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Blending new and old in sustainability transitions: Technological alignment between fossil fuels and biofuels in Norwegian coastal shipping

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ABSTRACT

Facing increasing pressure to decarbonize, innovation within the shipping sector has turned to low-and zero carbon solutions. In this paper we investigate how the development and implementation of biodiesel and liquefied biogas (LBG) in Norwegian coastal shipping has been influenced by the technological alignment with fossil fuels. We understand this influence to emanate from the (mis)match of biofuels with the structure of coastal shipping (e.g. infrastructure, knowledge, institutions, actors) which has been shaped by fossil fuels. This way we contribute to the development of Technological Innovation Systems (TIS) framework by discussing the effect of sectoral cross-technology externalities on the functionality of a TIS. Our core data consists of semi-structured interviews, supported by a firm survey with Norwegian shipowners.

Our results show that the technological alignment provides the biodiesel and LBG TISs with several benefits, such as access to established markets and infrastructure, which suggests that Norway to some extent has good conditions for maritime biofuel markets to form. However, two major barriers for implementation of biofuels are fuel availability and cost. Considering the competition with battery-electric and hydrogen solutions, the positive externalities of the interchangeability between fossil and biofuels are insufficient to make biodiesel and LBG competitive contenders for coastal shipping. In order to upscale implementation of biofuels in the Norwegian coastal shipping sector, which is needed to reach national and international emission targets, there is a need for strengthened policy interventions. To establish market formation, subsidies for biofuels and feed-in targets would be crucial policy instruments.

1. Introduction

While the carbon-intensity of maritime transport is low compared to air and road transport, the greenhouse gas (GHG) emissions of the sector nevertheless constitute 3% of global anthropogenic emissions. Thus, for the sector to contribute its part to the fulfilments of the Paris Agreement, the International Maritime Organization (IMO) in 2018 adopted an initial strategy for reducing maritime GHG emissions, aiming for reductions of 70% in carbon intensity and 50% in absolute GHG emissions by 2050, compared to 2008 [1]. The strategy is technology neutral, and it is generally acknowledged that a successful sustainability transition within the maritime sector will require a portfolio of low- and zero-carbon (LoZeC) technologies, including battery-electric, hydrogen, ammonia and various types of biofuels [2].

The empirical focus of research on sustainability transitions in transportation has so far been on road transport [3–5], with much fewer contributions focusing on maritime transport [6–10]. This is noteworthy given the importance, urgency and recent policy attention to transitioning the maritime sector. In comparison to other energy related sectors (such as electricity, which experience a rapid transition to renewables), the maritime sector's complexity and *trans*-nationality complicates introduction of alternative technologies. Thus, the introduction of LoZeC ship technologies has only recently begun. It is therefore necessary to study innovation related to the sustainability transition within the maritime sector [11]. Further, analyses of the role of biofuels in this endeavour remain surprisingly scarce.[1] To our knowledge, there are no studies that examine the development and uptake of biofuels in the maritime sector, even if pathway models on the

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[1] Previous literature on biofuels (mainly biodiesel and liquefied biogas) in the maritime sector focus on environmental and life cycle assessments [12–14], techno-economic analyses [e.g. 15], and biofuels' potential for compliance with emission control areas implemented by the IMO [e.g. 16].

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decarbonization of global shipping have assumed a share of about 20% biofuels in the total fuel mix of the sector [17,18].

Consequently, we analyse socio-technical challenges and opportunities of the implementation of biofuels as part of a sustainability transition within the maritime sector. Specifically, we investigate the application of biodiesel[2] and liquefied biogas (LBG) in the context of existing types of fossil fuels in Norwegian coastal shipping. While the majority of emissions by shipping comes from deep-sea operations, coastal shipping offers better opportunities for experimenting with LoZeC technologies [21]. We apply the technological innovation systems (TIS) framework [22,23], which enables comparative and extensive assessment of key functions of an innovation system for certain technologies in general or within particular geographical areas. Following this assessment, technology-specific policy interventions to address system strengths and weaknesses can be developed [22].

Established technologies, and the vested interests, infrastructures and knowledge embedded in them, are often understood to impede radical innovation [24,25]. However, it has also been recognized that innovations are based on existing technologies [26,27], and may use e.g. existing infrastructures [28]. Established technologies in a sector may therefore affect radical innovation positively or negatively [29].

Some recent studies have begun to explore how the functionality of a TIS may be influenced by established technologies [30,31], elaborating on e.g. how the dynamics of mature and novel TISs may co-evolve [29,32]. However, established technologies affect novel technologies also indirectly by shaping the structural configurations of the sector. For instance, the infrastructure and knowledge base of a sector tend to be designed to meet the needs of established technologies [33], existing institutions can have technology-specific features, and incumbent actors may or may not be engaged in the development of novel technologies [34]. Hence, the *alignment* of novel technologies with the existing configurations of a sector is relevant for innovation [35,36]. While the (mis) match of novel technologies with the configurations of sectors has been frequently discussed under the concept of regimes [37], prior literature has elaborated little on how the infrastructure, knowledge base, actor networks, institutions etc. centred around established technologies may affect e.g. the knowledge development, resource mobilization and legitimation around new technologies. Such effect can be conceptualized as externalities between technologies [38,39].

Empirically, we focus on the effect of the interchangeability of biodiesel and liquefied biogas (LBG) with, respectively, marine gas oil (MGO)/marine diesel oil (MDO) and liquefied natural gas (LNG) in the context of Norwegian coastal shipping. This interchangeability means that the two biofuels are technically aligned with their fossil equivalents as their characteristics allows the use of the existing bunker infrastructure, storage and engines [40]. Against this background, we aim to contribute to the understanding of *sectoral cross-technology externalities* by studying how the technological alignment with fossil fuels may impact the TIS performance of LoZeC technologies. This means furthermore that we our primary concern is to understand how the two biofuels TISs are influenced by the existing sectoral (maritime) context. We pose the following research question: *How has the alignment with existing fuels (MGO/MDO and LNG) influenced the functionality of the biodiesel and LBG TISs in the Norwegian coastal shipping sector?*

The remainder of this article is structured as follows: In section 2, our analytical approach utilizing the TIS framework is presented. In section 3, we present the institutional and technological setting for implementation of biodiesel and LBG in Norwegian coastal shipping. Our research design, methods and data are described in section 4. In section 5, we present the results of the TIS analyses of the respective technologies, which is followed up by a discussion around policy interventions in section 6. The final section concludes.

2. Analytical approach

2.1. Technological innovation systems

Technological innovation systems (TIS) consist of structural components in the form of actors, networks and institutions involved in the creation, diffusion and use of a technology [41]. TIS actors may be firms, interest organizations, research organizations, public authorities, and non-governmental organizations [42]. Actors may form formal and informal networks, which can contribute to identifying needs in technology development, creation of trust, and development of technical standards [42,43]. Institutions refer to the regulations, norms, culture and routines related to a technology [44]. Novel technologies often do not fully comply with existing institutions, and may need conscious shaping by actors [45]. The structure of a TIS is therefore dynamic and evolves over time.

The development of TIS can be understood through the contributions of structural components to innovation processes, i.e. the functions of the TIS [23,42]. These system functions refer to different dimensions of innovation system development, which through agentic processes and the influence of institutions, evolve over time. The functions may reinforce each other, leading to continued innovation, but might also lead to sequences which impede innovation, e.g. vicious circles of poor performance in innovation processes or conflicts between actors [46]. In order to understand the development of a technological innovation, it is therefore useful to analyse its performance in the respective TIS functions [42]. For our analysis, we use a conceptualization of the TIS functions based on [23,42], summarized in Table 1.

Besides TIS-internal developments, innovation is affected by external factors [29], including competing or complementing technologies and innovations [47], politics [48], geography [49], and sectors [50,51]. In their framework, Bergek et al. [22] include a seventh function: development of positive externalities. This function refers to creation of system-level resources, available to all actors in the innovation system. For our analysis, rather than identifying TIS internal positive externalities, we emphasize the effect of externalities, positive and negative, on each of the six core functions (F1-F6) following the interchangeability between established and novel technologies, reflecting to what extent

Table 1
Technological innovation system functions (F) [23,42].

Function	Description
Knowledge development and diffusion (F1)	Development, diffusion and evolution of knowledge regarding the technology, both in terms of depth and breadth.
Influence on the direction of search (F2)	The strength of incentives and pressures for actors to join a TIS. Mechanisms directing technology development through competing technologies, applications and markets.
Entrepreneurial experimentation (F3)	Reduction of uncertainty regarding the technology through experimentation with different technological concepts.
Market formation (F4)	Stimulation of demand for the technology in different phases of innovation.
Legitimation (F5)	Processes of improving the compliance of the institutions and social acceptance of the technology.
Resource mobilization (F6)	Mobilization of human and financial capital to e.g. knowledge creation and technology application.

