendix

Appendix

Annex I

Part 1: Definitions:

The Swedish aviation industry includes a range of different airports, airlines, aircraft manufacturers and fuel producers. In terms of targets for fossil-free aviation, emissions are counted from the departure at Swedish airports. International flights are accounting for at least double as many passengers as domestic flights. The largest market share has Scandinavian Airlines SAS, both international and domestic.

The Swedish maritime shipping industry includes a range of ports, shipping companies, shipyards and fuel producers. In terms of targets for fossil-free shipping, emissions are counted from the departure at Swedish ports. The vessels are divided into various segments, most importantly container ships and other solid cargo carriers, tankers and passenger ships. Passenger ships include various types of ferries, including small commuter ferries close to the main cities, as well as large cruise ships. Container ships are calling at Swedish ports and may be refuelling in Sweden, but are often owned by non-Swedish, international companies. Tankers are usually loading oil and other petroleum products. Other types of vessels include fishing vessels that often operate on the high seas.

Table 3
Different types of ships. Source: Amended from Marine Insights, 2021 and Harahap et al., 2023b.

Type of ship	Description
Bulk carrier	Cargo transport of dry goods in large quantities, can contain items like food grains, ores, coal and cement.
Container	Cargo transport of various goods in large quantities that are packed in containers.
Tanker	Vessels that transport large amount of liquid cargo (e.g. oil tankers).
Roll-on/roll-off (Ro-Ro)	Vessels that transport wheeled cargo.
Passenger ships	Vessels that transport passengers (can be large cruise ships or small local ferries).
Offshore ships	Vessels used for exploration and construction jobs at sea.
Fishing vessels	Vessels used for recreational or commercial fishing at sea, various sizes ranging from very large to small.
High speed craft	A special type of technologically advanced high-performance marine vessel.
Dredgers	Used for excavation activity in shallow water with the purpose of digging up bottom sediment and widening waterways.

Part 2: Fuel types:
Aviation:

- **Sustainable aviation fuels (SAF)**, which includes advanced biofuels and electrofuels (synthetic fuels made of electricity, hydrogen and a waste CO2 stream) (Wang et al., 2019). SAF is a drop-in fuel, making it available for use in aircrafts today, enabling blending up to 50 % without any modifications to aircraft design and using today's infrastructure. Swedish airline BRA modified one of their aircrafts to fly with 100 % SAF in June 2022 (Neste, 2022). The most commonly used fuel today is hydro-processed esters and fatty acids (HEFA), such as vegetable / plant oils and by-products of the animal processing industry
- **Electric propulsion**, based on electricity generated from renewable energy or nuclear power (Schäfer et al., 2019). Current electric aircrafts today are small, for example the 2-seater Velis Electro by Pipistrel. Electric aviation will in the foreseeable future mainly be an option for short-haul flights. Interviewees highlight that research and development (R&D) is ongoing for electric and hybrid-electric aircrafts with a range of up to 800 km for a 30 seater airplane, such as by Heart Aerospace ES-30 with a commercial launch expected for about 2028 or later.
- **Green hydrogen**, either in fuel cells or as hydrogen produced through electrolysis, based on electricity generated from renewable energy or nuclear power (Lai et al., 2022a; Baroutaji et al., 2019; Hoelzen et al., 2022). Interviewees highlight that hydrogen-based aviation will require different aircraft designs and new infrastructure for hydrogen production, storage and transportation. Universal Hydrogen made a hydrogen-powered test flight with a 40-passenger aircrafts in the USA in March 2023 (Electrek, 2023). Airbus aims for short- and long-haul commercial airplanes operating on hydrogen by 2035. Other forms of hydrogen, generated from fossil fuels, do not have a climate-positive impact.

Maritime shipping:

- **Liquid natural gas (LNG)**, is a fossil fuel that is cleaner than conventional fuel oil in the shipping industry and is relatively widespread, at least in segments that are more customer-aware such as ferries, cruise ships and container ships. There has been a large increase in the use of LNG in recent years, yet it is fossil-based (Hanson et al., 2019).
- **Green hydrogen**, for example hydrogen produced through electrolysis, based on electricity generated from renewable energy or nuclear power (Grahn et al., 2021; Kanchiralla et al., 2022; Harahap et al., 2023a). While this is still a niche technology, there is an increasing number of companies investing in R&D for hydrogen-powered vessels, such as Rederi AB Gotland (Gotlandsbolaget) and Destination Gotland which plan to develop the world's largest ship powered by green hydrogen (Gotlandsbolaget, 2021; Gotlandsbolaget, 2023). Other forms of hydrogen, generated from fossil fuels, do not have a climate-positive impact.

- **Advanced biofuels**, such as Hydrogenated Vegetable Oil (HVO), bio-methane and bio-methanol (Hanson et al., 2019).
- **Methanol**, either generated as bio-methanol produced from advanced biofuels or e-methanol produced from a waste CO2 stream and electricity (Hanson et al., 2019; Grahn et al., 2021; Kanchiralla et al., 2022; Harahap et al., 2023a)). Our interviews find that globally leading container shipping companies like Maersk and MSC are investing into methanol-driven vessels as a way to reduce their emissions.
- **Ammonia**, either bio-ammonia or e-ammonia, however there are health and safety concerns due to high risks of explosiveness and toxicity, as our interviews find.
- **Battery-electric propulsion**, powered by renewable energy or nuclear power which is likely to be mainly relevant for smaller vessels due to current limitations in battery technology, as the interviewees report.
- **Wind-based and solar-based propulsion**, although this is currently considered a niche technology. Ship-builders Wallenius' Oceanbird project aims to develop a wind-powered vessel by 2026 (Wallenius Marine, 2023).

