NTRANS
Norwegian Centre for Energy Transition Strategies

Forskningssenter for miljøvennlig energi

Socio-technical transition pathways and bottlenecks for Norwegian maritime transport

A qualitative case study

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1 Introduction

The transport sector has been identified as one of the sectors that are most challenging to decarbonize in time to meet international and national climate targets. For maritime transport, few alternatives to fossil fuels are available on the market today. There are multiple barriers to the deployment of alternative fuels, linked to economic costs and risk, infrastructure, and system integration, as well as acceptance and uncertainty concerning future regulations and framework conditions. At the same time, new and radical solutions are being explored. Besides battery-electric solutions, hydrogen and ammonia, synthetic fuels, and second and third generation biofuels are likely to become central in the future maritime fuel mix. Some of these are relatively close to full-scale implementation, whereas others are in the early stages of development.

Norway is interesting as a case for study of this transition to green shipping. In addition to being a seafaring nation, Norway has a strong focus on green solutions in the maritime industry and high ambitions for transitioning the transport and industry sectors. Moreover, Norway is an open, petroleum-dependent economy, which from nature's side is well endowed with renewable energy resources.

The range of opportunities and challenges identified call for a hybrid perspective on sustainability transition pathways, integrating techno-economic and macro-economic impact scenarios as well as socio-technical analysis of ongoing patterns of change within transport and related sectors. This report is a part of an interdisciplinary process in NTRANS RA4, where we explore ways to bridge these perspectives through a ten-step methodology. NTRANS Report 02/2023 (Espegren et al., 2023) provides an overview of this methodology and proposes four overarching socio-technical pathways that can be further used and developed to shed new light on alternative energy transition pathways for Norway. This report presents the results from a case study on the maritime sector, where we apply the overarching energy transition pathways for Norway developed in NTRANS (Espegren et al., 2023). Following an outline description of the regime of existing technologies, institutions, and practices in the maritime sector, we assess recent developments and current trends associated with emerging niche innovations, i.e., different electrification and alternative fuel solutions that may contribute significantly to maritime energy transition. The findings are discussed in relation to a parallel case study (Chang et al., 2024), based on modelling in IFE-TIMES-Norway, and the overarching pathway storylines. We contribute to the study of energy transitions by showing how a qualitative socio-technical transitions perspective (Geels et al., 2020; Turnheim & Nykvist, 2019) can supplement quantitative modelling by shedding light on current patterns of change and identifying potential bottlenecks.

The following chapter provides a brief background of previous research linking different pathway perspectives. Chapter 3 describes the methodology and quantitative modelling results used as basis for this case study. Chapter 4 presents a socio-technical analysis of recent developments that significantly shape maritime energy transitions. This includes a brief discussion of exogenous pressures in form of global market and geo-political trends, and the regime of existing solutions, systems, and practices in the maritime sector. However, we pay most attention to ongoing innovation activities, and the challenges, and prospects prevailing for the various niches where novel zero and low emission technologies are being developed, demonstrated, and pushed towards a wider market entry. Thereafter, in chapter 5, we discuss transition bottlenecks, by relating the findings from the qualitative analysis to the future trajectories generated through the quantitative modelling and the storylines for the overarching NTRANS pathways. Transition bottlenecks are understood as areas where the findings contradict each other, or there are tensions between the constructed trajectories and the opportunities and challenges identified via the empirical case-study (Geels et al., 2020). Lastly, chapter 6 provides a summary conclusion, with reflections on the implications of the study.

2 Linking pathway perspectives

While hybrid perspectives on sustainability transition pathways increasingly are called for, the effort to develop such perspectives is not new. In an early study based on the interdisciplinary Pathways project, Foxon (2013), discussed transition pathways for a UK low carbon future in a multi-level perspective, arguing that different factors are mediated by the actions of actors within an ‘action space’. In his perspective, three key types of actors influence change: government actors; market actors, such as large energy firms; and civil society actors, such as community and environmental groups. The different categories of actors have fundamentally different logics or framings of the key energy challenges, which were used to define three alternative pathways towards the future low-carbon energy system. A basic quantification and systems analysis of the three pathways shed light on the different risks, uncertainties, learnings, and challenges for the respective actor groups.

McDowall (2014) did a hybrid case study on hydrogen transitions, also in the UK, based on an iterative process with five steps: 1) Development of a theoretical framework for describing transitions, 2) participatory involvement of expert stakeholders to scope key issues, 3) mapping of the system in terms of actors, regime structure, niches, and landscape developments, and identification of key strategic uncertainties and branching points, 4) writing of storylines, and 5) “dialogue” with quantitative modelling; using scenarios to identify issues that may not be addressed with models, and using models to highlight potential weaknesses in the scenarios.

Turnheim et al. (2015) suggested the need to further bridge quantitative systems modelling, socio-technical transition analysis and initiative-based learning, focused on concrete projects and initiatives. The authors argue that a more structured dialogue between practitioners of the respective approaches is needed. Such integration should be organized around three areas: defining common analytical or governance problems to be tackled; establishing shared concepts (boundary objects); and establishing operational bridging devices (data and metrics, pathways evaluation and their delivery) (ibid.). Rosenbloom (2017) provides a conceptual discussion of transition pathways, shedding light on how biophysical, techno-economic, and socio-technical conceptions emphasize different, yet interconnected dimensions of the decarbonization challenge.

Based on an extensive literature review, he argues the different core conceptions are interlinked at different yet overlapping spatial and analytical scales. Low-carbon pathways cannot be reduced to a single dimension, so if the concept is to usefully frame the complexity of decarbonization, closer bridges between perspectives are needed.

Cherp et al. (2018) consider national energy transitions as a co-evolution of three types of systems: energy flows and markets, energy technologies, and energy-related policies. The three types of systems are associated with different perspectives on national energy transitions: techno-economic with its roots in energy systems analysis and various domains of economics; socio-technical with its roots in sociology of technology, STS, and evolutionary economics; and political, with roots in political science. The three perspectives are combined in a meta-theoretical framework for systematic mapping of hierarchically organized variables. The authors provide an illustrative application through a comparative analysis of transitions in the electricity systems of Germany and Japan, arguing that all three perspectives are needed to explain the differences between the two cases and how the interplay of relevant variables varies from one transition episode to another. What is interesting for our purposes, is that they take a national perspective and provide a concrete linking framework, where the influence of policy and politics at the national level are emphasized and analyzed as a distinct dimension.

Turnheim & Nykvist (2019) discuss the differences, complementarity, and connections between conceptions of sustainability transition pathways. They suggest that socio-technical perspectives fruitfully can be applied to mobilize different representations, broadening the perspective on alternatives and transition potentials, and assessing the feasibility of alternative pathways, by shedding light on four key dimensions:

- **The maturity of options**. The development of technologies and supply-chains, markets, business models and investment environments.
- **System integration and infrastructure**. The extent to which entirely new systems (e.g. to deal with intermittent energy and storage, batteries for electric mobility), transformation of existing systems, or no major infrastructure investments are needed.
- **Societal acceptability**. Societal issues, controversies, or anxieties regarding the expected deployment and use of a new solution need to be concerned, and how this may affect the likelihood of deployment.
- **Political feasibility.** The likelihood of decisions supporting the implementation of a particular pathway or addressing obstacles that may result from the resistance of actors with substantial influence, power, and vested interests.

With reference to previous research, they also note that socio-technical research can help unpack the temporal dimension of pathways, by providing knowledge on the multiplicity of temporal horizons, branching points, interim steps and dynamics that prevail (ibid.)

A systematic review of research that more specifically aims to link models and socio-technical transitions theories for energy and climate solutions (Hirt et al., 2020), identified three main justifications for increased methodological integration; 1) that it is needed in order to find practical solutions to energy and climate challenges, and/or 2) required to increase the realism of studied scenarios or pathways, and/or 3) beneficial in terms of enhancing interdisciplinary learning (see Figure 1). The reviewed studies were classified in terms of three main approaches:

- **Iterating**, where storylines considering governance, key actors and technological and behavioral developments are developed and used in iterative steps, for complementary assessment of model-based scenarios, most often applying a multi-level perspective (MLP),
- **Merging**, where the ambition is to integrate storylines based on socio-technical transitions theory with existing models, and provide new, computer-assisted socio-technical energy transition (STET) models, where the model outputs in turn are interpreted, and,
- **Bridging,** where socio-technical transitions analysis (through the MLP on transitions in particular) is combined with other methods or concepts, such as practice-based action research, focus business dynamics, or transition bottlenecks, which are used to bridge the modelling and socio-technical system perspectives.

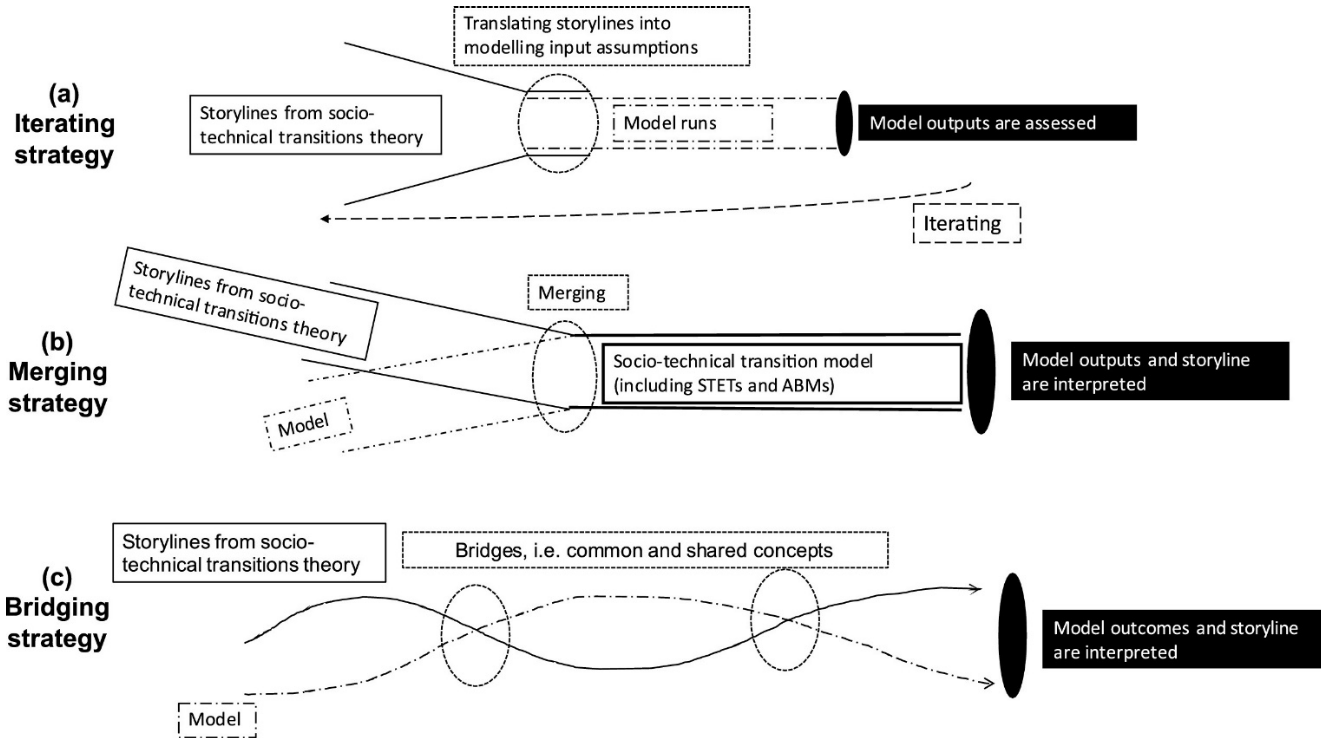

FIGURE 1: METHODOLOGICAL STRATEGIES FOR LINKING MODELS AND SOCIO-TECHNICAL TRANSITION THEORIES. SOURCE: HIRT ET AL., 2020, P. 172.

The review also showed that most of the publications linked socio-technical transition perspectives and existing techno-economic models, such as integrated assessment models (IAMs) and Energy System Models (ESMs). Only two publications (Mercure et al., 2015; Mercure et al., 2016) aimed to link socio-technical and macro-economic interactions and impacts. The choice of linking strategy varied, depending on the research questions and model frameworks applied, and while some more studies used a merging strategy, the authors do not rank the respective approaches in any way. However, they note that bridging necessitates more interdisciplinary clarifications, and in this sense may be the most ambitious one (Hirt et al., 2020)

Geels et al. (2020) discusses a hybrid perspective that would fall in the "bridging" category above, and provides a detailed, step-by-step description of their methodology. The **first step** is to provide a justified choice of systems and countries for the analysis. **Step 2** is to develop a baseline scenario for the selected country and system. In the case of Geels et al. (2020), this was done by use of two integrated assessment models, and one detailed, sectoral model. In the **third step**, a socio-technical perspective is brought in, to include consideration of how actors, social acceptance, and political feasibility, not only technologies and markets, are crucial in transitions. This is done by distinguishing two transition pathways, which differ in terms of lead actors, depth of change and scope of change. One is led by incumbents in existing industry, with radical technological substitution at the core, where the scope largely is limited to technical components and markets, and the other is characterized by new entrants, transformative change including both technologies, practices, and social structures, and multi-dimensional change (including organizational, policy, social, cultural, and consumer practices). **Step 4** consists of implementing the two alternative pathways in the models, while **step 5** is a qualitative analysis of the main innovations in a multi-level perspective (MLP). As the **sixth step**, the quantitative future scenarios from step 4 are discussed against the qualitative assessments of contemporary developments in step 5, with a view to feasibility and possible bottlenecks. **Step 7** is the development of qualitative scenarios, where plausible actor-based storylines for the quantitative pathways are developed, and **Step 8**, finally, is a discussion of the policy implications of the modelled and qualitative scenarios.

Since our study is based on an interdisciplinary energy transition study, with similar scope and ambitions, the approach developed to integrate model analyses and qualitative transitions research in NTRANS builds extensively on the methodology of Geels et al. (2020), while aiming to develop it further on some points. The following chapter provides a description of the approach, and how it was applied in the present case-study.

3 Method and materials

3.1 Hybrid pathway approach in NTRANS

Based on the hybrid approach presented by Geels et al. (2020), the interdisciplinary process defined in NTRANS has ten steps to bridge models and socio-technical transitions research through a systematic approach. The ten steps are as follows:

1. Develop scenarios
    - Develop different/contrasted pictures of the future based on socio-technical research
    - Describe national and sector/subsector development
    - Present and discuss scenarios with the user partners
2. Quantify the scenarios – in dialogue with partners in NTRANS
3. Analysis with NTRANS models
    - Based on common assumptions for each scenario
    - Interactions between models when useful

4. Discussion of analysis results and selection of case for in-depth analysis
5. Quantitative case study – in depth-analysis
    - Based on common assumptions for each future
    - Interaction between models when useful
6. Qualitative case study
    - Socio-technical perspective on selected case
    - Focus on critical points and bottlenecks in the transition
7. Analysis/discussion: what are important measures to reduce bottlenecks in the transition?
8. Include uncertainty (short, medium, and long term) and bottlenecks in model analysis
9. Discuss policy implications from the model-based analysis and the socio-technical analysis
10. Summarize the research in a policy paper and a result presentation

This report provides results from activity in step 6, presenting a qualitative case-study on current processes and conditions that influence the scope for transition in maritime transport. Following Geels et al. (2020) we apply the MLP, and focus on identifying transition bottlenecks which as of yet have uncertain outcomes but are likely to exert a strong influence on future options and developments.