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[2] For the purpose of this study 'biodiesel' is a general term for several types of biodiesel such as hydrogenated vegetable oil (HVO) and rapeseed methyl ester [19]. As the analytical focus is on socio-technical aspects of the implementation of biofuels in the maritime sector, we do not cover technical specifications of different types of biodiesel in detail. For such a review, see e.g. Mohd Noor [20].

the sectoral configurations are aligned with novel technologies.[3] This conceptualisation is further explained in the coming sections.

2.2. Sectoral contexts and technological innovation systems

We understand sectors as activities around a certain societal product or a service, consisting of networks of actors, institutions, and sets of knowledge and technologies [52]. They therefore have same kinds of structural elements as technologies. Sectors, such as the energy sector, use technologies (e.g. wind turbine generators) to provide its product or service for the society (e.g. electricity). Notably, sectors may use multiple technologies at the same time (e.g. multiple renewable energy technologies), which can lead to complementarities or competition between different technologies in a sector [38].

Sectors tend to be relatively stable entities with established technological infrastructures, and institutionalized social networks (including user-producer interactions), user practices and divisions of labour between organizations etc. [53]. They differ in their adaptability to accommodate new technologies, conditioned notably by the characteristics of its institutions and actors. While some sectors may, at first, ignore or underestimate novel technologies, other sectors may have institutional mechanisms that foster technology adoption [54].

The existing structure and institutionalization of sectors is an outcome of the co-evolution of its various elements over space and time, creating stability to the sector [55]. For innovation, the stability of sectors means that novel technologies may be more or less aligned with the existing sectoral structure and configurations. New technologies therefore differ in terms of their transformative capacity vis-à-vis the sectoral structure and characteristics of sectors [54]. The alignment or the "fit" between the novel technology and the sectoral characteristics may have significant implications for innovation and transitions. If the degree of alignment is high, the novel technology fits and conforms with existing institutions, actor networks, and technologies (e.g. knowledge, infrastructure). By contrast, if there is strong misalignment between a novel technology and the structural elements of a sector, stretching and transforming the sector is required [56]. In most cases, the alignment between sectors and TISs is presumably somewhere in between these two extremes [29].

2.3. Alignment

The technological capabilities, institutions and physical infrastructure in a sector have been shaped vis-à-vis specific established technologies [57]. If new technologies do not align well (i.e. they have transformative stretch-and-transform capacity) [54,56], as radical LoZeC technologies often do not, the sector may reinforce a lock-in to established technologies, potentially curtailing transitions [24,58]. For instance, the current infrastructure for cars in the mobility sector is not fully applicable for the introduction of LoZeC technologies, requiring investments in e.g. the production and distribution infrastructure of novel fuels [59].

However, if a novel technology is aligned with the sector's existing technologies (i.e. they have non-transformative fit-and-conform capacity) [54,56], this may have a positive impact on innovation. Novel and established technologies thus have features of interchangeability, potentially allowing novel technologies to be used in the existing structural configurations of a sector. For instance, biofuels can be used as a drop-in fuel in most combustion engines and oil refineries can be used for producing bio-based fuels [60]. Also, plugin-hybrid electric vehicles benefit from the existence of fossil fuel based infrastructure and sectoral knowledge [61], while former oil wells have been repurposed to provide geothermal heat [62]. While the formative phases for new technologies (e.g. fuels) are known to be lengthy, Bento and Wilson [63, p. 95] find that [64] technologies "*that are ready substitutes for incumbents have shorter formative phases.*"

To summarize, the (mis-)alignment of novel technologies with established technologies in a sector can influence innovation. Onufrey and Bergek [39] discuss such interactions through positive or negative cross-technology externalities, i.e. self-reinforcing mechanisms increasing or decreasing the attractiveness of a technology. Cross-technological externalities may affect the innovation dynamics in both the novel and the established technology [32]. For a novel technology, the alignment with the technological configurations of a sector may lead to positive externalities (understood also as complementarities) which consequently may support innovation because of e.g. interchangeability. Mis-alignment may lead to negative externalities (competition) between technologies, resulting in a situation where positive developments in one technology may "mirror" as negative effects on the other technology [39]. Such effects may be one-directional (i.e. having a neutral effect on one technology and positive/negative effect on another) or two-directional (positive or negative effect on both technologies) [38,47]. Hence, we understand the impact of (mis-)alignment with sector's structural configurations on innovation to take place through such positive or negative externalities in sectoral cross-technology interactions.

These effects are presumed to be particularly relevant for innovation in sectors whose structure and institutions invigorate path dependence, i.e. have low sectoral adaptability [54]. In other words, sectoral cross-technology alignment may be particularly relevant for understanding LoZeC innovation in sectors with high sunk investments in existing technological assets, such as power transmission infrastructure [31], process industry [65] and mobility systems [59]. Shipping, with its existing highly durable assets in vessels, harbours and fuel supply chains, and typically conservative approach to radical innovation, is arguably such a sector of low adaptability [cf. 54].

2.4. Summary: An analytical framework

In this paper, we study how the sectoral cross-technology externalities emanating from the configurations of the Norwegian maritime sector around MGO, MDO and LNG fuels have affected the innovation around biodiesel and LBG in the coastal shipping sector in Norway. For this purpose, we use the TIS framework with its six core functions [22]. We thus identify and assess how these externalities have impacted the function strength of biodiesel and LBG TISs. We thus extend the TIS framework, taking note of how TIS functions (F1-F6) may be impacted by sectoral cross-technology externalities either positively or negatively. We visualize our analytical approach in Fig. 1.

3. Methods and materials

3.1. Case study selection

The global shipping industry needs to transition to LoZeC technologies to live up to the recent IMO GHG [1] strategy, and as the sustainability transition in shipping is (globally) in a very early phase, there are few places where these relations can be studied. Norway, being a frontrunner country with high ambitions for reduction of GHG emission from ships [66], offers the possibility of studying technology development and implementation processes that can inform and possibly accelerate similar transitions in other regions and on a global level. Whereas the IMO target is a 50% reduction in GHG emissions by 2050, the ambition in Norway is a similar reduction (compared with 2005 emissions) by 2030. Furthermore, frontrunner nations and regions often play crucial roles during IMO negotiations concerning international regulations [67]. Thus, understanding these dynamics in the Norwegian context is of importance far beyond its national borders, and constitutes a highly "socially useful" [68, p. 14] research topic.

Biofuels are expected to play an important role in reducing GHG

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[3] Hence we do not conduct a TIS-TIS interaction analysis in this paper.

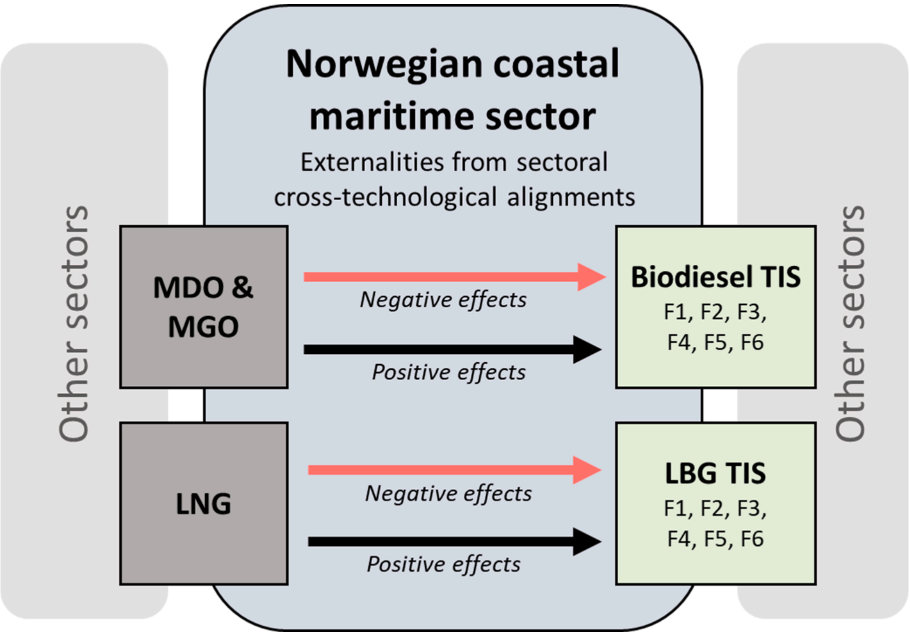

Fig. 1. The analytical framework.

emissions from the maritime sector both globally and in Norway [2,69], making it important to understand their relations to existing fossil fuels. There are several types of biobased fuels that potentially can be introduced to the shipping sector in the future, such as bio-ethanol and bio-methanol [70]. However, biodiesel and LBG are the only biofuels that currently are (in small scale) commercially available for the maritime sector, and that can be used in existing diesel and auxiliary engines (biodiesel), and gas engines (LBG) respectively [20].