Part 3: Detailed overview of fuel types

Table 4

Different sustainable aviation fuels[1] and their characteristics. Source: Amended from (Michaga et al., 2021; Quante et al., 2023; Trinh et al., 2021).

Fuel	Technology status[2]	Engine Compatibility[3]	Infrastructure Compatibility[4]	Scalability[5]	Volumetric Energy density[6]	Potential GHG Reduction[7]
Synthetic Kerosene	FT (High)	High	High	Low (biomass feedstock) to high (renewable electricity/PtL)	High	Medium to high
	HEFA (High)	High	High	Low (lipid)	High	Low to medium
	HFS-SIP (Medium to High)	High	High	Low	High	Medium
	ATJ (High)	High	High	Low	High	Low to high
Methanol	High	Medium	Medium	Low (biomass feedstock) to high (renewable electricity/PtL)	Low	Low to high
Ethanol	High	Medium	Medium		Medium	Medium
Butanol	High	Low	Medium		Medium	Low
Ammonia	PtL (Low)	Low	Medium (logistics) Low (airport)	High	Low	High
Methane	Power-to-methane (Medium to high) Biomethanation (High)	Low	Medium (logistics) Low (airport)	High	Medium (Liqufied methane)	High
Hydrogen	PtL (Low)	Low	Low	High	Low	High

[1] Sustainable aviation fuels (SAF), including advanced biofuels derived from biomass and electrofuels produced from electricity and CO_2, are recognized as viable alternatives to fossil-based jet fuel in the aviation sector, providing a range of feedstock options and production methods for diverse SAF solutions.

[2] Technology readiness level (TRL) of fuel related to aviation application. Low: 1–4, Medium: 4–7 High: 7–9. Abbreviations of technological pathway: FT (Fischer-Tropsch), HEFA (Hydroprocessed Ester and Fatty Acids), HFS (Hydrofermentet Sugars Synthesized Isoparaffins), ATJ (Alcohol-to-Jet), PtL (Power-to-liquid).

[3] Engine compatibility: High (no need for modifications), Medium (minor modifications required), Low (major modifications or new design required).

[4] Infrastructure compatibility: The extent to which logistics and transport infrastructures are currently available as well as relate to the necessary modifications, adaptations, or new developments for fueling infrastructure at airports.

[5] Based on feedstock potential and production capacities.

[6] Relative to traditional jet fuels.

[7] Based on potential life-cycle CO_2 eq. emissions for the examined fuel options, highly depends on the source of feedstock, electricity and production method.

Table 5

Different alternative marine fuels and their characteristics. Source: amended from Harahap et al., 2023b.

Fuel	Technology Readiness Level*	Engine Compatibility	Infrastructure Compatibility	Scalability	Volumetric Energy density**	Safety**	Potential GHG Reduction	SOx Reduction
Ultra-low sulphur diesel	High	High	High	High	High	High	Low	Medium
Liquid natural gas LNG	High	Medium	Medium	High	Medium	Medium	Low	High
Liquid petroleum gas LPG	High	Medium	Medium	Medium	Medium	Low	Low	High
Bio-methane	High	Medium	Medium	Low	Medium	Medium	Medium	High
Bio-methanol	High	Medium	Medium	Low	Low	Medium	Medium	High

(continued on next page)

Table 5 (*continued*)

Fuel	Technology Readiness Level*	Engine Compatibility	Infrastructure Compatibility	Scalability	Volumetric Energy density**	Safety**	Potential GHG Reduction	SOx Reduction
Dimethyl ether (DME)	Medium	High	Medium	Low	High	Medium	Medium	High
Biodiesel (HVO)	High	High	High	Low	High	High	Medium	High
Pyrolysis Oil	High	Medium	High	Low	Medium	High	Medium	High
Algae biofuel	Medium	High	High	Medium	High	High	High	High
Hydrogen	Low	Low	Low	High	Low	Medium	High	High
Ammonia	High	Low	Low	High	Low	Medium	High	High
Battery electric	Medium	Low	Low	High	N.A.	High	Low-High***	Low-High***
Solar/Wind	Low	Low	Low	Low	N.A.	High	High	High
Nuclear	High	Low	Low	Medium	N.A.	Low	High	High

* Technology readiness level of fuel value chain to be used for marine applications. Low: 1–4, Medium: 4–7 High: 7–9.

** Compare to traditional marine fuels.

*** Depends on the source of electricity and production method.

Annex II

Coding pattern for analysing sustainable energy transitions in aviation and maritime shipping

- New fuels and technologies for decarbonization
- Visions, challenges and opportunities
- Path dependency
- Breaking through carbon lock-in, disruption
- Policies and regulations (international, regional, national level)
- Economic issues (costs, investments, risks, incentives, financial instruments, business models, markets)
- Behaviour and customer practices
- Role of regime (incumbent actors including shipping / aviation companies, (air)ports, regulators etc. regime resistance, regime support)
- Role of niche
- Role of landscape
- Maritime shipping vs aviation (differences and similarities)

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