The previous steps in the NTRANS process have provided four alternative transition pathways, respectively named Incremental Innovation pathway (INC), Technological Substitution Pathway (TECH), Social Change Pathway (SOC), and Radical Transformation Pathway (RAD), distinguishing varying degree of change along two dimensions: architectural/socio-institutional change and technological change (Figure 2).

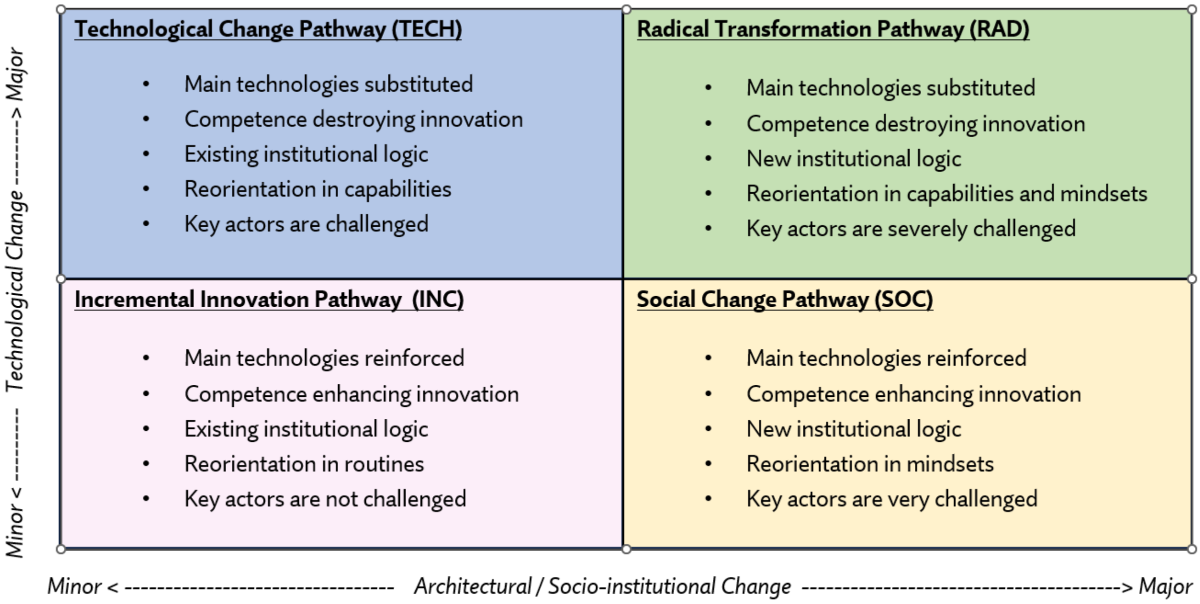

FIGURE 2: THE FOUR ALTERNATIVE TRANSITION PATHWAYS DEVELOPED IN NTRANS (ESPEGREN ET AL. 2023, P.10).

In the INC pathway, only minor changes in technological and socio-institutional dimensions occur, building on existing solutions. TECH sees a stronger and more sudden pressure for change, with more radical innovation in core technologies, but less so in institutions and lifestyle. It is assumed that population growth continues as projected and the national economy continues to grow, accompanied by increasing energy demand. The SOC pathway involves substantial institutional changes to focus on sustainable well-being rather than economic growth, but only small steps in technology development. Here, it is assumed that Norway's oil and gas production will shut down by 2034, and some of the most energy-intensive industry based on fossil fuels may struggle and subside, while circular economy and ICT-based solutions will give unprecedented growth in other sectors. RAD, finally, is characterized by radical social change as well as technological innovation, with a combination of core technology and architectural change (including e.g. flexibility technologies). Oil and gas production is phased out by 2050, and the demand for energy will stabilize, due to more sustainable lifestyles and increased focus on circularity.

We thus go beyond Geels et al. (2020) by including a fourth pathway, where there are strong drivers both on the techno-economic side, related to technology development and diffusion in existing markets, and in terms of socio-institutional change, e.g., emergence of new actors, change in social arrangements, and change in cultural norms and values. The decision to include a fourth, most radical scenario was made with a view to the urgency of the climate challenge and the limited progress towards realization of the present climate targets for Norway.

The four transition pathways were subsequently quantified, as outlined below (Table 1).

TABLE 1: QUANTIFICATION OF TRANSITION PATHWAYS (ESPEGREN ET AL. 2023, P. 17).

	Scenario	Incremental (INC)	Technological (TECH)	Social (SOC)	Radical (RAD)
Demand	Industry (excl. Oil & Gas)	137 TWh (+31%)	272 TWh (+105%)	106 TWh (+1%)	106 TWh (+1%)
Exogenous input	Oil & Gas	28 TWh (-63%)	28 TWh (-63%)	0	0
	Transport	NTP Road transport +37% Other transport +14%	NTP Road transport +37% Other transport +14%	Individual transport decrease with 10%. Modal shift increase bus and sea passenger by 14%. Sea freight constant (less transport but more by sea).	Individual transport decrease with 10%. Modal shift increase bus and sea passenger by 14%. Sea freight constant (less transport but more by sea).
	Buildings	84 TWh (+5%)	84 TWh (+5%)	65 TWh (-19%)	65 TWh (-19%)
El generation max potential	Onshore wind	15 GW 48 TWh	15 GW 48 TWh	5 GW 15 TWh	5 GW 15 TWh
Technology	Offshore wind	16 GW 35 TWh High cost	48 GW 207 TWh Low cost	16 GW 35 TWh High cost	32 GW 138 TWh Low cost
Transmission	Domestic	20% increase	20% increase	No new	No new
max potential	International	Allowed new	Allowed new	No new	No new
	Offshore wind	Hybrid	Hybrid	Radial	Radial
	Trade prices	Europe w/o CCS	Europe w/CCS	Europe w/o CCS	Europe w/CCS
End-use technologies					
CCS		No new	Yes	No new	Yes
Hydrogen	Electrolysers	High cost	Low cost	High cost	Low cost
	ATR with CCS	No	Yes	No	No
Industry	Hydrogen	4 TWh H2	15 TWh H2	4 TWh H2	13 TWh H2
Transport	Hydrogen	Limited	High	Limited	High
	Battery	< 90% el. Vehicles	Not all trucks	< 90% el. Vehicles	No limits
Flexibility		Low	Low	Medium	High
Hurdle rate	End-use	10 %	10 %	4 %	4 %
Bio energy	Biomass	Unlimited	Norwegian resources	Unlimited	Norwegian resources
	Municipal waste	As today	As today	Halved	Halved

3.2 Case study approach

As noted in the preceding section (3.1), the process for interdisciplinary exploration of alternative energy transition pathways in NTRANS has included a quantitative, as well as a qualitative case study. These studies have focused on maritime transport in Norway to ensure a cohesive approach and alignment between the two methodologies.

For the qualitative case study, which is the focus of this report, we use preliminary results from the quantitative case study as a backdrop, which the qualitative research findings are pitted against.

These preliminary, quantitative results, based on modelling in IFE-TIMES-Norway, are depicted below (Figure 3).

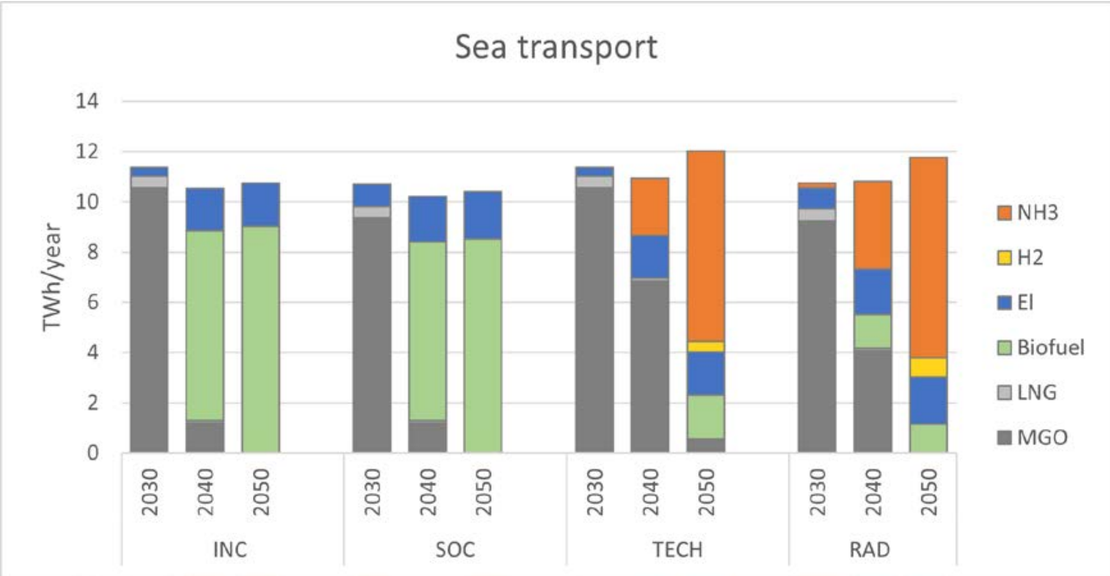

FIGURE 3: SEA TRANSPORT ENERGY CONSUMPTION IN THE FOUR PATHWAYS

The modelling suggests that the deployment of battery-electric propulsion systems will be slightly higher in the SOC and RAD pathways compared to the INC and TECH pathways. In the SOC and RAD pathways, battery-electric systems are projected to reach 1.8 TWh/year by 2040 and 1.9 TWh/year by 2050. In contrast, the INC and TECH pathways show a more modest deployment, starting at 0.4 TWh/year by 2030 and increasing to 1.7 TWh/year by 2040, where it remains ready until 2050.

Hydrogen is not deployed in Norwegian shipping at all in the INC and SOC pathways. It emerges only very slowly in the TECH pathway, where it is negligible by 2040 and amounts to 0.4 TWh by 2050, and in the RAD pathway, where it also remains negligible by 2040, but reaches a slightly higher level by 2050 (0.8 TWh/year). Ammonia enters from 2040 in the TECH pathway. However, it is taken up faster in the RAD pathway, which includes stronger policies and a higher degree of social change. Here, ammonia reaches 0.2 TWh/year already by 2030, 3.0 TWh/year in 2040, and 8.0 TWh/year by 2050 (as opposed to 7.6 in the TECH pathway). Whereas biofuels and biogas come out as main alternatives in the INC and SOC pathways (biofuels representing respectively 9.0 TWh/year and 8.5 TWh/year by 2050), their role is less prominent in the TECH and RAD pathways. It should also be noted that the total use of energy in Norwegian shipping goes down by 2050 in both the INC and SOC pathways, but not in the TECH and RAD pathways.

In line with the results of other integrated assessment models, the type of results that come out of the modelling in IFE-TIMES-Norway are descriptions of how demand- and supply-side energy system interactions may change, based on a number of preconditions and assumptions, and the overarching pathways outlined above. The qualitative case study aims to look beyond this techno-economic dimension to elucidate the complex processes, and patterns of socio-technical change in energy transitions (Rosenbloom, 2017). Thus, we place a stronger emphasis on historical dynamics, to learn from past and ongoing interactions and to consider the basis for future transitions.

Following Geels et al. (2020), we apply the MLP. The MLP was designed for analysis of complex transitions that involve multiple actors and activities (including not only investments, network-building, and goal setting, but also power struggles and conflict), as well as novel technologies, in the context of existing governance and value systems. At the core of the MLP is the tenet that transitions come about through a complex interplay between processes at different scales or levels of society, over time (Geels, 2019).

MLP specifies three levels of analysis: 1) The small-scale niches or "protected spaces" where radical innovations emerge, 2) the regime of shared rules and institutions that shape the perceptions and actions of social groups and stabilize existing systems and solutions, including social, cognitive, and institutional lock-in mechanisms that impede radical change, and 3) the socio-technical landscape or wider societal context wherein large-scale (e.g., macro-economic and geo-political) developments occur (ibid.).

The perceived dynamic is that niche innovations typically build up internal momentum, and together with landscape changes create pressure for change in the existing regime. One line of development of the MLP framework is the differentiation of distinct transition pathways, based on different patterns of change, such as those developed for analysis of energy transition pathways for Norway in NTRANS.

In line with Geels et al. (2020), our analysis focuses on the momentum for key niche innovations in maritime energy transition, and how this has developed during the last 5–10 years, after an initial assessment of current exogenous pressures and regime developments. We consider three main dimensions: a) techno-economic (market development, investments, price/performance improvements), b) socio-cognitive (social networks, beliefs, strategies, expectations), and c) governance (degree and continuity of policy support, regulatory drivers, and barriers).

Beyond presenting them as tensions between the model-based scenarios and socio-technical analyses, Geels et al. (2020) are not very explicit on how transition bottlenecks are to be identified. We therefore apply the four dimensions highlighted by Turnheim & Nykvist (2019) as crucial for pathway feasibility (maturity of options, infrastructure and system integration, societal acceptability, and political feasibility, as explained in chapter 2) to explore potential bottlenecks for each of the overarching NTRANS pathways, as applied to maritime energy transition.

The data material for the analysis stems from recent and ongoing research projects applying a socio-technical system perspective on maritime energy transition in Norway, e.g., Greening the Fleet (GREENFLEET), TRAansitioning towards Zero Emission Ports (TRAZEPO), and INTRANSIT, where the maritime is one of several sectors explored, as well as desk study of recent reports/grey literature, and insights from reviews and workshops conducted in NTRANS and related projects, including INTERPORT (INTegrated EneRgy systems in PORTs) , ACES (ACcelerating Energy Transition in portS), and MAREN (Maritime Energy Transition in the Nordics).

The following chapter presents the main findings from the socio-technical analysis, starting with exogenous pressures, and moving on to recent regime developments, before providing an assessment of the current status and momentum of some of the most relevant niche innovations (i.e., battery-electric ship solutions, hydrogen, ammonia, biofuels, biogas, and methanol).