3.2. Methodological approach

A TIS analysis requires extensive empirical material to cover both structural dimensions and functions [42]. As part of a larger TIS study of several types of LoZeC technologies, 74 semi-structured interviews performed over four years (2015–2019) constitute our core primary data. As stated in Appendix C, most interviews discussed LoZeC technologies (including biofuels) in general, and four interviews focused specifically on biofuels. The empirical material presented in section 5 is mainly based upon 17 interviews, conducted with senior level representatives of various key actors within the Norwegian maritime sector, including shipowners, yards, technology suppliers, public agencies and local governments. Our semi-structured interview guides were based on the TIS framework and tailored for different types of actors (see Appendix B for an exemplary interview guide). Interviews were conducted face-to-face or via telephone/online meeting and lasted on average for approximately 70 min. Most interviews were performed by groups of 2–3 researchers, recorded and transcribed.

Following transcription, the interview data was coded (using NVivo) according to the TIS functions (following the definitions in Table 1). To ensure consistent coding among researchers, a descriptive "codebook" was created to support individual coding by researchers. Moreover, a triangulating pilot round of coding was performed, where at least two researchers coded a batch of 2–3 interviews each, and then the results were compared. This pilot showed high consistency between coders, and thus the rest of the interviews were coded individually. Examples of quotes representing key findings for each TIS are provided in Appendix A. Bibliometric analysis and patent analysis was performed to identify crucial actors and networks that influence activities within F1 and F2[4] [71,72]. Furthermore, an analysis of EU-funded R&D projects (1998–2017) [73] and data on distribution of public funding support, shed light on both structural and functional aspects of the innovation systems [74]. Our analysis (notably of F2 and F4) is furthermore supported by a firm survey with 334 Norwegian shipowners. This survey was based on insights from the previously performed interviews and carried out in July-November 2019. The sample size was 1045 unique Norwegian shipowners within all commercial shipping segments, implying a 32% response rate. Additional information regarding the firm survey is available from the authors.

The analysis focuses on the application of biofuels in the Norwegian coastal shipping sector in relation to their alignment with the sectoral configurations centred around fossil fuel equivalents. However, we also consider external relations in the analysis when they matter for the Norwegian maritime transition, as for instance in terms of connections to other transport sectors and fuel production. We used our data sources in our assessment of TIS performance in two steps. First, we assessed the TIS functions' current status by combining the relevant data sources, identifying strengths and weaknesses, and scoring each TIS function as weak, intermediate or strong. We assessed a function as "weak" if we found very limited activities relating to the function, and "intermediate" if we could identify established interaction between actors, formation of institutions, access to R&D funding etc. To be scored as strong, a function would need several indications of good performance of several activities relating to the specific function.

In our second step, due to our interest in technological alignment, we assessed the effect of possible positive or negative sectoral cross-technological externalities on TIS functions from alignments with fossil fuels. We did this by analysing our data for indications where the existing sectoral characteristics, in terms of how they had been shaped by the existing fossil fuels, either had positive or negative effects on the respective biofuels TIS functions. However, as the biodiesel and LBG TISs are yet in their formative phases, these effects were yet mostly one-dimensional (i.e. having an impact on biofuels, not vice versa) [cf. 75]. We differentiated between major or minor (positive or negative) impacts, where major impacts refer to instances where a TIS function was

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[4] Referring to list of functions, see table 1.

impacted by multiple factors. Minor impacts stood for influence in only one factor, or a situation where both negative and positive impacts could be observed.

4. Empirical background

4.1. Norwegian coastal shipping

Coastal shipping is important in Norway in terms of providing crucial transport infrastructure and a market for the domestic maritime industry. While this sector in Norway is known to have high technological competences, the shipping sector in general has rather low adaptive capacity in terms of new innovations due to its capital intensive nature and longevity of vessels and infrastructure [10]. The Norwegian coastal shipping fleet consists of various segments, mainly cargo (300 vessels), fishing (5000 vessels), offshore services (600 vessels), and coastal car/passenger ferries (500 vessels). The respective segments are to some extent facing similar challenges for decarbonisation, however, their prerequisites for transitioning to alternative propulsion technologies varies with their operational patterns, market positions, and typical fleet size. The latter segment is mainly public transport, with routes subject to public procurement. As a result of national and regional policies on GHG emissions, specifications around emission levels have been included in public procurement contracts. To support technological development, publicly awarded “development contracts” (within the passenger segment) have been used to support the development of LoZeC solutions for shipping [21]. In addition, licenses to operate for the aquaculture sector and petroleum producers are controlled by the state and could include emission standards [6]. This implies that the shipowner awarded the contract are guaranteed a steady income during the operation period, decreasing the risk for them to invest in new technology, which distinguishes these sectors from other segments within coastal shipping.

4.2. Fossil fuels and mitigation measures

Currently, the vast majority of the Norwegian (and global) coastal shipping fleet runs on fossil fuels, mainly MGO and MDO [2]. As a first step towards reducing emissions and complying with new regulations regarding emission control areas for NO_x and SO_x [76], the shipping sector has been focusing on energy efficiency measures, and implementation of emission mitigation measures such as scrubbers, which removes NO_x, SO_x and particular matter (PM) from exhaust gases [77]. Additionally, LNG has gained increasing interest as a maritime fuel since the early 2000 s (Burel et al., 2013), with Norway among the first movers. In 2000 world’s first LNG powered car/passenger ferry began operating in Norway, resulting from a development contract initiated by the Norwegian Public Roads Administration. Given emission requirements in public procurement contracts, several additional LNG-ferries followed. While LNG is a fossil fuel it has significantly lower emissions of NO_x and PM, lower SO_x emissions and emits up to 20% less CO_2 than MDO/MGO [78]. The implementation of a NO_x-tax for heavy fuel oil in 2007 and the establishment of a NOx-fund (that since 2008 has supported measures for decreasing NO_x-emissions), has been an important driver for the implementation of LNG ships in Norway – both within public transport and merchant shipping. However, insufficient combustion of LNG causes a “methane slip”, which is problematic as methane has a high global warming potential [14]. Recently, in combination with the rise of additional alternative energy technologies, this has contributed to decreasing interest in and support for LNG within the public sector in Norway.

4.3. Alternatives to fossil fuels

As the above-mentioned measures will not be sufficient to reduce GHG emissions from shipping, alternatives to fossil fuels are needed. Currently, different LoZeC fuels and energy carriers are being developed and implemented within the Norwegian coastal shipping sector [74]. A range of different policy instruments have been introduced to support this development, ranging from basic research to market implementation, and also cluster programmes and networking activities (for an overview see NEA [69] and Steen, Bach, Bjørgum, Hansen and Kenzhegaliyeva [74]). While it is beyond the scope of this paper to provide details on these policy support measures, it can generally be said that they vary between being specific or generic in terms of types of technologies or shipping segments. As a principle, all energy solutions that can reduce GHG emissions (and local pollution) are eligible to support in one form or another. In the following we focus on LBG and biodiesel, which to some extent are established as road transport fuels, currently play a meagre role in maritime transport both globally [70] and in Norway [69].

Biofuels can be produced from various feedstock. Biodiesel is typically produced from residues from agriculture, forestry and specific energy crops, whilst biogas is made through anaerobic digestion of different types of organic waste. Various types and origins of feedstock have different environmental benefits and impacts, and also different production potential [79,80]. The potential for domestic production of biofuels depends on access to feedstock. Since the access to agricultural and forestry residues that can be commercially utilized is limited in Norway, so is biodiesel production and currently most of the biodiesel available on the Norwegian market is imported. Domestic biogas production and liquefaction however is increasing as new companies are exploring anaerobic digestion of biomass waste, including residues from Norway’s large aquaculture industry [81]. To be applicable as a ship fuel, biogas needs to be liquefied, in order to enable enough storage capacity to match the energy requirements of a ship [78].

Being interchangeable with MGO/MDO (biodiesel) and LNG (LBG), the two biofuels have the advantage compared with other LoZeC technologies such as hydrogen or battery-electric systems in that it is possible to implement them with limited adaptation of existing technology in ships (i.e. conventional diesel engines, modern gas engines or dual-fuel engines[5]), and thus have low transformative capacity in shipping [83]. The interchangeability also implies that it is technically feasible to blend biofuels with fossil fuels and make use of e.g. already existing bunker infrastructure [14]. Both the maritime biodiesel and LBG markets also have close connections with the road transport sector, wherein biodiesel already has been implemented in larger scale, whereas LBG is gaining traction for heavy road vehicles. Additionally, as all other combustion fuels, biodiesel and LBG can be combined with for example battery-electric systems, enabling hybridisation in combination with replacement of fossil fuels with biofuels.