4 Socio-technical analysis of recent developments (2015-2024)

4.1 Exogenous pressures

At a wider, societal level, increasing knowledge and awareness of climate change, together with increasing policy attention to adaptation and mitigation, have caused an increasing pressure for decarbonization of maritime transport. However, these trends interact with other developments, such as changes in international politics and the global economy. While maritime trade has grown steadily over the past 15 years, the growth was slowing down in 2019, amid tensions between major trading partners such as the US and China. When the corona pandemic hit in 2020, UNCTAD estimated that the volume of international maritime trade fell by 4.1%. By 2021, maritime trade was projected to increase 4.3%. The medium-term outlook was also positive, though moderated and associated with mounting risks and uncertainties (UNCTAD, 2021). The Russian invasion of Ukraine in 2022 and return of lockdowns in China during 2020-2022 caused disruption, but in 2024 growth is still expected in most segments except grain. Following the covid pandemic and the start of the Russian war in Ukraine, bunker fuel prices and fuel price spreads went close to record highs (Luman et al., 2022), but since the second quarter of 2022 they have subsided again, as illustrated in Figure 4.

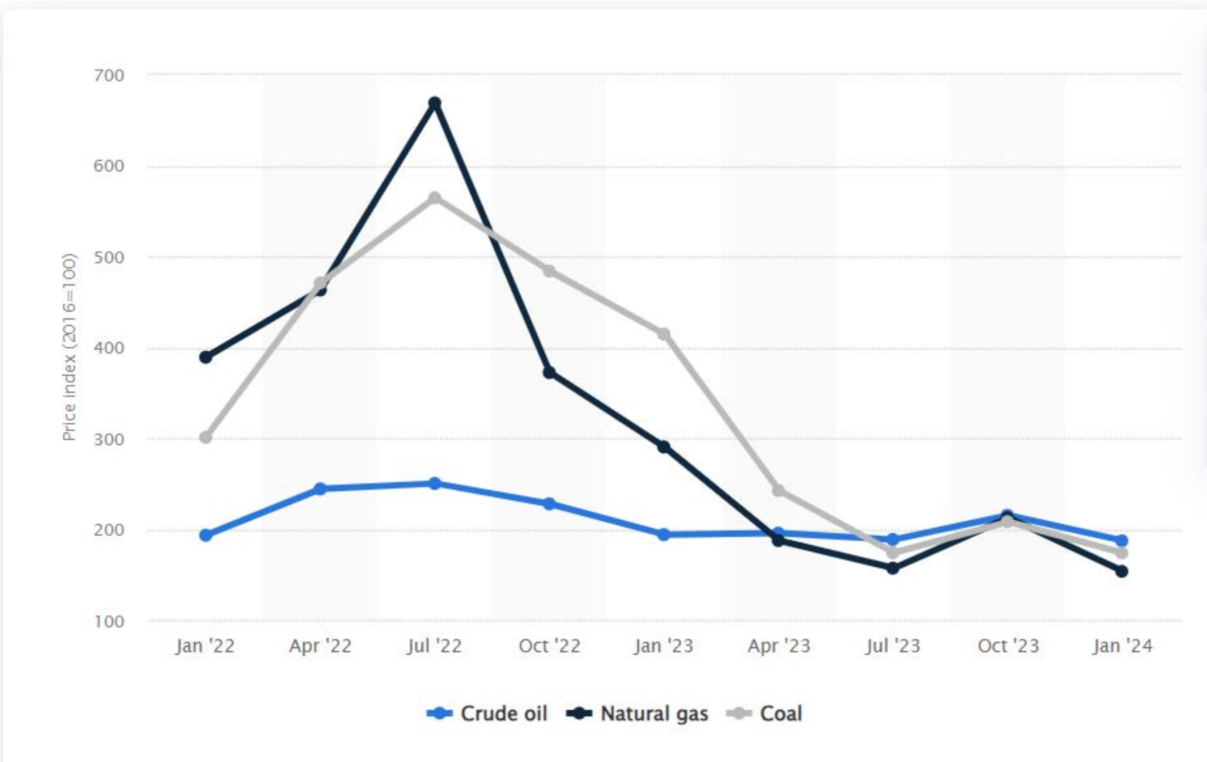

FIGURE 4: MONTHLY FOSSIL FUEL PRICE INDICES WORLDWIDE (STATISTA, 2024)

According to professional market analysts, such as Miller (2023), the future price development is uncertain. In interaction with operational challenges this has diverse impacts across segments, creating uncertainty about the scope for introduction of alternative propulsion systems.

The geopolitical tensions are also influencing energy policies. Security of supply has become a more critical issue, interacting with energy transition policies in diverse ways in different regions and countries. Notably, the RePower EU aims to accelerate the production of bioenergy and green hydrogen well beyond the Fit for 55 targets, and Germany, Belgium, Denmark, and the Netherlands have agreed to increase their combined North Sea offshore wind capacity to 150 GW by 2050, strengthening renewable energy production in the North Sea (Tang, 2022). On the other hand, rising costs of electricity in the aftermath of Russia's invasion of Ukraine have caused debate and social unrest in several countries, with uncertain implications for alternative fuel infrastructure and deployment in the maritime.

4.2 Regime developments

Norway has long traditions as a shipping and shipbuilding nation, and shipping is still a major part of the country's economy, especially along the western and southern coast. Norway is the fifth largest shipping nation in the world in terms of the market value of vessels, with gas tanker and offshore segments as the most valuable segments in Norway. Moreover, the passenger segment and coastal freight transport are important parts of the national transport system. The maritime industry is considered technologically advanced, and Norway has a full value chain of domestic companies ranging from vessel design, shipbuilding, and machinery companies to shipping, certification and shipbroker organizations.

Shipping is often considered as the most environmentally friendly means of transport. Environmental measures in shipping have until recently focused on topics such as preventing water pollutants like ballast, sewage, and oil spills, as well as reducing harmful aerial pollutants such as Sulphur oxides (SOx), Nitrogen oxides (NOx) and volatile organic compounds (VOC). Such pollutants have been subjected to regulations both at the international level (International Maritime Organization, IMO) and national level, including fees. However, ships also produce notable carbon emissions. According to Statistics Norway, the emissions of domestic shipping were 1,4 million tons of CO2eq in 2019, or about 2,7% of the overall CO2 emissions of Norway. The reduction of carbon emissions in shipping is therefore a priority in both industry and policymaking.

Techno-economic factors: Most commercial ships currently burn fuel oil with 0.5% sulfur content, known as very low sulfur fuel oil (VLSFO). Prior to implementation of the IMO 2020 regulations, they burned cheaper fuel oil with 3.5% sulfur content known as high sulfur fuel oil (HSFO), which continues to be used by ships with exhaust-gas scrubbers (Freight Waves, 2023). Owners of ships that do long-haul runs have commonly responded to NOx and SOx regulations through end-of-pipe solutions such as scrubbers. Liquefied natural gas (LNG) has also slowly gained ground due to its very low SOx, NOx, and particulate matter emissions, as well as somewhat lower CO2 emissions. DNV GL (2021) predicts that by 2050, more than 40 percent of marine fuels will be LNG. Currently, 61 ships operating in Norway are running on LNG (Norwegian Environment Agency, 2018). There are 15 LNG bunkering facilities, and eight more are planned. Due to the long lifetime of vessels, sunk costs in existing vessels and infrastructure using fossil fuels are notable sources of path dependence. This has raised interest in various biofuels which are interchangeable with fossil fuels (Bach et al., 2021). However, these alternatives remain more expensive and less available than fossil fuel options. Another factor that affects the uptake of alternative fuels is the available volume onboard vessels. Some of the most promising alternative fuels require more space than conventional fuels, limiting the applicability of such solutions in vessels operating with long distances (due to too large volume requirements to store aboard enough energy for propulsion). While hydrotreated vegetable oil (HVO) and biodiesel may be used as drop-in fuels, most alternative fuels require changes to ship design.

Socio-cognitive factors: As already noted, shipping has long roots in Norway, and the industry is often considered conservative. At the same time, Norwegian maritime companies have been frontrunners in the development and uptake of alternative fuels. Norwegian shipowners have been early adopters of e.g., LNG and battery-electric vessels, especially in passenger and offshore segments where emission reductions have been included in contracting conditions. This has been motivated by e.g. expectations of higher competitiveness in future, encouraging shipowners to engage in green innovation and consequently emission reduction (Mäkitie, Steen, et al., 2022). Such expectations of new opportunities through green innovation are particularly present in the Norwegian maritime supply chain which has taken a key role in developing the technologies necessary for cutting the emissions of shipping (Mäkitie et al., 2020). However, high costs, perceived risks associated with adopting first generation technologies, and lack of infrastructure remain as important barriers for shipowners (Mäkitie, Steen, et al., 2022). Importantly, in many types of shipping such as bulk transport, customer demand for use of alternative fuels remains low, reducing incentives for fuel switching (Poulsen et al., 2016).

Governance: In recent years, reduction of carbon emissions in shipping has become a policy priority. Guided by the Norway's Climate Action Plan (Meld. St. 13 (2020-2021)), the Norwegian Government aims to cut domestic shipping and fishery emissions by 50% by 2030 (compared to 2005 levels). It has been argued that the Norwegian state has even taken an entrepreneurial or mission-oriented approach to decarbonizing shipping, especially in the ferry segment, thus going beyond the typical "de-risker" role towards more actively pushing the decarbonization efforts (Bugge et al., 2022; Sæther & Moe, 2021). Several policy measures have been rolled out to achieve this. For instance, the carbon fee for emissions in shipping has been announced to triple by 2030 from 2021 levels. Alternative fuel innovation has been supported by various R&D funding, as well as public procurement, especially in the ferry segment (Ystmark Bjerkan et al., 2019).

Importantly, there has been little contestation in the political sphere regarding the aim of reducing emissions in shipping. One key reason for this has been the expectation of creating new economic opportunities for Norwegian maritime actors through innovation in maritime green technologies (Bugge et al., 2022). Illustratively, also the Norwegian Shipowners' Association, representing the interests of shipping companies with vested interests through sunk investments in vessels powered by conventional fuels, has embraced the decarbonization aims and pledged to achieve climate neutrality by 2050. At the EU level, Fit for 55 provides a "basket of measures" to address emissions from transport. The Fuel EU Maritime aims for a gradual reduction of emission intensity from shipping, to -75% in 2050, and requires that from 2030, container and passenger ships (>5000t) shall use onshore power supply (OPS). Moreover, in January 2024 the EU ETS was extended to include all large vessels (>5000t) entering EU ports. The revised Energy Taxation Directive will include parts of the maritime industry and apply to all fishing, cargo, and passenger vessels, also those below 5000 gross tonnes (GT). Conventional fossil fuels will be subject to the highest minimum rate, LNG slightly lower, sustainable biofuels will be subject to half of the fossil fuel reference rate, and the lowest minimum rate will apply to electricity, advanced sustainable biofuels and biogas, and renewable fuels of non-biological origin such as renewable hydrogen and ammonia. The EUs TEN-T and Alternative fuels infrastructure regulation (AFIR) is important in terms of infrastructure development. Internationally, the direction towards reducing the carbon emissions of shipping, albeit with less ambitious targets, is also set by the IMO, with its goal of 50% carbon emissions by 2050. The MARPOL (Convention for the prevention of Pollution from Ships) frames several measures to improve energy efficiency and reduce the carbon intensity of ships, some already in place and others implemented from 2023.

4.3 Niche innovations

In the following sub-sections, we outline the techno-economic and socio-cognitive and governance features of a number of alternative fuels and energy carriers in the Norwegian maritime sector, i.e., the niche innovations battery-electric, hydrogen, ammonia, biofuels, biogas, and methanol. These six niche innovations were selected as they are typically the most considered alternative fuel options in the Norwegian maritime sector.

4.3.1 Battery-electric vessels

Battery-electric vessels, both hybrid and fully electric ones, have diffused rapidly in Norway since 2015, through building of new vessels designed to have batteries as the main energy source, as well as retrofitting battery packs to existing vessels. However, the volumetric and gravimetric energy density of lithium-ion batteries is low, implying that batteries are relatively large and heavy. This limits the feasibility of using fully battery-electric propulsion for short voyages, even where charging infrastructure is available.

Techno-economic factors*:* The limited operational range of electric vessels is reflected by the types of shipping where they have primarily emerged: car and passenger ferries (fully electric and hybrid) and offshore supply vessels (hybrid). The first fully electric vessel, car ferry MF Ampere, began to operate in 2015. Since then, electric car ferries have spread rapidly in Norway with about 90 electric ferries operating in January 2024 (Norsk Klimastiftelse, n.d.). Since 2020, Enova has supported battery installations on 263 aquaculture vessels, 39 fishing vessels and 12 offshore ships (both fully electric and hybrid), [1] making it the most adopted alternative energy source in Norwegian shipping.

Meanwhile, Norwegian companies (including Norway-based technology suppliers such as Rolls Royce Marine, Wärtsilä, ABB and Siemens) and research organizations (for instance IFE, NTNU and SINTEF Ocean) have played pivotal roles in advancing knowledge concerning maritime battery-electric solutions in Europe (Steen et al., 2019). While modern electric vessels are relatively new, technology development around batteries has benefited from longer R&D in land-based transport (Mäkitie, Hanson, et al., 2022). Moreover, the availability of electricity has so far been relatively high in Norway, and the price has been affordable. However, the Norwegian Environment Agency estimates that in a 2050 perspective, electrification of the transport sector will require a massive

[1] Enova kutter støtte til maritime batterier – Kystrederiene reagerer - Tu.no

increase in power production and grid expansion.[2] Other parts of the battery value chain are emerging, e.g., Corvus and Siemens have invested in maritime battery production plants in Norway. The US Inflation Reduction Act caused some of the large actors in battery technology to put their initiatives on hold, exploring better framework conditions in other countries for their investments. Indeed, the Norwegian government responded in June 2023, promising a new, substantial innovation subsidy for large battery project (IPCEI type).[3] Research and development on offshore charging stations has started.[4]

Another issue, especially considering the increasing tensions in the global political economy, is the availability of raw materials, where as much as 74% of all battery raw materials currently are provided by China, together with Africa and Latin America, and the EU provides less than 1% of Li-batteries. Besides lithium, niobium, cobalt, and natural graphite are key materials in high demand, which also are associated with a high supply risk (European Commission, 2020b).

Socio-cognitive factors: Battery-electric solutions are met with relatively high expectations among Norwegian shipowners. Indeed, in a survey from the early part of the 2020s, Norwegian shipowners considered battery technologies as the most imminent alternative energy solution (Mäkitie, Steen, et al., 2022), and a similar result appeared from a survey among members of the Norwegian Shipowners' Association in 2023, where 60% considered battery-electric vessels as relevant for reaching the 2050 targets (Norwegian Shipowners' Association, 2023). The continued success in implementing battery-electric propulsion systems without major failures has further increased these expectations and optimism. Especially the perceived success of the Ampere project has been important for the uptake of battery-electric vessels in Norwegian shipping, by showing that environmental benefits and cost-savings can be combined (Sjøtun, 2019). Battery-electric solutions have also been promoted by e.g. industry networks such as Maritime Battery Forum and Maritime CleanTech and individual companies, as a key solution for cutting emissions in coastal shipping (Steen et al., 2019).