5. Findings

In the following sections we present the main findings of our study. For each technology, we first give a short background of the previous development of the respective TISs. Thereafter, the functions strengths and weaknesses as well as the impact of externalities of technological alignment is presented following the structure of the TIS framework.

5.1. The biodiesel TIS

5.1.1. Biodiesel TIS structure and maturity level

The Norwegian maritime biodiesel TIS has not yet experienced extensive market formation or reached a high legitimacy, despite that

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[5] However, it should be noted that different types of biofuels require varying extensive adaption of existing infrastructure [82]

biodiesel technology matured in the early 2000 s, and has since been implemented in small scale [84].[6] Currently, there is a limited number of actors (shipowners, combustion engine technology suppliers, R&D institutes etc.) involved in the biodiesel TIS, and the declining national market indicates that the maritime biodiesel TIS is withdrawing from the niche market phase that was reached around 2010.

5.1.2. Knowledge development and diffusion

Functionality: The research interest in biodiesel increased during the early 2000 s, and up until 2007 Norwegian actors (predominantly private firms) were among the most prominent in acquiring biodiesel technology patents. However, since 2009 only a small number of patents have been approved (or applied for), both in Norway and globally, indicating technological maturity [72]. Norwegian biodiesel publications have slightly increased in the last decade, suggesting a renewed interest in biodiesel in general [71]. Knowledge development and diffusion concentrate on investigating different sustainability aspects (e.g. environmental impact assessments of production, evaluations of emission levels) of biodiesel from various biomass feedstock, rather than aspects related to technical development (R&D2, 2017). Presently, activities aiming for knowledge development regarding biodiesel in the Norwegian maritime sector are limited. Existing knowledge networks and major research projects are focused on biodiesel as a road transport fuel, and do not include any actors from the maritime sector (R&D6, 2019). Therefore, the current assessment is that the function is weak.

Sectoral cross-technology externalities: The interchangeability with fossil fuels allows actors to use their existing knowledge regarding diesel fuels in maritime use (TS6, 2017; SO5, 2017). However, we found little indications of this directly contributing to knowledge development and diffusion in the biodiesel TIS.

5.1.3. Influence on the direction of search

Functionality: In addition to global climate policy and emission regulations, the Norwegian government and regional administrations have over the last few years implemented stricter emission regulations for domestic harbours and coastal waters [66]. In combination with emission regulations in public procurement contracts, this motivated earlier shifts to biodiesel in the first decade of the 21th century (TS6, 2017; PSA2, 2017). However, given the higher price for biodiesel, regional governments have shifted from requirements of minimum use of biodiesel to technology-neutral public procurement contracts, limiting the incentive to invest in biodiesel (PA4, 2017). The strength of the direction of search for biodiesel has consequently decreased in the last years, and the function is currently assessed as weak.

Sectoral cross-technology externalities: Despite the interchangeability of biodiesel with MDO/MGO, shipowners believe the potential for biodiesel in the long run to be limited. Biodiesel was deemed too expensive and non-scalable, and hence few shipping companies saw it as an attractive option even in the short-term (PA4, 2017; SO5, 2017). For one interviewed shipowner, however, the interchangeability encouraged to continue equipping their new vessels with conventional diesel motors, as the option to use biodiesel allows them to adapt to possibly stricter emission regulations in future (SO1, 2017). Hence, interchangeability could thus be seen extend the use of fossil fuels in this company.

5.1.4. Entrepreneurial experimentation

Functionality: Experimentation with biodiesel technology is presently very limited within the Norwegian maritime sector. Since 2014, Norwegian actors are no longer participating in EU-funded R&D programmes relating to biodiesel, and there are no signs of experimentation with new business models [72]. This indicates the maturity of the technology, but also reflects the limited use of and interest in biodiesel as a maritime fuel. The entrepreneurial experimentation function is therefore assessed to be weak.

Sectoral cross-technology externalities: The interchangeability with conventional diesel has not encouraged entrepreneurial exploration regarding biodiesel, but rather the opposite. It may allow extending the lifetime of current technologies, thus making exploration redundant (SO1, 2017).

5.1.5. Market formation

Functionality: Potential market drivers, such as LoZeC specifications in public procurement contracts (which are a direct result of stricter emission regulations), do not seem to have an impact on the growth of the biodiesel market currently. Regarding the public procurement contracts, one explanation for this is the requirements of sustainability-certificated biodiesel, resulting in that battery-electric and other solutions are preferred to biodiesel due to the uncertainties regarding biodiesel availability and high fuel cost (SO1, 2017; PA4, 2017; PA1, 2018a). Another potentially strong market driver would be mandatory drop-in of biofuels in conventional fossil fuels. This has been assessed by the Norwegian Energy Agency, but implementation is yet to be decided upon [85].

Results from our survey indicate that interest in biodiesel may increase in the coming 10 years (see Fig. 2). Shipowners who have either implemented biodiesel already or expect to do so are primarily smaller shipping companies with 1–5 vessels mainly engaged in fishing or aquaculture. However, survey results indicate more negative expectations for biodiesel beyond the coming 10 years from now. In addition, nearly half of the respondents answered that they do not believe their company will implement biodiesel at all, further indicating that biodiesel is seen primarily as a temporary solution until other LoZeC technologies have developed and matured. The market formation function is therefore assessed as weak.

Sectoral cross-technology externalities: Existing diesel-powered vessels provide an existing market for biodiesel. Also, the interchangeability of the fuels lowers the threshold for biodiesel implementation since it can be introduced gradually through a feed-in in the conventional bunker infrastructure (TS6, 2017; IA5, 2019). However, limited fuel production makes biodiesel around 100–130% more expensive than conventional diesel, resulting in a low market share for biodiesel on the Norwegian maritime fuel market.[7] Hence, the cheaper price of conventional fuels currently impedes the market formation of the interchangeable biodiesel.

5.1.6. Legitimation

Functionality: At present biodiesel holds a small share of the maritime fuel market in Norway. Interviews suggest that it is considered a controversial fuel due to doubts concerning environmental benefits compared to its high costs, uncertainties regarding long-term fuel availability, possible competition between biodiesel and food production, etc. (SO1, 2017; IA4, 2018; O1, 2019; R&D6, 2019). Burning of biodiesel produces similar emission levels as conventional diesel, further limiting the legitimacy of biodiesel as a future LoZeC fuel [87]. Lack of government support also influences legitimacy negatively [84].

The risk of fuel shortage and further increasing fuel prices has created hesitance towards implementing stricter sustainability regulations for the biodiesel feedstock, resulting in biodiesel production from numerous more or less environmentally sustainable sources. A sustainability index is expected to be developed in the next five years, and is predicted to become an important addition to the current classification

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[6] However, it should be noted that in comparison to conventional ship fuels, the recent introduction of biodiesel as a maritime fuel is still a novel endeavour, given that HFO has been the main ship fuel since the beginning of the 1960′s [40].

[7] The total market for biofuels in Norway sunk from 659 million litres in 2017 to 496 million litres in 2018, while the sale of advanced biofuels grew from 138 L to 196 million litres [86].

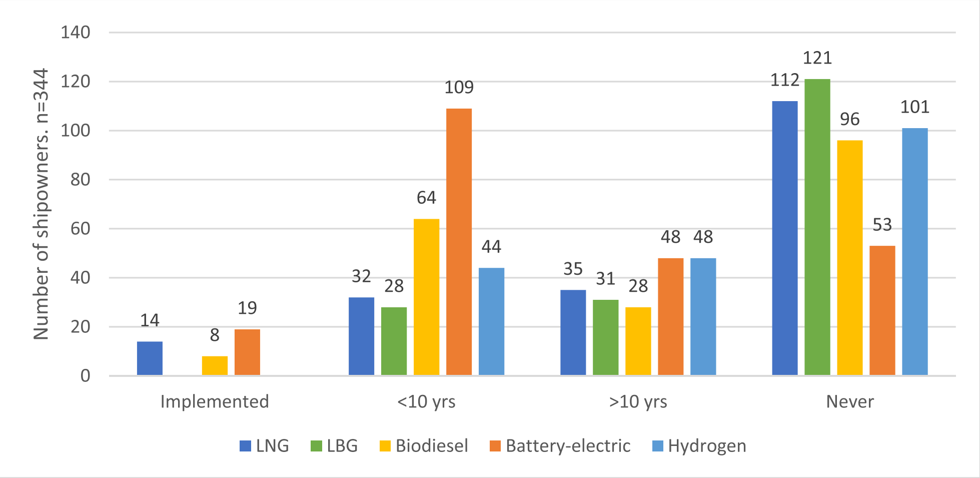

Fig. 2. Shipowners expectations regarding implementation of various LoZeC technologies and LNG within their company (own source).

rules regarding safety (R&D6, 2019). Furthermore, international standards for marine use of biodiesel are currently lacking [20]. Implementation of such standards could potentially accelerate market formation, similar to the developments within the road transport and aviation sectors [88], although lack of standards were not mentioned as a barrier for implementation of biodiesel in the Norwegian maritime sector by our interviewees. However, at present, the legitimation function is assessed as weak.