The well-functioning Norwegian innovation system with close collaboration between the public and private sector has been a key success factor for the rapid diffusion of electric vessels (Bach et al., 2020; Bugge et al., 2022). This large involvement and engagement of actors across the maritime value chain has also reduced uncertainty regarding battery-electric propulsion as a key solution to decarbonizing domestic shipping (Bugge et al., 2022). For instance, in the electric ferry segment, the collaboration and coordination among the local maritime industry and policymakers, ambitious policymaking combining elements of both environmental and industrial policy, and efforts to undermine resistance from vested interests by creating new markets for potentially negatively affected actors have been mentioned as some of the success criteria (Sæther & Moe, 2021).

Governance: Policy support has played a decisive role for the relatively fast deployment of battery-electric vessels. Especially the use of green public procurement in the ferry segment has been a key factor in creating early markets for electric vessels which have then demonstrated their ability

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[2] https://www.miljodirektoratet.no/publikasjoner/2022/november/kraftbehov-til-transport-nullutslippsscenarier-for-2050/
[3] https://www.regjeringen.no/no/aktuelt/nye-tiltak-for-raskere-omstilling-til-gronn-industri/id2987527/
[4] https://www.vard.com/articles/the-ocean-charger-project-has-officially-started

to cut emissions while also creating new economic opportunities for companies in the Norwegian maritime industry (Bugge et al., 2022; Sjøtun, 2019). Such formation of niche markets for battery-electric solutions has been complemented with other support mechanisms, such as public R&D funding through Enova, Research Council of Norway, Innovation Norway, and the NOx Fund. Pilot-E, for instance, has been critical in providing funds for experimentation in different technologies. The NOx Fund provided funds for the implementation of battery packs in 33 Norwegian vessels during 2018 and early 2022. Since 2020, Enova's program "Batteries in ships" has provided 1 700 million NOK. This program shuts down in 2023, to be replaced by a new scheme, dedicated to zero-emission ships.[5]

In addition, governing bodies such as Norwegian Public Road Administration (NPRA) and Norwegian Maritime Authority were actively involved in the early phase of developing alternative fuel vessels. This has been visible especially in public procurement where NPRA and county administrations (procurers of public ferry services) established close interactions with the industry in the planning and design of procurement processes, thus reducing the risk for companies to invest in novel technologies. Strong governance support has thus been cited as a key reason for rapid growth for battery-electric vessels (Bugge et al., 2022; Sæther & Moe, 2021).

4.3.2 Hydrogen

Hydrogen has recently emerged as a promising solution to contribute to the decarbonization of coastal shipping in Norway but is yet in a nascent phase. Hydrogen can be used as an energy carrier in multiple forms, e.g., as compressed gas or liquefied in combination with fuel cells, for combustion, and as an input material in ammonia (discussed below, in section 4.3.3) or methanol, or by way of liquid organic hydrogen carriers (LOHCs). Compared to battery-electric solutions, hydrogen vessels are foreseen to have higher capital and operational expenditures, but have higher gravimetric density, making them applicable in longer and more energy-demanding voyages than battery-electric vessels.

Techno-economic factors: Hydrogen production can be based on multiple energy resources. Currently, natural gas reforming is the dominant method. Alkaline electrolysis (AE) is the market leader among electrolyers, with an energy efficiency that in most cases is reported to be at 65-82% (Adolf et al., 2017; Dincer & Acar, 2015). However, Proton Exchange Membrane (PEM) electrolysis has increased in recent years because it works at high current density, requires less space, and makes it easier to compress the hydrogen, which may reduce operating costs. Younas et al. (2022) reports an energy efficiency of electrolysis in general, at 70%. In a short- to medium-term perspective, natural gas reforming with CCS is also associated with a high potential, especially in terms of volumes and costs, but is not strictly zero emission and depends on the future development of CCS and demand for natural gas. Other processes and sources, e.g., biomass, microbes such as bacteria and microalgae, and direct solar water splitting, are also relevant for upscaling,[6] but so far less in focus in Norway.

The development of hydrogen as an energy carrier is linked to that of fuel cells. Fuel cells may reach efficiencies of over 80%, but due to voltage losses current achieved efficiencies are lower. Moreover, fuel cells use catalysts, commonly made from platinum or platinum-group metals

[5] https://www.energiaktuelt.no/dreier-stoetten-i-retning-av-nullutslippsfartoey.6598985-575597.html

[6] https://www.energy.gov/eere/fuelcells/hydrogen-production-processes

(PGMs), for the fuel to power conversion. Altogether, around 30 raw materials are needed for producing fuel cells and hydrogen storage technologies. A large part of these, including cobalt, magnesium, REEs, platinum, palladium, borates, silicon metal, rhodium, ruthenium, graphite, lithium, titanium, and vanadium, are on the EU's critical raw materials list (European Commission, 2020b).

Storage and distribution of hydrogen is associated with technical, as well as economic and regulatory barriers. For intermediate storage pressures of up to 1,000 bar, special solid steel or steel composite pressure vessels are required (Adolf et al., 2017). Liquefaction is more suitable for distribution of large quantities, but this consumes 25-35% of the original energy content and requires extremely low temperatures, associated with technical challenges and high costs (Rivard et al., 2019). Recent studies suggest the potential to reduce liquefaction costs by 67% (Cardella et al., 2017). Nevertheless, liquid hydrogen currently lacks competitiveness compared to other fuels. However, a significant milestone was achieved with the introduction of the world's first hydrogen-powered ferry, "Hydra", in Norway in 2023, operating on a combination of liquid hydrogen and fuel cells and batteries. Enova has further sanctioned support for three hydrogen-powered ships and five production hubs targeting the maritime sector. Notably, there is an ongoing project focused on developing a complete value chain for a hybrid hydrogen-electric cruise ships, and there was an Enova-supported effort to build a hydrogen-powered fishing vessel, which was cancelled in 2023, due to high costs and uncertainties.[7]

Despite these uncertainties, the International Transport Forum (ITF) (2023) notes that hydrogen is a highly relevant alternative fuel for the maritime sector towards 2050 but emphasize that the emission-saving potential depend on its production pathway. DNV (2022) expect that hydrogen will make up around 2 % of the global fuel mix in 2030, 10 % in 2040 and 14 % in 2050. However, DNV GL (2019) identified 186 vessels in Norwegian coastal shipping with an operation pattern that may be suited for hydrogen propulsion systems. Based on an assessment of the maturity of hydrogen solutions for different vessels, they estimated that a total of 18 vessels could be converted to hydrogen by 2030.

While infrastructure for storage and distribution is a challenge for hydrogen energy deployment more generally, the development of onshore bunkering facilities is considered less problematic (Damman et al., 2020; Ministry of Transport, 2019). Norway has vouched to take a special responsibility in this area. Bunkering facilities are addressed in several of the ongoing development projects and may build on existing solutions and standards for hydrogen refueling stations.

Socio-cognitive factors: Hydrogen has been produced and deployed in Norwegian industry for almost hundred years. Hence, major incumbents have a stake in it, and Norwegian institutions were active in international hydrogen and fuel cell research programs since their inception. The Norwegian Hydrogen Association was established in 1996, mainly with large industry incumbents as partners. The early 2000s saw several national prestige projects, but these were put on hold following the fiscal crisis from 2008-2009. Smaller technology providers kept on, from 2014 investments increased. By August 2020, the membership of the Norwegian Hydrogen Association counted 45 companies, and at least 23 additional actors with key roles were identified (Damman

[7] https://www.tu.no/artikler/rederi-dropper-planene-om-verdens-forste-havgaende-hydrogenfiskebat/525195?utm_source=newsletter-tudaily&utm_medium=email&utm_campaign=newsletter-2023-01-20&key=EcFx0amQ

et al., 2020). A majority of these are engaged in hydrogen hub initiatives, where maritime transport and industry are the main target groups.

The sector is still small and transparent. However, there has also at times been a rhetoric of competition between proponents of 'blue' and green' hydrogen. Most of the actors expect substantial cost reduction towards 2030, but also describe a *"chicken or the egg dilemma".* This dilemma arises from uncertainty regarding supply hindering deployment, while large-scale production requires committed users. While certain regions envision ambitious scenarios for regional development, some stakeholders still regard hydrogen as a hype and question its long-term sustainability (Damman et al., 2021).

While key actors in the maritime industry are engaged in hydrogen development and demonstration activities, the expectations among ports and users in the shipping industry are variable. A recent survey showed that around 16% of Norwegian ports expect to offer hydrogen within 5 years, while 40% thought it will be relevant around 10 years from now. Around 20% did not expect to implement hydrogen solutions until 20 years from now, and a number of private ports, especially, did not see hydrogen as relevant in the foreseeable future (Steen et al., 2022). On the side of shipowners, a survey conducted in late 2019 shows that Norwegian shipowners consider hydrogen as medium-term option for decarbonization. At the time of survey, 15% of respondents estimated that would adopt hydrogen in at least one vessel within 5 years, and 42% in more than 5 years, while the rest did not expect to ever adopt hydrogen as an alternative fuel (Mäkitie, Steen, et al., 2022). The Norwegian Shipowners' Association survey of 2023 (Norwegian Shipowners' Association, 2023) indicates that hydrogen is falling behind, in that both biofuel and LNG, and novel alternatives such as ammonia and methanol, currently are seen as more relevant.

Governance. Local and regional authorities have been crucial in specific initiatives to test and implement hydrogen energy solutions. Following calls for more direction and coordination, a new national hydrogen strategy was launched in 2020 and R&D support has been increasing steadily. This included the launching of two Centers for Environment-friendly Energy Research (FME) in 2022, FME Hydrogeni and FME HyValue. The Government's action plan for green shipping (2019) sees hydrogen as important in a longer-term perspective. Furthermore, the National plan for infrastructure for alternative fuels for transport (Ministry of Transport, 2019) states that Norway will take a special responsibility for the development and implementation of bunkering infrastructure, as and when a demand develops. The public-private partnership Green Shipping Programme has been important in co-creation of hydrogen knowledge and demonstration of solutions. The Pilot-E scheme, which offers mission-type of funding, has so far given high priority to holistic value chains for hydrogen, in most cases relating to maritime applications, and the more recently established Pilot-T scheme may also support hydrogen solutions. In 2021, Enova funded 15 pre-projects on hydrogen in the maritime, and by June 2022 a billion-range funding package was launched, for support to five production plants for green hydrogen and seven new hydrogen and ammonia-fueled vessels. Several maritime hydrogen projects have also been funded through the Green Platform scheme. A report conducted for the Ministry for petroleum and energy (Oslo Economics, 2023) signals that the government may apply long-term contracts for difference to enable economically viable green hydrogen production. This would be a powerful instrument and considering how fossil fuel prices recently have dropped (section 4.1, p. 11), key actors are waiting for the outcome before making their final investment decisions.

The increasing effort aligns with current EU policies, as most Member States have plans for clean hydrogen. Specifically, 26 Member States have joined the "Hydrogen Initiative", and 14 have included hydrogen in their national policy framework for alternative fuels infrastructure (European Commission, 2020a). The RePowerEU strategy includes increased effort to develop green hydrogen for transport by 2030. Additionally, the recent establishment of the EU Hydrogen Bank is a major milestone in scaling up green hydrogen production within the EU, where its first auction in 2024 aim to allocate up to 800 million Euro to renewable hydrogen producers over ten years (European Commission, 2023). However, driving hydrogen development past the tipping point needs critical mass in investment, as well as an enabling regulatory framework, new lead markets, infrastructure, and intensified R&D, necessitating public-private collaboration and coordination across a wider scale. This may be challenging, considering the ongoing war in Ukraine and the repercussions this and political tensions in other parts of the world may have on the global economy.

Thus far, hydrogen solutions for maritime application have also faced legal-administrative barriers. The national Regulation of ships using fuel with flashpoint below 60°C makes the IMO IGF Code mandatory for new constructions or reconstructions in Norway. While the use of fuel cells is being worked on, this has so far not been regulated and approval must be sought through the IMO Alternative Design approach, as defined in MSC.1/Circ.1455 – guidelines for the approval of alternatives and equivalents. It is estimated that this procedure takes at least one extra year, as compared to gaining final approval for conventional ships. On top of this, there is the need for technology qualification and development of standards (Damman & Gjerløw, 2018).

Onshore landing and bunkering installations for hydrogen fall under the same legislation as those for of other inflammable gases, that is the Norwegian Regulation for safe handling of inflammable, explosive and pressurized substances, including relevant installations and equipment. Currently, all hydrogen bunkering installations require special consent from the Directorate for Civil Protection, and a comprehensive, quantitative risk assessment is required. While these issues are expected to be solved, they presently add further uncertainty to technological innovation projects, which are financially risky at the outset. [2]

4.3.3 Ammonia

Ammonia is currently used mainly in fertilizer production, and chemical industries, and derived from fossil fuels. It can however be produced without or minimal carbon emissions, either through using green hydrogen and nitrogen as feedstock for the Haber-Bosch method, by capturing and storing carbon from natural gas reformation, using other sources to provide renewable hydrogen, or deploy other synthesis methods than the established Haber-Bosch method. EMSA (2022) provides an overview of alternative processes, but concludes that in the short term, it is most feasible to improve the Haber-Bosch process and replace the gas reforming unit with a renewable hydrogen production system.

Compared with hydrogen, ammonia has less energy content per ton, but volumetric energy density is higher and extremely low temperatures are not required for storage (DNV GL, 2020). Thus, the cost and complexity of storage are less. A recent study by EMSA (2022) sees ammonia as a promising marine fuel, which could be used both for combustion engines and/or with fuel cells. Ammonia onboard tanker ships, as cargo, is already an established option, and dual fuel engines are under development which also could be used in this subsegment (DNV, 2021). While engine developments related to the use of ammonia are ongoing, there are still concerns on nitrogen oxide (NOx) and nitrous oxide (N2O) emissions, as well as detrimental effects of ammonia slip from engines. Using ammonia in onboard fuel-cell systems would reduce such emissions, but this technology is still not mature. Moreover, ammonia is corrosive to some materials and its toxicity will add complexity to ship designs (compared to those for conventional and other low-flashpoint fuels and gases), potentially making it more appropriate deep-sea cargo ships rather than short-sea, passenger, or inland waterway craft (EMSA, 2022).

Techno-economic factors: Globally, 170 million tons of ammonia was produced in 2018 (DNV GL, 2020). However, green or blue ammonia production was non-existent. Consequently, utilizing ammonia for maritime decarbonization necessitates significant investments in zero-carbon ammonia production, distribution, and storage capacity. Despite strong interest in ammonia as maritime fuel, immature converter technologies currently restrict its adoption. However, estimated from DNV suggest that onboard ammonia fuel technologies could become available within the next three to eight years (DNV, 2022b).

The average price of ammonia during 2008-2017 was about USD 400 per ton, and largely dependent on the price of the feedstock (natural gas). The price of renewable ammonia will depend heavily on the cost of electricity, as well as advances in capex. DNV GL (2020) estimates that renewable ammonia would cost between USD 650 and 850 per ton, but this number can be expected to reduce if electricity and electrolyzes become cheaper. In principle, ammonia does not have scalability issues, as it can be produced out of hydrogen and air. In practice, however, ammonia production would naturally compete with other uses of renewable electricity, including other decarbonization efforts.

In Norway, the Green Shipping Programme initiated a pilot in 2022 whose objectives were to enable an Equinor-hired tanker to run on ammonia. This pilot was finalized in 2023[8]. Offshore shipyard Eidesvik has several ammonia projects, including a collaboration with Equinor, Prototech AS, Wärtsilä and NCE Maritime CleanTech to rebuild the existing supply ship Viking Energy from LNG to ammonia propulsion. They also work with SINTEF in the AEGIR project, where a combination of SOFC and PEM fuel cells and advanced membrane technology is used to further develop the ammonia propulsion system.[9] Grieg Edge has an ambition to build the world's first ship to run on ammonia by 2024, which according to their plan also will be used to ship ammonia, from Finnmark to Svalbard[10]. Moreover, Amon Maritime has launched a new company called Amon Offshore, to build, own and operate a fleet of ammonia-driven supply ships, with technology delivered by Kongsberg Maritime. The ammonia will be provided from floating bunkering terminals through another entity called Azane Fuel Solutions – with fuel delivered by Yara Clean Ammonia[11]. Færder Tankers Norway has also received support through Enova, to build a dual fuel ship for transport of cars, with a combustion engine that may use ammonia as well as diesel. Furthermore, Yara Clean Ammonia, NorthSea Container Line and Yara International are joining forces to realize the world's first container ship that will use ammonia as fuel. The Yara Eyde will operate between Norway and Germany and aim to be in operation from 2026[12]. Furthermore, Enova has announced

[8] Ammonia powered tanker - Green Shipping Programme

[9] https://www.sintef.no/siste-nytt/2021/ammoniakk-pa-skipstanken-kan-gi-stor-gevinst-ogsa-for-miljoet/

[10] https://e24.no/det-groenne-skiftet/i/Bj6OJl/derfor-snakker-alle-om-skip-paa-ammoniakk.

[11] https://www.mtlogistikk.no/ammoniakk-amon-maritime-azane-fuel-solutions/et-skritt-naermere-utslippfrie-ammoniakk-skip/709125

[12] Verdens første ammoniakkdrevne containerskip | Yara International

that they will launch a new program for investment support for infrastructure for receiving, storing, and bunkering ammonia for maritime transition during the autumn of 2024[13].

Socio-cognitive factors: In a case-study carried out by SINTEF in 2020, key actors in the energy sector saw a high potential in ammonia for maritime transport. However, many stakeholders seemed less aware and did not bring it up as an alternative application of hydrogen (Damman et al., 2021). Also, a survey among Norwegian shipowners in late 2019, showed that about three quarters of the respondents did not believe that they ever would adopt ammonia as an alternative fuel (Mäkitie, Steen, et al., 2022). However, the survey among Norwegian ports that was conducted two years later found expectations concerning ammonia that were more or less on the same level as those for hydrogen. That is, a significant share (around 11%), expected to offer ammonia within 5 years, while 25% thought it will be relevant in 10 years, and around 23% expected ammonia to be implemented only in a 20-year perspective (Steen et al., 2022). As noted above, the 2023 survey of the Norwegian Shipowners' Association (Norwegian Shipowners' Association, 2023) suggests that expectations regarding ammonia are rising: 40-50% of the respondents are currently considering ammonia as a solution to achieve the emission targets by 2050. Together with the above-mentioned project activities, this shows that ammonia rapidly is gaining momentum as an alternative fuel in shipping. Several of the large incumbents in Norwegian energy and maritime industry are engaged. New, specialized entities are formed, and internationally the number of studies and pilots is also increasing.

On the other hand, ammonia can cause severe eye damage and skin burn, and is toxic when inhaled, in addition to being corrosive, hence there are health and safety concerns. Internationally, availability and land-usage for the renewable energy required for green ammonia are other issues of concern (EMSA, 2022), but in Norway the links to the potential for offshore wind energy and green business development are highlighted.

Governance factors: EMSA (2022) provides a detailed regulatory gap analysis. Their study highlights the need for IMO to develop interim guidelines for ammonia as a marine fuel, to identify acceptable limits for discharge of ammonia to air and water in normal and emergency scenarios, and to support the IGC Code review for greater harmonization with the IGF Code and consider amendments enabling the combustion of ammonia cargoes, as well as other standards, training and certification programs. The toxicity of ammonia brings new sets of safety challenges, and currently, IMO is working on the interim guidelines for ammonia, which are to be finalized in 2024.

Norway's National action plan for infrastructure for alternative fuels in transport (2019) does not discuss ammonia specifically. However, ammonia, as well as hydrogen, are important in the green industry strategy for Norway, and since 2022 government support (e.g., through Enova, the Research Council and Innovation Norway) has increased significantly. Nationally, the Norwegian Directorate for Civil Protection (DSB) is the responsible authority for handling of ammonia, and due to the hazardous properties of ammonia, it imposes strict requirements on the equipment to be used and the individual responsible for handling the fuel. The handling of ammonia, as well as the equipment and facilities used for handling, are regulated to the Regulation on the Handling of Dangerous Substances. While no specific rules or standards for ammonia bunkering exist as such, the Norwegian Directorate for Civil Protection recently approved the construction of the planned

[13] Nå skal grunnmuren for satsningen for hydrogen og ammoniakk til maritim sektor bygges | Enova

ammonia bunkering facility at Fjord Base in Florø, Norway, a permit that is an important milestone for enabling ammonia as a safe alternative fuel for ships.[14]

4.3.4 Biofuel

Biofuels are expected to play an important role in the maritime energy transition both globally (IEA, 2017) and nationally (Bach et al., 2021; Norwegian Environment Agency, 2020a). They can also be considered as the most 'technologically ready' of existing alternative fuels. However, biofuels have so far received less attention in public discourse and policy debate in Norway. Two reasons for this may be that first-generation biofuels are not zero-emission and that less is required in terms of infrastructure and system changes. However, the scant attention is probably also related to the fact that almost all biofuel used in Norway currently is imported, and up to recently there were no large industry proponents or visions for national value creation associated with them.

Techno-economic factors: Biodiesel is commercially available for the maritime sector (in small scale) and can be used in existing engines. Conventional biodiesel comes in two main categories, FAME (Fatty Acid Methyl Esters), which has physical properties that are closer to fossil fuels and therefore is used as blend-in fuel, and HVO (Hydrotreated Vegetable Oil) which rather is used as a drop-in fuel. Other types, such as bio-ethanol and bio-methanol, may also be introduced to the shipping sector (IEA Bioenergy, 2017) but require specialty engines. While first generation biofuel is associated with sustainability challenges, in terms of changing land use, deforestation and threats to food security, second-generation biofuels are based on raw material that cannot be used for food production.

Of the biofuel currently used in Norway, 75% is waste based, but only 1% is domestically produced. Norway has two recently established plants which are starch and cellulose-based, requiring additional refining. Pyrolysis and Hydrothermal Liquefaction (HTL), involving supercritical conversion of biomass at high pressure and temperature are the main technology alternatives. Both are associated with a considerable improvement potential, both in terms of carbon yield, ensuring carbon negativity and price competitiveness with alternative fuels. There are also associated R&D efforts, to increase circularity and enable deployment of biooil as a carrier for hydrogen energy (LOHC).

While Norwegian biofuel production still is in its infancy, Swedish wood-based industry is profitable and expanding, with ability to pay more for Norwegian wood than local actors. Norwegian plants must be profitable enough to compete. This level of profitability depends on being able to capitalize on all parts of the tree, for different uses.[15] At a broader level, biofuel is associated with a negative impact risk in scalability, as availability may be limited due to competing uses (e.g. in aviation or for decarbonization of industry) (Dawe et al., 2021). As noted by the Norwegian Environment Agency, the war in Ukraine has also increased the price of biofuels significantly, and

[14] https://www.yara.com/corporate-releases/yara-clean-ammonia-and-azane-granted-safety-permit-to-build-worlds-first-low-emission-ammonia-bunkering-terminal/
[15] Biodrivstoff fra sukkerrør- en miljøsuksess (dnva.no)

it is uncertain what the long-term impacts of the conflict will be, both for biofuels and for fossil fuels.[16]

In Norway, one ferry has been prepared for HVO, but due to the noted uncertainty regarding both availability and price of biodiesel, this ferry is running on fossil diesel at present. As assessed in Klimakur 2030, a biofuel mandate for shipping is foreseen to bring in 90% liquid biogas (LBG) and 10% advanced HVO.

Socio-cognitive factors: There is a growing commercial interest in utilizing forest residues as feedstock for biofuels in Norway. As noted above, two plants are in operation, however still at pilot stage. One is a biorefinery run by Borregaard which provides wood-based ethanol, and the other is a new actor called Adesso Bioproducts Ltd, which produces vegetable biodiesel. In addition, there have been three more initiatives: Silva Green Fuel, owned by Statkraft, operates a demonstration at Tofte, and aims for commercial production based on HTL and forest residues. Biozin at Åmli aimed for 120 ML/year based on IH2-technology, and was originally supported by Shell and Bergene Holm, but ceased in May 2023, when new cost calculations shed doubt about the economic feasibility of the project. Lastly, Equinor is testing new refining processes combining fossil and biofuels at Mongstad, where the core technology is a catalytic cracker.

Beyond this, Exxon Mobil acquired a 49.9% stake in the Norwegian biofuels company Biojet AS in 2022. Biojet intends to produce biofuels and biofuel components through conversion of forestry and wood-based construction waste, reaching commercial scale by 2025.[17] Furthermore, Quantafuel aims to provide sustainable aviation fuel (SAF), based on waste and wood residues. A pilot plant has been established with part funding by Enova and a pre-purchase agreement with Avinor, and preliminary targets of minimum of 7-9 million liters of fuel per year. Bio4Fuels, an 8-year R&D center involving all relevant research institutions, industry partners, major forestry resource owners and regional authorities in Norway, has been an important platform. Still, Norway seems to lag behind other countries (e.g. Sweden, Finland) in biofuel production.

The previously mentioned survey among Norwegian shipowners indicated that interest in biodiesel may increase in the coming 10 years, mainly for smaller aquaculture and fishing vessels, but that biodiesel is seen primarily as a temporary solution (Bach et al., 2021). Although some public ports either offer it today or foresee doing so within the next 5 or 10 years, these are few, and most of the private ports in Norway do not think biofuel will be relevant for them (Steen et al., 2022). While one reason for this could be the relatively high cost, the strong emphasis on electrification, hydrogen, and ammonia in the national discourse on maritime energy transition and focus on biofuel as a sustainable aviation fuel are also part of the background. It should be noted, however, that the Norwegian Shipowners' Association's 2023 survey (Norwegian Shipowners' Association, 2023), suggests that biofuel, together with ammonia, ranks second only to battery-electric solutions, in terms of reported relevance towards achieving the 2050 emission targets.

In terms of social acceptance, the sustainability of biodiesel in comparison with other low emission fuels is questioned and must be better documented (Bach et al., 2021). Future availability and

[16] https://www.miljodirektoratet.no/aktuelt/nyheter/2022/juni-2022/avansert-biodrivstoff-oker-pa-norske-veier/

[17] https://renewablesnow.com/news/exxonmobil-to-buy-into-norwegian-biofuels-co-biojet-768833/

competing uses of land and biomass are critical issues. A more general lack of awareness of bioenergy products, weak supply chains, a low level of technology readiness and limited policy attention are considered as key challenges, in addition to financial and economic barriers (IRENA, 2022).

Governance. The National action plan for green shipping (2019) presents biodiesel as a possible solution for all segments, with the advantage that it may be blended or replace LNG in existing engines. However, barriers in terms of availability, infrastructure and cost are noted. Up to now, deployment of biofuels has been politically driven, and production has depended on support schemes closing the gap between production costs and market price. Despite front-end technology development, unconducive institutions and unpredictable governance have hindered the development of a domestic biofuel industry (Aakre, 2015).

While other alternative fuels have had more focus, the Støre coalition government (led by the Labor party) has a stated intent to also stimulate biofuel production (amongst other expressed in the 2021 government program, Hurdalsplattformen), and state support is increasing, e.g. the Biozin project received 507 million NOK in support from Enova in 2022.[18] The National Climate Plan 2021-2030 prolongs the blending mandate as the primary tool for biofuels until 2030, and states that this will be expanded to include the construction industry and shipping, in addition to road transport and aviation. A biofuel mandate of 6% (advanced biofuels) was implemented by 1. October 2023.[19] While public procurement also has helped introduce biofuels in transport, there is only one economic incentive: no CO2 tax. Road tax is the same as for fossil fuels, relative to their energy content, leaving the total tax for biodiesel about 30% lower than for fossil diesel, and about 60% lower for bioethanol compared to gasoline (Skjelhaugen et al., 2021). With the revised Energy Taxation Directive (ETD) of the EU, parts of the maritime industry, including all fishing, cargo, and passenger vessels, will be subject to a new structure of tax rates, where conventional fossil fuels and non-sustainable biofuels will have the highest minimum rate. Sustainable biofuels will be taxed at half this rate, while the lowest minimum rate (of EUR 0.15/GJ) will apply to electricity, advanced sustainable biofuels and biogas, and renewable fuels of non-biological origin (e.g., renewable hydrogen). ETD is not binding for Norway but may still influence the uptake of biofuel and other alternative fuels.

Bach et al. (2021) note that while the chart for green coastal traffic (which is segment and technology neutral) co-founded the construction of the above-mentioned car/passenger ferry with planned full biodiesel operation, public funding for deployment of biofuels in the maritime has been limited. It has also been noted that international standards for marine use of biodiesel, which potentially could accelerate market formation, so far are lacking (Mohd Noor et al., 2018).

In maritime applications, both availability and cost pose challenges for the adoption of biofuels. In the short term, the feasibility of biofuels for deep-sea shipping is limited, particularly due to very cheap fossil fuel in non-regulated zones. However, there is greater potential for biofuel adoption in regulated regions, such as Europe and the western coast of the US, where environmental regulations and sustainability initiatives drive demand for cleaner alternative fuels (Sandquist, 2022).