Sectoral cross-technology externalities: The interchangeability of biodiesel with conventional fuels reduces technical barriers for its implementation, and biodiesel is therefore seen, in purely technical terms, as a feasible and a "low-hanging fruit" among LoZeC fuels. However, among our respondents, this potentially positive effect on biodiesel innovation is overshadowed by the substantially higher fuel prices and the above-discussed legitimacy problems.

5.1.7. Resource mobilisation

Functionality: The private–public R&D and piloting programme "Green coastal shipping" (which is segment and technology neutral) has co-funded the construction of a new car/passenger ferry with planned full biodiesel operation. Due to uncertainty regarding both availability and price of biodiesel, the ferry is solely running on fossil diesel at present [89]. Otherwise public funding has been limited, as biodiesel, according to funders, in general is considered to score low in their sustainability rankings and there is no funding for covering higher fuel costs due to shift to biodiesel. Consequently, funding applications for other LoZeC solutions, such as battery-electric and hydrogen, have been prioritised in funding allocation (O1, 2019, see also [21]). Moreover, there is limited interest in biodiesel as a maritime fuel, resulting in lack of resource mobilisation for upscaling of fuel production. Consequently, this function is considered weak.

Sectoral cross-technology externalities: The existing distribution infrastructure (tankers, storage at ports, etc.) of conventional fuels can be used for biofuels. However, this potentially positive effect on biodiesel innovation has nevertheless not yet been realized, as little biodiesel is currently available in ports.

5.2. The liquefied biogas (LBG) TIS

5.2.1. LBG TISs structure and maturity level

Implementation of LBG in Norwegian coastal shipping will start in 2021, as there are plans to use locally produced LBG to bunker the big cruise/ferry company Hurtigruten's newly converted LNG passenger/goods vessels [90]. The innovation system for maritime use of LBG is therefore in an early formative phase. From the maritime sector, the main actors involved are shipowners and combustion engine technology suppliers. The increased use of LBG within the heavy road transport sector will create a general marked demand that provides potential for a rapid development of the maritime LBG TIS. Furthermore, due to LBG's interchangeability with LNG, implementation of the new fuel does not require immediate extensive investments in bunkering infrastructure. However, compared to infrastructure for MDO/MGO, bunker infrastructure for LNG/LBG is limited, and will be needed to develop in order to upscale the use of gas as a fuel within the maritime sector. As of 2018, LNG is available in 10 locations in Norway, half of which are petroleum supply bases [91]. On a general note, it should also be noted that substantial political disagreement over the domestic use of natural gas has hampered the development of gas/LNG infrastructure in Norway [92].

5.2.2. Knowledge development and diffusion

Functionality: Knowledge development and diffusion for LBG TIS is currently focused on sustainable fuel production and distribution, similarly to the biodiesel TIS. Over the last ten years, a variety of Norwegian actors including firms (e.g. Lindum and Nofima), universities (e.g. NTNU & NMBU) and industry associations (Nobio) have taken part in a number of EU funded R&D projects [73] and in 2017, the world's largest LBG factory, in the Trøndelag region, was completed. The factory owner Biokraft is participating in several R&D projects on LBG production, mainly in collaboration with other Scandinavian biogas producers. Such collaborations within a Scandinavian network is of great importance to the Norwegian actors, since there is no national network focused on biogas yet (FP1, 2017). However, there is a national network on gas as an energy source in general, which provides an opportunity for the maritime sector to participate in knowledge sharing with LNG and heavy road transport, although activities around LBG and maritime application are so far limited (IA5, 2019). Considering this, and additionally the low number of Norwegian actors involved in the LBG TIS, this function is judged as weak.

Sectoral cross-technology externalities: The interchangeability with LNG has led to a situation where maritime actors already are knowledgeable of the use of liquefied gas (methane) in maritime use. We can therefore observe that there were few on-going LBG-specific knowledge development and diffusion activities in maritime use. These were rather linked to gas/LNG technologies in general.

5.2.3. Influence on the direction of search

Functionality: National and international policy on emission standards for the maritime sector provides incentives to investigate alternative LoZeC solutions, such as LBG. Currently, two main themes are in focus for the influence on the direction of search: emission requirements and LoZeC specific regulations within public procurement and public funding support, and, following the requirements for sustainability certification for fuel within public procurement contracts, sustainable LBG production (PA4, 2017; O1, 2019). Furthermore, similarly to knowledge development and diffusion, LNG and heavy road transport influence the direction of search for the implementation of LBG in the Norwegian maritime sector (FP1, 2017). However, public support agencies are shifting away from LNG, as early pilot projects have not been succeeded by additional projects with further support. Furthermore in the capital Oslo, three LNG passenger ferries that started operating in 2010 were converted to fully-electric in 2019 following the local environmental goals [93], which indicates that LBG is not necessarily the go-to green solution for existing LNG ships. There is limited attention around maritime use of LBG, but nevertheless clear climate and emission policies, which in combination with the potential positive influence from the heavy road transport and LNG sectors, clearly steer the search towards LoZeC technologies and LBG. The function is therefore assessed as intermediate.

Sectoral cross-technology externalities: The interchangeability of LNG and LBG means that companies that have knowledge and assets in LNG technologies, e.g. gas engine suppliers and shipping companies with LNG vessels, are usually interested in LBG, thus willing to join the LBG TIS and advocate it (IA5, 2019; O1, 2019). The entry of large players, such as Hurtigruten with its investment in conversion to gas engines and implementation of LBG, may also inspire others to follow.

5.2.4. Entrepreneurial experimentation

Functionality: Given that technological innovation within maritime gas engines so far is taking place within the LNG sector, entrepreneurial experimentation within the LBG TIS is focused on the production side of the value chain (FP1, 2017; O1, 2019). Following the need to identify sustainable ways of production, experimenting with LBG production from residues from the Norwegian aquaculture industries was initiated in 2018 by Biokraft. In 2019, Hurtigruten signed a seven-year contract with Biokraft for delivery of LBG when docking in Trondheim harbour, starting in 2021 [94], indicating initiation of experimentation regarding business models for the maritime use of LBG. Within academic research, much attention is given to research on biogas production from algae, which is still at an early stage (R&D1, 2017). Nevertheless, there are limited number of actors involved in entrepreneurial experimentation regarding LBG, especially maritime application. The function is therefore currently assessed as weak, although recent activities suggest potential for more large-scale experimentation.

Sectoral cross-technology externalities: There have been experiments regarding liquefaction techniques and blending of LBG and LNG (IA5, 2019). Hurtigruten has invested in conversion to LNG propulsion for six of their ships, and stated their ambition to operate on a mix of LNG and LBG [90]. However, due to the COVID-19 crisis, in May 2020 the order of gas propulsion systems in three of their vessels was cancelled for the time being, and the company announced to use biodiesel instead to meet requirements set by the Ministry of Transport for the vessels [95].

5.2.5. Market formation

Functionality: Being in an early formative phase, the only known investment in LBG for maritime use is the cruise/passenger company Hurtigruten's contract with Biokraft (one of three LBG suppliers in Norway). Hurtigruten has received several types of public funding support (O1, 2019), and the challenge to create a larger, more self-sustaining commercial market for LBG within the maritime sector remains. A potential driver of market formation also within the Norwegian maritime sector is the increased interest in LBG as a fuel for the heavy road transport sector (FP1, 2017). This is likely to spur upscaling of production and liquefaction of biogas, which in all probability would enable the necessary decrease of the high fuel price to eventually match the LNG price.

Similarly to biodiesel, there is uncertainty regarding fuel availability produced from sustainable feedstock. Estimates of currently available biogas volumes in Norway equal the gas consumption of the existing Norwegian LNG fleet, indicating great potential for maritime use of LBG (O1, 2019). However, there is currently only one liquefying plant in Norway, and the major part of the biogas is used for road transport (FP1, 2017), showing the competition around liquid gas fuel (both LNG and LBG) between the two sectors.