[18] https://kommunikasjon.ntb.no/pressemelding/biozin-far-507-millioner-kroner-i-enovastotte?publisherId=17848299&releaseId=17946223
[19] Biodrivstoff i Norge - Miljødirektoratet (miljodirektoratet.no)

4.3.5 Biogas

Biogas is produced through anaerobic digestion of organic material, which commonly yields around 60% of methane and around 40% CO2. In Norway, biogas production utilizes sewage, municipal waste, manure, and sludge from fish farming. Beyond contributing to decarbonization, biogas production can also help eliminate waste and reduce resource scarcity, as the digestate may be used for fertilizers and soil products and the CO2 may be captured and used, e.g., for food production. This can result in negative emissions, in the range of – 150%) (Avfall Norge, 2017). According to the EU Renewable Energy Directive (RED II), biogas production gives a 200% cut in GHG emissions, when manure is used as input.

Techno-economic factors: Currently, there are around 50 biogas production plants in Norway, and according to the national waste management association (Avfall Norge), domestic biogas production could reach 5 TWh by 2025 – 2030, if the right policy measures are implemented. According to the Norwegian Environment Agency, the realistic potential in 2030 is 2.5 TWh, with production costs spanning from 0.3-3.6 NOK/kWh across feedstocks and production chains.

Liquid biogas (LBG) is interchangeable with LNG and may therefore be used directly in ships with gas propulsion systems. Biogas is currently applied in small passenger ferries on the Oslo fjord and is/has been considered as an alternative also for other local ferry routes. In 2019, Hurtigruten signed a seven-year contract with Biokraft for delivery of LBG when docking in Trondheim port, starting in 2021, indicating initiation of experimentation regarding business models for the maritime use of LBG (Bach et al., 2021). However, Hurtigruten cancelled this biogas plan during COVID and will instead go for a hybrid solution, combining batteries and biodiesel.[20]

One measure considered in Klimakur 2030 is deployment of 0,9 TWh biogas in the maritime sector, triggered by a mandate for blending or direct replacement of LNG with LBG. The Norwegian Environment Agency assumes no extra costs in terms of ship adjustment or development of new infrastructure (Norwegian Environment Agency, 2020b). A recent report by Stakeholder (Thompson, 2022) notes that the explosive increase in price of natural gas since 2020 has made the production of bio-methane more competitive. In the fall of 2022, LBG provided to end-users in road transport had a slightly lower price than the same amount of energy from diesel. With continued low prices, we may get a sharp increase in trucks running on LBG in Norway, and LBG may also become more relevant as alternative fuel for ships.

Socio-cognitive factors: In the survey among Norwegian shipowners by Bach et al. (2021), eight out of the 19 shipowners who had already implemented LNG aboard at least one of their ships, did not expect that they will implement LBG. Of the ten of the 34 respondents who expected their company to implement LNG within five years, none believed that they would ever implement LBG. Among the ports interviewed in TRAZEPO, perceptions regarding biogas were similar to those concerning biofuel, except that even fewer of the public-owned ports provide biogas today (Steen et al., 2022).

[20] https://www.nrk.no/vestland/soksmal-mellom-hurtigruten-og-gasnor-_-krev-over-300-millionar-tilbake-etter-bygginga-av-bergen-lng-1.15969331

Governance. Both the National action plan for green shipping (2019) and the National plan for infrastructure for alternative fuels in transport (2019) highlight biogas as important for the future maritime energy mix, along with sustainable biofuels. Recognizing that biogas does not add CO2 beyond the natural cycle, the Norwegian Maritime Directorate considers liquid biogas as an alternative fuel that can limit climate gas emission in Norway's world heritage fjords and be important in a short to medium-term transitional period. By January 2023, they therefore proposed regulatory changes to define LBG as a zero-emission fuel and allow it for ships with a gross tonnage of 10 000 or more, up to 2035.[21]

4.3.6 Methanol

While methanol is not distinguished in the quantified transition pathways, it has gained increased attention as a viable alternative fuel for maritime shipping. There are two main types: green methanol, derived from biomass or captured CO2, and blue methanol, produced using blue hydrogen and CCS. However, methanol sourced from fossil fuels can mitigate tank-to-wake emission (emissions from the use of fuel onboard vessels) from ships but is deemed unsustainable when considering the entire lifecycle of well-to-wake (emissions from fuel production to end-use).

Techno-economic factors: Methanol has been adopted by international companies such as AP Møller-Maersk, CMA CGM, COSCo and Stena (Methanol Institute, 2023). Sweden has been a pioneer, with the RoPax ship Stena Germanica has running on methanol since 2015 and a converted pilot boat owned by the Swedish Maritime Administration since 2021. Otherwise, methanol is primarily used as fuel on methanol tankers, the first one being the Norwegian Westfal Larsen in 2016. As of 2023, of the 6.52% of alternative fuel used in operating ships globally, 0.05 % were methanol, while of the 51.3% of alternative fuel in the order book 8.01% is methanol (DNV, 2023a). In 2022, methanol was the second most popular alternative fuel choice (after LNG) with 22 methanol ships ordered (The Maritime Executive, 2023). The Norwegian MPC Container Ships and the North Sea Container Line aim to launch the first North Sea green corridor, including Norway's first methanol-powered container ships.

ITF (2023) underscores methanol as a promising low-carbon fuel for shipping. A significant advantage of methanol lies in its onboard storage capacity in liquid form at ambient temperatures and atmospheric pressure. Furthermore, methanol handling and power conversion technologies are mature, complemented by a robust existing infrastructure in ports. On the other hand, methanol has a lower energy density than heavy fuel oil (HFO) – about 15 MJ/L, as compared to 35 MJ/L – which means that more volume will have to be stored onboard for the same amount of stored energy. There are also challenges in terms of availability, the cost of green and blue methanol, and onboard safety assurance. [22] Moreover, a recent IEA report suggests that green methanol could be 25-100% more expensive than ammonia, due to the need to provide captured CO2 — from biogenic sources or direct air capture — to ensure that it is carbon-neutral over its lifetime (IEA, 2024).

[21] https://www.sdir.no/sjofart/fartoy/miljo/utslipp-fra-skip/nullutslipp-i-verdensarvfjordene-fra-2026/

[22] https://marine-offshore.bureauveritas.com/inside-look-methanol-fuel

Still, methanol fuel technologies currently exhibit a higher technological readiness level compared to ammonia and hydrogen (DNV, 2022b). Tankers carrying methanol have been using dual-fuel 2 methanol engines for propulsion since 2017 (DNV, 2022b), and the Lindager, the world's first dual-fuel methanol-fuelled tanker was built in 2016[23]. In Norway, the Green Shipping Program ("Grønt Skipsfartprogram") has undertaken a pilot project to explore the technical and economic feasibility of methanol as a marine fuel. This initiative aims to lower the barriers for methanol's large-scale adoption[24].

Socio-cognitive factors: Actors consider methanol as a good solution in a shorter-term perspective, since it is not associated with the same level of health and safety challenges as ammonia. Both are hazardous chemicals, but ammonia is toxic at much lower concentrations, necessitating extra costs for corrosion-resistant tanks and on-board safety measures such as spacing out storage, double piping, leak detectors and dedicated ventilation systems (IEA, 2024). The interest in methanol as an alternative fuel has thus increased since 2021, e.g. the 2023 survey of the Norwegian Shipowners' Association (Norwegian Shipowners' Association, 2023) indicates that more than 40% of their members now consider methanol as one of their main options towards achieving the emission targets by 2050. This interest is supported by its current large-scale production and existing transportation by ships, indicating an established supply chain and handling experience.

Governance: The adoption of the IMO interim guidelines for ships using methyl or ethyl alcohol as fuel (MSC.1/Circ.1621) has been an enabler for methanol-fueled ships. Together with the IMO's IGF Code for ships using low-flashpoint fuels and DNV's mandatory class rules for methanol-powered ships, this provides a comprehensive regulatory framework for the use of methanol as shipping fuel. From a regulatory point of view methanol gained an advantage over ammonia and hydrogen in December 2020 when the IMO approved the interim guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (DNV, 2022b). Moreover, the Norwegian Government's Green Industrial Initiative includes methanol as one of the priority sectors for green growth (Norwegian Government, 2023).

5 Discussion: Transition bottlenecks

In Geels et al. (2020), the concept of transition bottlenecks is used for tensions between the MLP analysis and goal-oriented model-generated pathways. As noted in chapter 3, we choose to discuss such tensions in terms of the four dimensions Turnheim & Nykvist (2019) present as conditions for pathway realization, e.g., where theoretical potentials collide with real-world settings and systems: Maturity of options, system integration and infrastructure, societal acceptability, and political feasibility. We focus on bottlenecks for the three pathways that involve radical technological and/or social change, and do not include the Incremental Innovation pathway, since this is the least

[23] Methanol as fuel heads for the mainstream in shipping (dnv.com)

[24] Metanol drevet containerskip – nybygg - Grønt Skipsfartsprogram (grontskipsfartsprogram.no)

demanding type of reorientation, without any major breaks from the current development trajectory.

5.1 Bottlenecks in the Technological Substitution Pathway

As discussed above, the TECH pathway describes a transition characterized by a high degree of technological change, but less change in social practices, values, and institutions. This means that decarbonization shall take place mostly through technological innovation instead of, e.g., lifestyle changes.

5.1.1 Maturity of options

The maturity of alternative fuels, particularly hydrogen and ammonia, constitutes a central concern within the TECH pathway. Despite ongoing pilot initiatives, these fuels remain immature for maritime use (DNV GL, 2020). Adding to this issue is the uncertainty regarding what is the potential future dominant design of hydrogen propulsion: fuel cells, gas turbines and/or combustion engines (DNV, 2019). Moreover, storage and transportation challenges for hydrogen, as highlighted in section 4.3.1, are associated with high costs and constitute major barriers for adoption. This may be one of the reasons why the quantitative modelling suggests that ammonia will be upscaled sooner and deployed more widely than compressed or liquefied hydrogen in the TECH pathway. As regards ammonia, the qualitative assessment draws attention to remaining challenges linked to corrosiveness and toxicity, which add complexity and possibly can make ammonia more suited for deep sea than for coastal shipping in Norway (EMSA, 2022).

Conventional fuels have lower prices in comparison to alternative fuels, due to e.g. achieved economies of scale, and maturity of supply chains and technologies. The absence of mass-produced and cost-efficient supply chains for novel propulsion systems, such as those for hydrogen and ammonia, creates a bottleneck for rapid development of both. Scaling up of the key novel fuels of the pathway, especially ammonia and hydrogen, is thus necessary to lessen the bottleneck of relatively higher fuel prices (Mäkitie, Hanson, et al., 2022). Creation of markets, further development of knowledge, and investments in production capacity are needed, which will take time and require significant investments.

Furthermore, the future availability of critical raw materials for the production of, e.g., batteries and fuel cells pose a potential challenge across all alternative pathways, including the TECH pathway. These critical raw materials, such as lithium and cobalt, are pivotal components in key technologies for electrification and decarbonization, however, also constrained by factors such as geopolitical tensions and supply chain disruptions.

Moreover, the qualitative assessment suggests that methanol increasingly is expected to play a crucial role in maritime decarbonization. Methanol can be produced from a variety of sources, including natural gas, biomass, and renewable electricity. It can also be applied as a hydrogen carrier and converted onboard to generate electricity for propulsion. This way, it can be an option for use of hydrogen avoiding storage issues (Aluko, 2023). Thus, it could become a crucial element in the TECH pathway.

5.1.2 System integration and infrastructure

Since low-carbon hydrogen and its derivatives are expected to be crucial also in the decarbonization of other sectors, these value chains must become large in scale (DNV, 2019). This creates a major coordination challenge for both industrial and public actors (DNV GL, 2020; Mäkitie, Hanson, et al., 2022). In comparison, the value chains for conventional fuels such as marine gas oil (MGO) and marine diesel oil (MDO) are well established (Bach et al., 2021). This may lead to path dependence in these conventional fuels, slowing down transitions. In the TECH pathway, the successful decarbonization of the maritime sector hinges on the timely breakthrough of ammonia and hydrogen into dominant fuels in the sector. Thus, overcoming this path dependence on conventional fuels is a key challenge in this pathway.

Furthermore, the production, infrastructure, and use of zero-emission hydrogen for energy (i.e. value chains) are, as of yet, virtually non-existent. The situation for ammonia is partly the same, although larger ports internationally, including the port of Grenland in Norway, have infrastructure for storage and distribution of (fossil-based) ammonia for other purposes. In contrast, conventional fuel bunkering is widely available globally, giving it a central competitive advantage. Meanwhile, the infrastructure for ammonia and hydrogen as energy carriers is still poor. This discourages the further adoption of ammonia and hydrogen as shipping fuels, while their yet limited adoption discourages the building of infrastructure, which may lead to delays in the transition. This chicken or the egg problem requires simultaneous development of both supply and demand (Mäkitie, Hanson, et al., 2022).

Considering the need for electricity for battery-electric vessels and production of alternative fuels, future grid capacity and availability of new renewable energy will be a challenge in this transition pathway. In Statnett's[25] base scenario towards 2050 (Statnett, 2023), 220 TWh is deployed, and at least 50 TWh new production is required, preferably by 2040. Of this, 30-40 TWh must be ocean wind. However, this capacity will not be available until the 2030s. In their Extra tall increase scenario, which includes development of competitive offshore wind as a key driver for a much higher increase in demand for energy from green industry, and forms the basis for Statnett's future strategy to avoid that grid capacity is a barrier to sustainable development, 260 TWh is deployed, and 30 GW offshore wind power is included. Thus, the TECH pathway seems highly dependent on an accelerated offshore wind development.

5.1.3 Societal acceptability

The full-scale implementation of ammonia as marine fuel depends on the development of solutions and designs that can address the present concerns regarding toxicity and corrosiveness. Handling of ammonia in the maritime industry is not unknown, as it has been transported as cargo, and some ships also have refrigeration systems with ammonia as refrigerant (Green Shipping Programme, 2021). The risk of fire and explosion is reduced compared with other hydrocarbon fuels, but ammonia has a characteristically pungent smell, and is highly toxic. It can cause skin irritation and respiratory problems, and in the case of direct contact, it is immediately life threatening. It is also categorized as very toxic to aquatic life, with long lasting effects (ibid.). Moreover, the GHG emissions from the various sources of ammonia varies significantly, depending on the production process as well as the CO2 emissions from the power mix used. Another potential contribution to global warming is nitrous oxide (N2O) produced during the process of utilizing ammonia in the power producer. This gas has a global warming potential that is much

[25] Statnett is the national and publicly owned transmission system operator in Norway.

higher than CO2 (ibid.). Technology development in this area will therefore be important for the acceptability of ammonia as an alternative fuel.

Another crucial factor for shipowners is the uncertainty and risk associated with the multiplicity of technologies currently being promoted for the decarbonization of maritime transport (Gabrielii et al., 2024). As most categories of vessels have a lifetime of 30-40 years, there is a considerable risk associated with adoption of first-generation technologies, and many actors therefore choose hybrid solutions or ships that are prepared for alternative fuel technologies, instead of opting for completely novel ship designs.