Compared to biodiesel, fewer of our survey respondents expected that their company will implement LBG within the next 20 years and more respondents answered that they never expect their company to implement LBG (see Fig. 2). Among the 53 shipowners who had already implemented LNG, or expected to implement LNG within five years, 19 respondents expected their company to also implement LBG within five years (see Fig. 3). Among the 58 respondents who expected their company to implement LNG within five to 20 years, a total of 22 respondents also expected implementation of LBG. However, 18.9% did not expect implementation of LBG at all.

With only one current customer, the market formation is assessed as weak. Considering the estimated potential for maritime use of LBG and market formation within the heavy road transport sector that could potentially benefit the maritime sector, this function may strengthen in the near future.

Sectoral cross-technology externalities: The existing (yet rather few), and forthcoming LNG vessels create a market also for LBG in Norway. However, LBG is currently at least 50% more expensive than LNG, which reduces demand. Furthermore, it was expressed in the interviews that the most likely scenario for the maritime sector is feed-in of LBG into the existing LNG infrastructure (O1, 2019; FP3, 2019). Estimations of the theoretical potential for feed-in of LBG in 2030 range between 50 and 100% (from 20% in 2020), depending on policy measures and assuming a five-fold increase of the current production capacity [96].

It is nevertheless interesting to note that in our survey 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. In addition, among the ten of the 34 respondents who expected their company to implement LNG within five years, none believed that they would ever implement LBG. These results suggest that interchangeability with LNG does not yet seem to act as a strong pull-factor to enter the LBG TIS.

5.2.6. Legitimation

Functionality: The main issues regarding legitimacy for the LBG TIS is the uncertainty regarding fuel availability and the sustainability of the production (R&D5, 2018; SY4, 2018). Compared to battery-electric and hydrogen solutions, LBG has a lower sustainability score within requirements for public procurement contracts, which result in prioritisation of battery-electric and hydrogen technology. This applies both in competitions for public tenders, and in terms of receiving public funding support connected to these tenders (O1, 2019). Hence, while the increased use of LBG as a fuel within the heavy road transport sector helps to increase the legitimacy for LBG as a maritime fuel, uncertainties regarding fuel availability and sustainability result in an assessment of this function as weak.

Sectoral cross-technology externalities: Due to their interchangeability, LBG fits the regulatory framework already developed for LNG (PA2, 2017). Moreover, LNG vessels have performed well, thus also showcasing gas as a power source for ships. However, following the end of the NO_x tax relief for shipping in 2018, the interest in LNG has somewhat decreased in Norway (O1, 2019).

5.2.7. Resource mobilisation

Functionality: Public funding support for gas engines, and LBG production and infrastructure is available from most public support agencies, although with a focus on the road transport sector (O1, 2019; IA5, 2019). Enova has supported the two biggest Norwegian LBG production facilities (owned by Biokraft and VEAS) with NOK 82 and 37.5 million respectively [97], in order to initiate LBG production for the

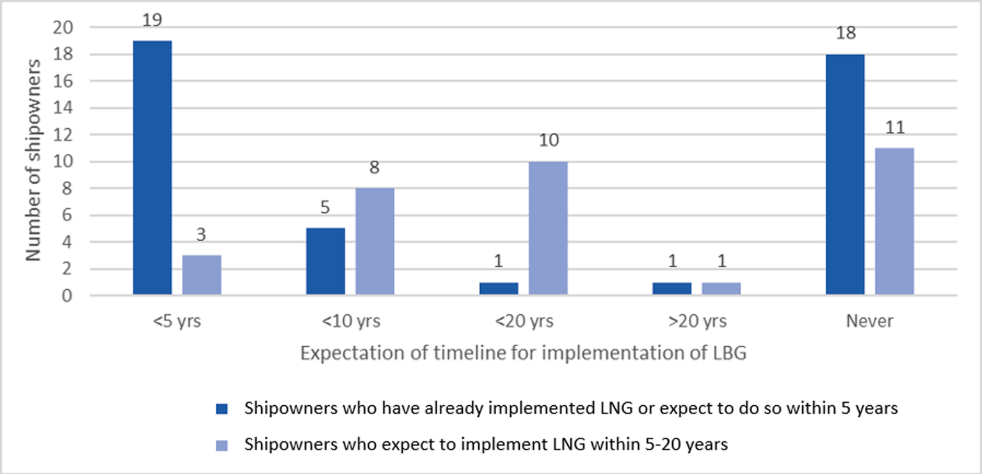

Fig. 3. Expectation of timeline for implementation of LBG for shipowners that have implemented or expect to implement LNG.

heavy road transport sector. In addition, Biokraft was awarded a NOK 55 million "innovation loan" from Innovation Norway. In combination with a signed ten-year contract with AGA, this external funding enabled another NOK 215 million loan from a Norwegian-Swedish funding consortium which together with investments from Biokraft's main owners supported the operation start in 2018 [98].

Following the seven-year contract with Hurtigruten, part of Biokraft's production will be delivered to their three converted cruise ships (potentially also three more in future), which were enabled by NOK 625 million in financial support from the NOx-fund. However, this is the only recorded financial investment support regarding LBG in the maritime sector. Competition around public funding support and public procurement contracts with other LoZeC technologies, especially battery-electric solutions, is perceived as a great challenge for the implementation of LBG as a maritime fuel, as battery-electric technology scores higher on the environmental assessment scale (FP1, 2017). Hence, there is limited funding awarded to LBG projects within the maritime sector. However, considering that the aggregated financial support includes relatively large sums, the function is assessed as intermediate. Following maturation of the technology, there is furthermore potential for rapid strengthening of the resource mobilisation.

Sectoral cross-technology externalities: LBG can use part of the existing distribution infrastructure and technological knowledge as LNG. Moreover, the entry of large established firms is positive for resource formation in the LBG TIS. Table 2 summarizes the findings presented above.

6. Discussion

As the vast majority of existing vessels run on fossil fuels, the interchangeability between fossil fuels and biofuels (e.g. in terms of infrastructure, regulations, and knowledge) could potentially provide an opportunity of a rapid transition to fossil free energy sources. Indeed, current scenarios of emissions reductions from shipping suggest that biofuels could make up 20% of shipping's fuel mix already in 2030 [17], making it important to understand whether there are obstacles or not to such developments.

Biofuels in shipping can be described as a case of a potential fit-and-conform innovation of low transformative capacity in a sector of low adaptability [54,56]. The high degree of alignment with the sectoral configurations, which have been shaped by conventional fuels, could therefore be expected to drive innovation and increase the attractiveness of biofuels. However, our empirical analysis shows that, despite the several positive sectoral cross-technology externalities, the performance of biodiesel and LBG TISs is low (see Table 2). Instead, e.g. the broader legitimacy, upscaling and cost issues pose significant obstacles for biofuel innovation. As such our findings resonate with previous research on biofuels that highlights controversies and governance challenges [see e.g. 99,100].

One implication of low innovation performance for biofuels TIS is furthermore that a transition strategy for coastal shipping based heavily on the upscaling of biofuels could prolong the current fossil fuel-based trajectory, especially if biofuel endeavours fail. In other words, while biofuels may benefit from existing technologies (combustion engines) and infrastructure (e.g. bunkering) in the maritime sector, they could also contribute to further carbon lock-in [24].

Our paper therefore contributes to the study of sectoral cross-technology externalities [38,39] by showing how even a high degree of alignment and interchangeability with established technologies, and the consequent positive externalities, do not necessarily translate into accelerated technological innovation. This is particularly remarkable in studying sustainability transitions in sectors of low adaptability, such as shipping, as such sectors could be expected to favour non-transformative and fit-and-conform technologies like (drop-in) biofuels to respond to increasing GHG reduction pressures [cf. 54,56]. Instead, our results show that such "low-hanging" sustainable innovations may nevertheless be stalled because of poor overall TIS performance, and actors may opt to pursue innovation in more transformative and stretch-and-transform

Table 2
Summary of TIS assessment and the effect of alignment with the structural configurations of sector, shaped by established technologies (++ = major positive effect, + = minor positive effect, o = neutral effect, - = minor negative effect, – = major negative effect).

	Biodiesel TIS	Interchangeability with MDO/MGO	LBG TIS	Interchangeability with LNG
Knowledge development and diffusion	Weak	+	Weak	+
Influence on the direction of search	Weak	+	Intermediate	++
Entrepreneurial experimentation	Weak	–	Weak	+
Market formation	Weak	o	Weak	+
Legitimation	Weak	+	Weak	+
Resource mobilization	Weak	o	Intermediate	+

technologies (such as battery-electric and hydrogen in our case) [74]. Hence, while we agree that externalities can be important for accelerating sustainable transitions [38], the potential of sectoral cross-technology externalities to accelerate transitions has to be assessed in the context of overall performance of innovations. Future studies should therefore further investigate the conditions for when cross-technology externalities may drive innovation, and when this is unlikely to take place.

Interchangeability between fossil fuel and biofuels is observed in the characteristics of the Norwegian coastal maritime sector. Most evidently, shared infrastructure and the existing fleet with combustion or gas engines provide a market base as well as possibilities for fuel distribution. In addition, the knowledge base regarding combustion engines implies that there was no need for e.g. education of on-board personnel [cf. 54]. However, availability of biofuels for the Norwegian maritime market remains very limited. Considering the differences in the supply chain, where actors involved in the production of and the market formation for biofuels to a large extent are disconnected from conventional fuel suppliers, this provides a barrier for implementation of biofuels in the maritime sector [83].

Also negative sectoral cross-technological externalities were observed, affecting individual functions especially in biodiesel TIS. For instance, the implementation of biodiesel is not eligible for public funding due to its interchangeability with MDOs/MGOs, which weakens resource mobilisation. The interchangeability was also discouraging entrepreneurial experimentation. Moreover, the argument that biodiesel and LBG can be implemented on existing ships may even extend the use of fossil fuels, rather than promote a general transition to LoZeC technologies.

In comparison to biodiesel, LBG production from biological waste does not include the same uncertainty regarding sustainability as biodiesel production. The LBG TIS nevertheless faces challenges connected to technology alignment. The implementation of LBG as a heavy road transport fuel implies potential synergies for the shipping sector, as well as competition around available fuel. The decrease in interest in LNG following the introduction of the CO_2-tax on LNG in shipping is a potential barrier for the implementation of LBG. On the other hand, the increased fuel cost for LNG decreases the price difference between LNG and LBG, which possibly can benefit market formation for LBG. The future effects following technological alignment between LNG and LBG are consequently ambiguous and more research is needed to analyse the implementation of LBG in the maritime sector.

Our case study also reveals insights on how public procurement may direct sustainability transitions to certain technologies. In Norway, much innovation in shipping has occurred within the passenger segment that is subject to public tendering. In the last decade, there is a notable shift from requiring relatively minor emission reductions to demanding “zero emissions” in new tenders for high speed passenger vessels and car/passenger ferries. As this excludes biofuels, innovation regarding battery-electric and hydrogen solutions have been favoured, influenced by the availability of cheap renewable electricity in Norway [21]. A similar pattern has been observed within green public procurement of transport in Sweden [101]. Considering that some LNG-ferries procured around 2010 have recently been converted to battery-electric propulsion, this suggests that LBG is not the obvious choice for improving emission reduction for gas powered ships. This shows the power of green public procurement on the direction of search, determining which novel technologies become the focus for the shipyards and technology suppliers, and in the entire domestic coastal shipping sector. As tenders and licenses to operate have the possibility to contribute to market formation for alternative fuels, making it easier for other segments to enter the new fuel markets as prices decrease, the exclusion of biofuels from these instruments complicates the establishment of a biofuel market that can compete with fossil fuel prices. Furthermore, such policy action drives the development of competence, infrastructure, etc. around battery-electric and hydrogen solutions rather than biofuels, contributing to trumping the positive sectoral cross-technological externalities from conventional fuels to biofuel innovation.

7. Conclusion and policy implications

The aim of this analysis was to investigate how the sectoral cross-technological externalities through the technological alignment with fossil fuels may impact the biodiesel and LBG TISs in Norwegian coastal shipping. These externalities result from the (mis)match of biofuels with the sectoral configurations of coastal shipping, shaped by fossil fuels. We found that technological alignment provides the biodiesel and LBG TISs with several positive externalities, such as access to established markets and infrastructure, which suggests that Norway, to some extent, has good conditions for maritime biofuel markets to form. However, our results also showed that due to the poor overall performance of TISs, and in competition with the surge for battery-electric and hydrogen technology, the positive externalities were insufficient to promote innovation and implementation of biofuels in the Norwegian maritime sector.

To stimulate the uptake of biodiesel and LBG, policy plays an important role in creating incentives for development and implementation, also in such “low-hanging” innovations with potential alignments with conventional technologies. Two of the major barriers for implementation of biofuels are fuel availability and cost. As biodiesel and LBG currently misses out on the potential for public procurement to speed up market formation, as tenders are focused on battery-electric and hydrogen solutions, it is crucial to direct policy measures towards other market incentives. First, to level out the price range between the two fuel types and create market formation, it is necessary to increase the price of fossil fuel, in combination with subsidies for biofuels. Second, to further create economic incentives, harbour and fairway fees could be differentiated depending on the ship’s emissions, and licenses to operate within the aquaculture and offshore sectors could include emission requirements. Third, feed-in targets should be established to ensure an increasing ratio of biofuels in the conventional bunker infrastructure, similar to the feed-in requirements for the road transport sector.

Upscaling of production is essential for both biofuels. For biodiesel especially, it is important to ensure sustainable production from a life cycle perspective. R&D support to further develop production processes would therefore be beneficial to strengthen the biodiesel TIS. Regarding LBG, in addition to investment support for fuel production and development of bunker infrastructure, technology specific policies could focus on pilot projects that include upstream LBG production.

To conclude, whereas the production potential for biodiesel and LBG remains uncertain, decarbonization pathway models for global shipping assumes around 20% biofuels in the total maritime fuel mix. However, currently available biofuel volumes are far from sufficient, implying a need for upscaling (sustainable) biofuel production globally. For shipping to reach emission reduction targets by 2030 and 2050, biofuels will by all accounts be part of the necessary portfolio of LoZeC solutions. More research is therefore needed to fully understand the prospects for biofuels to contribute to the greening of shipping in years ahead.