The introduction of alternative fuels may cause changes to routes and speed of transport, which may raise objections. Moreover, the maritime sector lacks skills and competences regarding ammonia and hydrogen as propulsion technologies. Developing relevant competences along the whole maritime value chain is therefore a critical precondition for wide use of such alternatives (Normann et al., 2023).

Moreover, recent research indicates that social acceptance for additional wind power development in Norway is low, with a negative preference for prioritizing regions for installation ("not-in-anybody's-backyard" effect) (Dugstad et al., 2020). This implies that other sources of renewable energy, such as upgrading hydropower, or offshore wind power tend to be preferred, however costlier. However, IEA (2021) notes that offshore wind projects also tend to experience resistance among coastal and port communities. They involve a more diverse and complex range of stakeholder and interests (Skjølsvold et al., 2022). Therefore, conscious work towards increased social acceptance, e.g., to build institutional capacity, to ensure collaboration between host communities and project promoters, and to address perceptions of distributional and procedural fairness, is seen as crucial for the expansion of offshore wind power (ibid.).

5.1.4 Political feasibility

The TECH pathway is well aligned with the high ambitions regarding green shipping solutions that prevail in Norway (as noted in chapter 4.2). Thus, the political feasibility of this pathway can be considered as high.

However, sustaining this momentum requires continued strong support for alternative fuel technologies, to address the identified challenges in terms of maturity of options, and system integration and infrastructure. It has also been argued that whereas the current support schemes are important to reduce the added costs and economic uncertainty associated with largescale investments, they do not address the market risk associated with demand and changing prices, which depend on both international and domestic energy and climate policies. To accelerate hydrogen and ammonia production, the risk associated with cost per unit must also be kept at a reasonable level, e.g., by risk relief in the form of contracts of difference (Oslo Economics, 2023; ZERO, 2022).

Moreover, there is the need to overcome remaining legal-administrative barriers in the TECH pathway. As noted above, processes to establish specific standards and guidelines for hydrogen and ammonia ships, as well as for onshore bunkering facilities, are ongoing. However, the decision-making procedures in organizations such as the IMO are slow. Use of MSC.1/Circ.1455 – guidelines for the approval of alternatives and equivalents adds uncertainty and costs, and some of the required amendments to the IGF and IGC Codes and development of guidelines for alternative fuels and related technologies, are not foreseen to enter into force until 2028 (DNV, 2023b). This may therefore also be considered as a bottleneck.

Besides limited willingness to pay among customers, Norwegian shipowners consider uncertainty regarding how to choose between alternative low emission technologies as the two main barriers to investment in climate and environment-friendly technologies (Norwegian Shipowners' Association, 2024). Given the multitude of solutions being developed and promoted, there is a need for more knowledge and clearer signals regarding which technologies that are deemed most sustainable for which applications, in a longer-term perspective (see e.g., Gabrielii et al., 2024). The principle of technological neutrality stands strong in Norway, in e.g., green public procurement and requirements linked to licensing for offshore activities, but may in some instances be unconducive for the least mature alternative solutions. The recent report for the Norwegian Ministry of Energy, on value chain development for hydrogen (Oslo Economics, 2023), finds that for the maritime sector, where hydrogen technologies remain relatively immature, technology-neutral requirements are less likely to unleash investments in hydrogen. However, the report alsobut notes that more specific requirements may lead to less efficient solutions.

TABLE 2: OVERVIEW TRANSITION BOTTLENECKS IN THE TECH PATHWAY

Dimension	**Transition bottleneck**
Maturity of options	• Lock-in to conventional fossil fuels • Multiple, competing options • Critical raw materials for BEVs • Storage and transport of hydrogen • Corrosion and toxicity challenges of ammonia • High investments costs, risk
System integration and infrastructure	• Value chain development, zero-emission hydrogen and ammonia • Timely increase of grid capacity • Lack of bunkering infrastructure
Societal acceptability	• Resistance against largescale onshore and offshore wind power expansion • Health and safety concerns, new fuels • Resistance against changing routes and freight times • Lacking skills and competences
Political feasibility	• Dependence on continued support for alternative fuels • Calls for risk relief (e.g., contracts of difference) • Unclear political prioritization between alternative fuel technologies • Pace of development of specific rules and guidelines for use and bunkering of hydrogen and ammonia

5.2 Bottlenecks in the Social Change Pathway

The SOC pathway describes a transition where the currently existing energy technologies are reinforced and there are no strong drivers in terms of radical innovation or substitution of core energy technologies. Rather, changes in consumer behavior and values are driving the transition, leading to a development where the use and integration of current technologies takes place within an altered socio-technological logic, where degrowth and sufficiency are higher on the agenda, together with a stronger emphasis on circular economy and digital transformation. As noted in chapter 3.2, the amount of energy deployed for maritime transport goes down in this pathway, as modelled in IFE-TIMES-Norway, whereas the maritime transport volume remains constant (due to modal shift of freight from road to sea).

5.2.1 Maturity of options

In the SOC pathway, biofuels emerge as the primary solution for decarbonizing maritime transport, accompanied by an increasing adoption of battery-electric propulsion system, according to the modelling. This is in line with international studies, where advanced biofuels such as drop-in, microalgal, and electro biofuels, especially from inedible biomass, are considered as a promising solution (IEA Bioenergy, 2021; Oh et al., 2018). Biofuels (such as biodiesel, liquefied biogas) can to some degree be used without requiring change of current propulsion systems based on fossil fuels (e.g., MDO, LNG). As they play a key role in SOC pathway, path dependence in conventional fuels therefore causes less severe issues for this pathway, as biofuels pose less of a socio-technical change (e.g. in terms of value chains, institutions, and technologies) to the shipping system.

As noted above, a 6% biofuel mandate for shipping has been implemented in Norway. However, several barriers hinder widespread adoption of biofuels. Firstly, there is a limited availability of biomass feedstocks. Currently, over 90% of the biofuels produced globally (e.g., bioethanol, biodiesel) are made from edible biomass such as grain or vegetable oil (Oh et al., 2018). Considering the need to feed a growing world population, as well as competing uses for biomass feedstock (e.g., heat, power and bioproducts), this constitutes a major bottleneck. Moreover, the energy content of bioethanol and biodiesel is significantly lower than those of fossil fuels, and high blending levels may impact fuel properties and compatibility with fossil fuel systems negatively (Oh et al., 2018). Advanced biofuels (based on waste and residues, in Norway including both class A and B, i.e. biofuel based on used cooking oil and animal fats) are emerging as an alternative. The biofuel mandate for shipping in Norway relates specifically to this category. Still, although the gap vis-à-vis fossil and conventional biofuels is declining, costs have so far remained higher. Second-generation biofuel technologies, which utilize residues from agriculture, forestry, and waste materials as feedstocks, are expected to expand in the coming years, and third generation biofuels, based on seaweeds and algae, may have advantages in terms of scalability. However, these solutions are still early stage, and high costs of production and sale constitute a major barrier (Maliha & Abu-Hijleh, 2023). Comprehensive process optimization for diversification of products and cost-effective scale-up are needed before these alternatives can be implemented widely (Oh et al., 2018).

However, the observation that bio-methane of recent has become competitive due to rapid, unexpected increase in the price of natural gas following the war in Ukraine suggests that there is a high degree of uncertainty regarding the future market for biofuels. While battery-electric propulsion systems are in use in Norway today, this is limited to shorter routes. Since conventional lithium-ion batteries need frequent recharging, and batteries are heavy and take a lot of space, direct electrification is considered as less suited for large ships and/or smaller boats that sail long distances. However, a recent study suggests that battery costs are declining and as much as 40% already (Kersey et al., 2022). On the other hand, the future availability of critical raw materials, noted as a bottleneck for the TECH pathway, may also constitute a bottleneck for the SOC pathway, as shortages of lithium are forecasted for the coming fifteen years, and foreseen to create a barrier to widespread use of fully battery-electric solutions in the shipping sector (Gregoir & van Acker, 2022).

5.2.2 System integration and infrastructure

While this pathway emphasizes radical change through social innovation and circular economy, significant challenges are foreseen when it comes to infrastructure and system integration. New forms of system integration, leveraging ICT technologies and smart integration, as necessary, but require further technological development and widespread implementation. Additionally, the development of energy storage technologies present a bottleneck, as fluctuations in the supply of energy from intermittent renewable sources, can make it challenging to match electricity supply with real-time demand. We find support for this in Statnett's low-demand scenario (Statnett, 2023), which also is characterized by increased energy efficiency, limited availability of new renewable energy, and reduced petroleum usage, and suggests that addressing these challenges is critical.

According to the IFE-TIMES-Norway results, the amount of electricity required will be in the same range as in the other pathways, suggesting that development of sufficient power infrastructure is a critical factor also in this case. More extensive use of battery-electric propulsion systems will require a network of charging facilities that does not exist today. This constitutes a major bottleneck, considering the foreseen limitations in grid capacity.

Moreover, the SOC pathway introduces challenges related to "problem shifting". As noted above, increased reliance on battery technology may help reduce climate gas emissions, but they also introduce new challenges related to resource depletion. Batteries contain critical raw materials, provided through extraction processes associated with environmental degradation. Furthermore, the potential of recycling is limited, due to e.g., the long lifespan of products, decentralization of recycling sources, and technological difficulties (Guo et al., 2023). Current recycling rates are low and only slowly increasing, and recycling processes often require substantial energy inputs and virgin raw materials.

While digitalization and automation are speeding up in the maritime industry and seen as promising both for overall energy management and more environment friendly operations, these technologies are also energy consuming. Digital integration among stakeholders, e.g., cargo-owners, forwarding-, and shipping companies, is seen as crucial, to streamline operations and procedures, but depends on the whole value chain, and if even one actor is poor in terms of digitalization, this will be a bottleneck (Ichimura et al., 2022). Moreover, new competencies, such as remote control, cyber security, programming, data processing, and commercial skills to assist work at sea from ashore, take time to develop (ibid.).

Local system integration, and industrial symbioses based on circular economy principles, have up to recently had limited attention in Norway, but are now increasingly promoted, e.g., the most recent grant schemes for OPS and hydrogen energy hubs emphasize flexibility and locally integrated energy systems in ports, and frontrunners such as Borg Port are active in this area, with increased integration of locally production and use of renewable energy. However, lack of knowledge and data is a common barrier, noted e.g., in the ongoing INTERPORT project.

5.2.3 Societal acceptability

The SOC pathway relies on reinforcing social and cultural trends that prioritize quality of life over material consumption, fostering better coordination and implementing energy efficiency measures across the maritime sector. Behavioral change and reshaped societal values and norms, particularly towards reduced consumption and travel, are pivotal for this pathway. While some behavior change is possible and indeed can be observed where there are co-benefits, such as changing towards healthier and more climate-friendly diets, or where incentives are provided, such as for battery-electric vehicles, drastic reductions in consumption and travel patterns may be more difficult to achieve. Recent interviews in the INTERPORT project suggest that whereas all parties want to become as green as possible, customers in coastal freight are not willing to pay significantly more for greener shipping. Therefore, sailing flexibility for optimal efficiency remains crucial, and alternatives which imply dependence on a limited number of quays with facilities for recharging or bunkering of alternative fuels do not seem feasible for all segments.

Currently, biofuels that can be applied with existing ship technologies do not face the same market acceptance challenges. However, in SOC pathway where biofuels stand for most of the energy demand in Norwegian shipping, that situation may change. This may be particularly true for conventional biofuels, where public and socio-political acceptance can be a challenge, considering the dilemmas and trade-offs associated with land use, land-use change and forestry (LULUCF). Hence, there is a shift towards second- and third generation biofuels, which pose fewer conflicts with food production, higher-value biobased industries, and nature conservation.

At the same time, there are mixed expectations regarding digitalization as an enabler of green transition in the maritime sector. A study by PWC (2017) showed that Norwegian actors increasingly foresee crewless ships and a changing role for shipping companies. However, there is also skepticism, considering the vulnerability of ships and entire value chains to cybercrime, longer (expensive) berth times since the absence of crew means maintenance and repairs cannot be carried out immediately, and high development costs for the necessary hardware and software (ibid.) Internationally, smartships, AI, and big data analysis for optimization of commercial or operational activities, and digital integration among stakeholders are considered as most influential for the maritime sector (Ichimura et al., 2022).

As technologies for electricity generation are assumed to be high cost in this pathway, and the integration of new renewables is limited, as compared with the TECH pathway, rising energy expenditures present a notable challenge. As resources are extracted, cheaper options are typically utilized first, leading to increasingly resource- and energy-intensive processes. Additionally, cost-effective energy efficiency improvements may have rebound effects, as they tend to reduce the effective price of energy services, such as OPS, and may hence encourage increased consumption of those services, which in turn will partly offset the energy savings. They may also trigger indirect and macroeconomic responses, with rebound impacts on energy consumption throughout the economy (Brockway et al., 2021).

Furthermore, cost shifting, i.e., externalization of environmental impact, is a significant issue of concern, in two main ways. First, high -consumption countries, such as Norway, via importing large volumes of biofuels, can shift the negative environmental impacts and costs of their high energy use onto low-consumption countries. In the case of first-generation biofuels, this also involves potential conflicts with food production, being shifted to parts of the world where food security already is a key concern. Secondly, concerns over cost shifting effects are voiced regarding flexibility and prosumption, where critics suspect that the credits utilities pay for energy delivered to the grid ultimately results in higher bills for non-producing customers[26]. This can lead to higher bills for non-producing customers, raising equity and fairness issues.

5.2.4 Political feasibility

The political feasibility of transitioning maritime transport towards more sustainable practices through the SOC pathway requires stronger policy incentives and commitment due to the magnitude of change needed. Closing oil and gas operations by 2034, as defined in the overarching SOC pathway (chapter 3) presents challenges, including acceptance of welfare implications and potential job losses, which may limit political support (Egli et al., 2023; Korsnes et al., 2023). However, initiatives such as the EU's Biodiversity Strategy for 2030 highlight conservation efforts, calling for 30% of landmass and oceans to be designated as protected areas. Together with increased public awareness, this may strenghten the momentum for shut-down of the offshore oil and gas activity. However, there are also potential trade-offs between preserving ecosystems and accelerating the transition away from fossil fuels. Alternative economic activities, such as data centres, increase in other offshore industries, e.g., fishery and aquaculture, or enhanced circular bioeconomy, based on exploitation of seaweed and/or more intensive forestry and agriculture, may imply land use change and adverse impacts on biodiversity. This underscores the complexity of gaining broad political and public support for climate actions.

While the overarching SOC pathway anticipates a very limited increase in energy demand, the Statnett (2023) low demand scenario, which has similar characteristics, e.g., little new power production and reduced growth in energy consumption, and increased focus on energy saving, leading to less energy use by private consumers, still forecast a substantial increase in energy consumption. This scenario necessitates much stronger political efforts to control the demand from industry, channeling more electricity to industries where it contributes to emission reduction, and preventing other industrial activities from spending too much of the limited renewable production that is available. Here, electrification of existing industry is prioritized over supply for new green industry. This approach is linked with ecological–economic decoupling, aiming to achieve economic growth while preserving a healthy environment by coupling rising gross domestic product (GDP) with a reduced material footprint and decreasing (or net-zero) carbon emissions. This is also a key component of the European Green Deal, which emphasizes two core components: Efficiency (doing more with less, e.g. lower consumption of resources and energy), and sufficiency (living well with less).

TABLE 3: TRANSITION BOTTLENECKS IN SOC

Dimension	Transition bottleneck
Maturity of options	• High cost of advanced biofuels production • Critical raw materials for batteries
System integration and infrastructure	• Timely increase of grid capacity • Domestic value chain development, advanced biofuels • Availability of sustainable biomass

[26] https://pvbuzz.com/unveiling-the-controversial-phenomenon-of-solar-cost-shifting/

	• Sharp increase in efficiency depends on smart/ICT technology • Data and knowledge to enhance circularity
Societal acceptability	• Land use conflicts (biodiversity, food production) • Rebound effects associated with efficiency improvement • Cost shifting (if most biofuel imported) • Radical behavior change depends on change in cultural values and norms
Political feasibility	• Limited will to stop oil and gas production by 2034 • Tension between climate change mitigation policies and conservation policies • Need strong policies steering renewable energy towards decarbonization of existing industry

5.3 Bottlenecks in the Radical Transformation Pathway

As noted above, the RAD pathway describes a development where both technology and market developments and socio-political conditions, i.e. stronger policies and increased public awareness and will to change social practices, constitute strong drivers for sustainable energy transition. Thus, this is our most ambitious and optimistic pathway. However, it is also associated with multiple bottlenecks, which partly are described above, in the sections on the TECH and SOC pathways.

5.3.1 Maturity of options

In the quantitative model-based analysis using IFE-TIMES-Norway, the RAD pathway is associated with a level of technology development quite similar to that of TECH pathway, with the exception that ammonia is taken up a bit sooner, and the use of hydrogen by 2050 is slightly higher (Figure 3). This can be because the technology development is boosted by increasing public awareness and stronger policies, and/or because it benefits from the local symbioses and smart integration that also characterizes the SOC pathway. As in the TECH pathway, existing path dependencies may pose inertia, but as the socio-political drive towards the 2050 climate goals is assumed to be much stronger in RAD, lock-in mechanisms linked to the petroleum industry and conventional fuels are likely to be weaker in this pathway.

As shown in Figure 3, in the RAD pathway, multiple, competing alternative technologies are available. Consequently, navigating uncertainty and managing associated risks is likely to be a major challenge, as the technology choices of Norwegian shipowners will be strongly influenced by actors and decisions made in other countries, as well as national policies. Additionally, the establishment of robust value chains for hydrogen and ammonia can be considered as main bottlenecks, here as in the TECH pathway. The uptake of compressed and/or liquid hydrogen will also depend on progress in fuel cell development, and hydrogen storage and transport technologies. For ammonia, we have seen, the current issues as regards corrosion and toxicity need to be solved before the technology can be mainstreamed as an energy solution for the maritime sector.

Furthermore, the availability of critical raw materials for batteries and fuel cells may further constitute a bottleneck, here as in the TECH and SOC pathways. In addition, the high costs and remaining technological challenges associated with advanced biofuel production will be challenging, but maybe less so than in SOC, given that the expected volume of biofuel deployed in maritime transport is lower and there is a higher level of technology development in RAD.

5.3.2 System integration and infrastructure

The RAD pathway will also involve a high need for infrastructure development, which may be considered as a bottleneck. An increasing share of offshore wind power must be integrated, and increased capacity in the electricity grid will be critical for the development of value chains for green hydrogen and ammonia, as well as for large scale implementation of OPS and charging facilities for battery-electric vessels. However, compared to the TECH and SOC pathways, the RAD pathway offers a higher degree of flexibility (see Table 1), potentially mitigating the severity of this bottleneck.

The successful deployment of ammonia and hydrogen in the maritime sector will depend on the establishment of bunkering facilities along coastal regions. Given the lower energy density of these alternative fuels compared to fossil fuels, a more extensive network of bunkering points than today will be necessary. Moreover, investments in infrastructure and bunkering facilities for hydrogen, ammonia and methanol in ports depends on volumes, which again depends on demand, and the cost of investment can be a bottleneck in itself (Basso et al., 2022). Furthermore, the establishment of bunkering facilities must align with regulatory frameworks and safety standards to mitigate the potential risk of handling and transporting alternative fuels (ibid.)

In the RAD pathway, biofuels based on Norwegian bioresources play a crucial role. This requires the development of domestic value chains for advanced biofuels, which constitutes a substantial bottleneck, given the high costs and level of maturity of the most promising technologies. Moreover, an increase in the demand for sustainable biomass can be expected, and the total, global demand for all industries that could process biomass is indeed anticipated to exceed the sustainably available capacity by 2050 (Kircher, 2022).

5.3.3 Societal acceptability

While the RAD pathway presupposes less onshore wind power expansion than the TECH pathway, it includes a large increase in offshore wind power. Gaining acceptance for the latter may be challenging. As noted above, offshore wind projects also tend to experience resistance among coastal and port communities (IEA, 2021). In the RAD pathway, we assume a higher level of environmental awareness than in TECH, as well as a higher share of advanced biofuels, which in this case are assumed to stem mainly from domestic bioresources (onshore and/or offshore). This implies that social acceptance, i.e., conflicts of interest and increasing resistance to offshore wind expansion may become a transition bottleneck. On the other hand, there may be less land use conflicts, as there is less onshore wind power in RAD than in TECH, and less biofuel than in the SOC pathway.

At the outset, the health and safety concerns regarding alternative fuels, such as hydrogen and ammonia, and resistance against changing freight times and frquency/volumes could also make themselves felt in this pathway. However, if there is increased awareness and willingness to change existing practices and lifestyles, we may assume that the public also is more willing to accept changing travel and freight conditions to enable green solutions that are safe and economically viable.

Furthermore, limited knowledge and security concerns regarding ICT and digital integration, and possible rebound effects associated with energy efficiency improvement, are other factors that may influence the societal acceptability of this pathway.

5.3.4 Political feasibility

In terms of political feasibility, the RAD pathway is challenging since it involves a high level of investments to accelerate the development of new technologies and value chains as well as radical measures to disrupt existing production and consumption patterns. Gaining acceptance for shutting down oil and gas by 2050 may be less challenging than to achieve this by 2034, as in SOC, since the RAD pathway includes more alternative technologies and potential sources of value creation to replace oil and gas, including CCS.

However, a major bottleneck here will be how to build consensus for large-scale development of wind and solar energy to meet the increasing total energy demand for maritime transport towards 2040 and 2050. This may be challenging considering the increasing focus on environmental protection and biodiversity in national and EU policies.

In this pathway, policies addressing several of the known barriers to zero emission fuels are strongly implemented, e.g. carbon pricing and differential energy taxes are used actively, and heavy R&D&I support is used to enable the development of new value chains. Risk relief may also be required, but with stronger policies and more awareness, the willingness-to-pay for alternative solutions may be higher. The pace of development of specific rules and guidelines for use and bunkering of hydrogen and ammonia is a critical factor. Since the RAD pathway is characterized by stronger policies, this may be less of a bottleneck here than in TECH, but it depends on international agreements, as much as national decision-making.

However, a key challenge that remains is that a multiplicity of alternative energy solutions is being promoted, and there is a high level of uncertainty as to which zero emission technologies that will be preferred for which applications, in the maritime sector and beyond. A related bottleneck foreseen is that of coordination across sectors, e.g., drive towards deployment of biofuels in maritime transport, versus their deployment in aviation, and struggle between forces promoting CCS for blue hydrogen and ammonia in transport, and forces pushing CCS for decarbonization of select industries.

While the overall demand for energy and food are assumed to stabilize in RAD, there will be potential socio-political challenges in terms of procedural and distributive justice, e.g., with some regions benefitting strongly from renewable energy hubs and others suffering due to the restructuring of oil and gas related industry, and/or higher transport and travel costs and less convenient schedules. This could feed political populism.

TABLE 4: TRANSITION BOTTLENECKS IN RAD

Dimension	Transition bottleneck
Maturity of options	• Multiple, competing options • Availability of critical raw materials • Fuel cell development for H2 • Storage and transport of H2 • Corrosion and toxicity challenges of ammonia • High cost of advanced biofuels production
System integration and infrastructure	• Timely increase of grid capacity • Value chain development for hydrogen and ammonia • Availability of sustainable biomass • Domestic value chain development, advanced biofuels • Development of bunkering infrastructure for hydrogen and ammonia
Societal acceptability	• Skepticism and conflicting interests related to largescale offshore wind power expansion • Rebound effects associated with efficiency improvement • Radical behavior change depends on change in cultural values and norms
Political feasibility	• Uncertain political will to stop oil and gas production by 2050 • Trade-off between climate change mitigation and conservation of biodiversity • Coordination across sectors • Prioritization between alternative fuel technologies • (Pace of development of specific rules and guidelines for use and bunkering of hydrogen and ammonia) • Social justice issues

For the RAD pathway, the absence of biofuels and liquid biogas in maritime applications by 2030, and the minimal share of liquid biogas thereafter until 2050, raises questions. This outcome appears counterintuitive given current policies emphasizing biofuels as a vital component in the future energy mix, also in the maritime sector.

6 Summary and implications

6.1 Common challenges and differences

In synthesizing the common challenges and differences across the three pathways, several observations emerge. Two key challenges that resonate across all studied pathways are high investment costs and associated risks, and the need for domestic value chain development to enable uptake of alternative fuels. Another challenge that cuts across the pathways is the necessity for increased grid capacity to accommodate increased demand and supply of renewable energy, reflecting a requirement for enhanced grid infrastructure, and more production of renewable energy. Furthermore, all the studied pathways highlight challenges related to critical raw materials.

However, the pathways also differ. The TECH pathway is facing a bottleneck in terms of lock-in to conventional fossil fuels, which is stronger than in SOC and RAD, which partly continue to utilize conventional technologies (biofuels). Resistance to large-scale wind development (onshore and offshore) and health and safety concerns are critical obstacles for, e.g., ammonia. While political feasibility for TECH pathway can be considered as high, the need to prioritize between alternative solutions and address market costs stands out as key issues. The SOC pathway ultimately depends on the deep cultural changes, which may take considerable time to develop. Otherwise, availability of sustainable biomass, sharp increase in efficiency, challenges stemming from land-use conflicts, and rebound effects are key topics. In addition, a critical bottleneck is how the political will to cease Norwegian oil and natural gas production by 2034 can be mobilized.

The RAD pathway, finally, is associated with less lock-in to conventional fossil fuels, a larger leap in offshore wind power production, and a broader mix of alternative fuels/propulsion systems in maritime transport in Norway towards 2050, than in the other alternative pathways. Here, the need to prioritize and coordinate across sectors stands out as a key challenge. Although land use and social distribution may be less conflictual than in the SOC pathway, there are potential trade-offs between climate change mitigation and biodiversity conservation which constitute an important bottleneck also in this pathway. Garnering support for the shut-down of Norwegian oil and gas exploitation is a considerable bottleneck but may be more feasible than in RAD due to the 2050 perspective, when more alternative technologies are assumed to be commercially available.

Thus, the case-study highlights certain challenges and bottlenecks that need to be considered regardless of which future pathway is foreseen to be most likely or desirable. It also draws attention to some challenges and bottlenecks that are more pathway specific. Interestingly, the RAD pathway, which in principle combines the characteristics of TECH and SOC, and is the most ambitious of the three, is associated with a development where some of the bottlenecks associated with TECH and SOC are reduced, but trade-offs, prioritization, and coordination across sectors stand out as key challenges. This suggests that supplementing the approach by Geels et al. (2020), by including a fourth, more radical pathway, indeed may be fruitful, for analytical purposes, as well as in subsequent dialogue with stakeholders, on alternative pathways towards the realization of Norway's 2050 climate goals.

6.2 Implications of the study

The above-mentioned observations have certain practical implications. **In terms of policy**, some general recommendations can be made. Considering the common challenges identified across the studied pathways, the following can be suggested:

- Continue enforcing stronger taxation of climate gas emissions, as "the polluter pays" principle benefits all alternative energy solutions in the maritime sector.
- Use consumer demand (e.g., public procurement, cargo-owning) to incentivize uptake of low- and zero-carbon energy solutions in all relevant shipping segments.
- Implement stricter environmental requirements for vessels in government-awarded licenses in fishing, aquaculture, and offshore energy sectors.
- Support collaborative efforts to incentivize low and zero-emission solutions through harmonized fee systems, such as EPI and ESI.

- Ensure holistic planning, incorporating also upstream (energy) value chain developments (and potential bottlenecks) such as renewable energy production and grid distribution capacity, both within and across sectors.

Looking at the SOC pathway, in particular, but also for the TECH and RAD pathways, the following can also be highlighted:

- Stronger measures to promote local energy communities, and smart integration of different energy solutions.

With a view to the TECH and RAD pathways we would add:

- Strengthen regulatory capacity of public sector in terms of emerging energy technologies, to address remaining regulatory barriers and lack of standards for alternative fuel solutions.
- Provide technology-specific support while using sectoral- and general-level policies to the greatest extent possible, as alternative fuels differ with regards to maturity, risks, and costs.
- Increase the effort to provide suitable risk-reducing measures, to address the 'chicken or the egg' dilemmas that alternative fuels face.

When it comes to **further research**, our study shows that interdisciplinary approaches, such as ours, that combine both numerical modelling and qualitative assessments may provide a more holistic understanding of the features and challenges related to energy transition pathways. Specifically, it opens for critical evaluation of the feasibility of various pathways by seeking to outline the central potential bottlenecks related to each modelled future.

In terms of analyzing the energy transitions in the maritime sector, more knowledge on value chain development and actual and potential interactions across solutions and sectors is needed. This should not only include interactions between different energy technologies, but also the interaction between these core technologies and technologies related to the communication and integration of different solutions and systems, i.e., ICT and digital transformation, and in turn, integration of circular economy principles. Such interactions are considered in the SOC and RAD pathways defined in NTRANS, but yet little researched within the field of socio-technical transition studies, and also weakly implemented in energy system models, such as IFE-TIMES-Norway.

The case study further reveals that there is limited research on the social acceptability of alternative energy solutions in the maritime sector so far, and how it interacts with market, technology development, policy formation and wider cultural change processes in sustainability transitions. Considering how the technological options, traffic patterns, market, ownership, and actor-networks vary, we also see the need for more detailed research on the conditions for and perceptions of alternative transition pathways for different ship segments in Norway.

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