Our work had limitations which open opportunities for further research. First, as our analysis was limited to the Norwegian context, it is left unclear how broadly applicable our results are to coastal shipping contexts in other countries. Second, while our analysis was limited to biofuels and shipping, further research should seek to investigate the conditions for when cross-technology externalities either propel or hamper innovation also in other sectors and technologies. Third and finally, whereas our empirical work was limited to low-carbon solutions in early development phases, further research on interaction dynamics of technologies that are in more mature development phases are needed to improve our understanding of acceleration processes in sustainability transitions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] IMO, Initial IMO Strategy on Reduction of GHG Emissions from Ships, 2018.
[2] D.N.V. Gl, Kartlegging av teknologistatus - Teknologier og tiltak for energieffektivisering av skip, DNV GL, Høvik, 2016.
[3] F.W. Geels, R. Kemp, G. Dudley, G. Lyons, Automobility in Transition. A Socio-Technical Analysis of Sustainable Transport, Routledge, Oxfordshire, 2011.
[4] A. Klitkou, S. Bolwig, T. Hansen, N. Wessberg, The role of lock-in mechanisms in transition processes: The case of energy for road transport, Environmental Innovation and Societal Transitions 16 (2015) 22–37, https://doi.org/10.1016/j.eist.2015.07.005.
[5] M. Dijk, R.J. Orsato, R. Kemp, The emergence of an electric mobility trajectory, Energy Policy 52 (2013) 135–145, https://doi.org/10.1016/j.enpol.2012.04.024.
[6] A. Bergek, Ø. Bjørgum, T. Hansen, J. Hanson, M. Steen, Towards a sustainability transition in the maritime shipping sector: The role of market segment characteristics, International Sustainability Transitions Conference (2018).
[7] S.G. Sjøtun, A ferry making waves: A demonstration project 'doing' institutional work in a greening maritime industry, Norsk Geografisk Tidsskrift - Norwegian Journal of Geography 73 (1) (2019) 16–28.
[8] I. Stalmokaitė, J. Yliskylä-Peuralahti, Sustainability transitions in Baltic sea shipping: Exploring the responses of firms to regulatory changes, Sustainability 11 (7) (2019) 1916.
[9] K.Y. Bjerkan, M. Ryghaug, T.M. Skjølsvold, Actors in energy transitions Transformative potentials at the intersection between Norwegian port and transport systems, Energy Research & Social Science 72 (2021), 101868.
[10] S. Pettit, P. Wells, J. Haider, W. Abouarghoub, Revisiting history: Can shipping achieve a second socio-technical transition for carbon emissions reduction? Transportation Research Part D: Transport and Environment 58 (2018) 292–307.
[11] J. Markard, The next phase of the energy transition and its implications for research and policy, Nature Energy 3 (8) (2018) 628–633, https://doi.org/10.1038/s41560-018-0171-7.
[12] B. Jeong, H. Wang, E. Oguz, P. Zhou, An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems, Journal of Cleaner Production 187 (2018) 111–130, https://doi.org/10.1016/j.jclepro.2018.03.184.
[13] P. Gilbert, C. Walsh, M. Traut, U. Kesieme, K. Pazouki, A. Murphy, Assessment of full life-cycle air emissions of alternative shipping fuels, Journal of Cleaner Production 172 (2018) 855–866, https://doi.org/10.1016/j.jclepro.2017.10.165.
[14] S. Brynolf, E. Fridell, K. Andersson, Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol, Journal of Cleaner Production 74 (2014) 86–95.
[15] S. Horvath, M. Fasihi, C. Breyer, Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040, Energy Conversion and Management 164 (2018) 230–241.
[16] H. Lindstad, I. Sandaas, A.H. Strømman, Assessment of cost as a function of abatement options in maritime emission control areas, Transportation Research Part D: Transport and Environment 38 (2015) 41–48.
[17] International Transport Forum, OECD, Decarbonising Maritime Transport - Pathways to zero-carbon shipping by 2035, Paris, 2018.
[18] D.N.V. Gl, Maritime Forecast to 2050 - Energy Transition Outlook 2017, DNV GL, Oslo, 2017.
[19] K. Jivén, A. Mellin, L. Styhre, K. Garme, Fossilfri kollektivtrafik på vatten - hinder och möjligheter för färjor med hög miljöprestanda, Gothenburg, 2020.
[20] C.W. Mohd Noor, M.M. Noor, R. Mamat, Biodiesel as alternative fuel for marine diesel engine applications: A review, Renewable and Sustainable Energy Reviews 94 (2018) 127–142, https://doi.org/10.1016/j.rser.2018.05.031.
[21] H. Bach, A. Bergek, Øyvind Bjørgum, T. Hansen, A. Kenzhegaliyeva, M. Steen, Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis, Transportation Research Part D: Transport and Environment 87 (2020) 102492, https://doi.org/10.1016/j.trd.2020.102492.
[22] A. Bergek, S. Jacobsson, B. Carlsson, S. Lindmark, A. Rickne, Analyzing the functional dynamics of technological innovation systems: A scheme of analysis, Research Policy 37 (2008) 407–429.
[23] M.P. Hekkert, R.A.A. Suurs, S.O. Negro, S. Kuhlmann, R.E.H.M. Smits, Functions of innovation systems: A new approach for analysing technological change, Technological Forecasting and Social Change 74 (4) (2007) 413–432, https://doi.org/10.1016/j.techfore.2006.03.002.
[24] G.C. Unruh, Understanding carbon lock-in, Energy Policy 28 (12) (2000) 817–830, https://doi.org/10.1016/S0301-4215(00)00070-7.
[25] A. Rip, R. Kemp, Technological change, in: S. Rayner, E.L. Malone (Eds.), Human Choice and Climate Change, Resources and technology., Battelle Press, Columbus, Ohio, 1998, pp. 327–399.
[26] W.B. Arthur, The Nature of Technology: What it is and How it Evolves, Allen Lane, London, 2009.
[27] C. Berggren, T. Magnusson, D. Sushandoyo, Transition pathways revisited: Established firms as multi-level actors in the heavy vehicle industry, Research Policy 44 (5) (2015) 1017–1028.
[28] R. Raven, Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: An assessment of differences and pitfalls, Energy Policy 35 (4) (2007) 2390–2400.
[29] A. Bergek, M. Hekkert, S. Jacobsson, J. Markard, B. Sandén, B. Truffer, Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics, Environmental Innovation and Societal Transitions 16 (2015) 51–64, https://doi.org/10.1016/j.eist.2015.07.003.
[30] A. Mirzadeh Phirouzabadi, D. Savage, K. Blackmore, J. Juniper, The evolution of dynamic interactions between the knowledge development of powertrain systems, Transport Policy 93 (2020) 1–16, https://doi.org/10.1016/j.tranpol.2020.04.018.
[31] A.D. Andersen, No transition without transmission: HVDC electricity infrastructure as an enabler for renewable energy? Environmental Innovation and Societal Transitions 13 (2014) 75–95.
[32] A. Mirzadeh Phirouzabadi, D. Savage, J. Juniper, K. Blackmore, A dynamic approach to socio-technical interactions between technological systems, The 11th International Sustainability Transitions conference 18-21 August, Vienna, Austria, 2020.
[33] T. Vadén, A. Majava, T. Toivanen, P. Järvensivu, E. Hakala, J.T. Eronen, To continue to burn something? Technological, economic and political path dependencies in district heating in Helsinki, Finland, Energy Research & Social Science 58 (2019), 101270.
[34] M. Dijk, R.J. Orsato, R. Kemp, Towards a regime-based typology of market evolution, Technological Forecasting and Social Change 92 (2015) 276–289.
[35] F.W. Geels, J. Schot, Typology of sociotechnical transition pathways, Research Policy 36 (3) (2007) 399–417.
[36] B. Walrave, R. Raven, Modelling the dynamics of technological innovation systems, Research Policy 45 (9) (2016) 1833–1844.
[37] F.W. Geels, Low-carbon transition via system reconfiguration? A socio-technical whole system analysis of passenger mobility in Great Britain 1990–2016, Energy Research & Social Science 46 (2018) 86–102.
[38] J. Markard, V.H. Hoffmann, Analysis of complementarities: Framework and examples from the energy transition, Technological Forecasting and Social Change 111 (2016) 63–75.
[39] K. Onufrey, A. Bergek, Self-reinforcing mechanisms in a multi-technology industry: Understanding sustained technological variety in a context of path dependency, Industry and Innovation 22 (6) (2015) 523–551.
[40] S. Bengtsson, K. Andersson, E. Fridell, A comparative life cycle assessment of marine fuels:liquefied natural gas and three other fossil fuels, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 225 (2) (2011) 97–110.
[41] B. Carlsson, R. Stankiewicz, On the nature, function and composition of technological systems, Journal of Evolutionary Economics 1 (2) (1991) 93–118.
[42] A. Bergek, M. Hekkert, S. Jacobsson, Functions in innovation systems: A framework for analyzing energy-system dynamics and identifying goals for system-building activities by entrepreneurs and policymaker, in: T. Foxon, J. Köhler, C. Oughton (Eds.), Edward Elgar, Cheltenham, (2008), pp. 79–111.
[43] J. Musiolik, J. Markard, M. Hekkert, Networks and network resources in technological innovation systems: Towards a conceptual framework for system building, Technological Forecasting and Social Change 79 (6) (2012) 1032–1048.
[44] W.R. Scott, Institutions and organizations: ideas, interests, and identities, 4th ed., Sage, Thousand Oaks, California, 2014.
[45] J. Battilana, B. Leca, E. Boxenbaum, How Actors change institutions: Towards a theory of institutional entrepreneurship, Academy of Management Annals 3 (1) (2009) 65–107.
[46] R.A.A. Suurs, M.P. Hekkert, Cumulative causation in the formation of a technological innovation system: The case of biofuels in the Netherlands, Technological Forecasting and Social Change 76 (8) (2009) 1003–1020.

[47] B.A. Sandén, K.M. Hillman, A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden, Research Policy 40 (3) (2011) 403–414.

[48] H.E. Normann, The role of politics in sustainable transitions: The rise and decline of offshore wind in Norway, Environmental Innovation and Societal Transitions 15 (2015) 180–193.

[49] C. Binz, B. Truffer, L. Coenen, Why space matters in technological innovation systems—Mapping global knowledge dynamics of membrane bioreactor technology, Research Policy 43 (1) (2014) 138–155.

[50] B. Haley, Low-carbon innovation from a hydroelectric base: The case of electric vehicles in Québec, Environmental Innovation and Societal Transitions 14 (2015) 5–25.

[51] T. Mäkitie, A.D. Andersen, J. Hanson, H.E. Normann, T.M. Thune, Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power, Journal of Cleaner Production 177 (2018) 813–823.

[52] F. Malerba, Sectoral systems of innovation: A framework for linking innovation to the knowledge base, structure and dynamics of sectors, Economics of Innovation and New Technology 14 (1–2) (2005) 63–82.

[53] J. Markard, B. Truffer, Innovation processes in large technical systems: Market liberalization as a driver for radical change? Research Policy 35 (5) (2006) 609–625.

[54] U. Dolata, Technological innovations and sectoral change: Transformative capacity, adaptability, patterns of change: An analytical framework, Research Policy 38 (6) (2009) 1066–1076.

[55] F. Malerba, Sectoral systems of innovation and production, Research Policy 31 (2) (2002) 247–264.

[56] A. Smith, R. Raven, What is protective space? Reconsidering niches in transitions to sustainability, Research Policy 41 (6) (2012) 1025–1036.

[57] A.D. Andersen, M. Gulbrandsen, The innovation and industry dynamics of technology phase-out in sustainability transitions: Insights from diversifying petroleum technology suppliers in Norway, Energy Research & Social Science 64 (2020), 101447.

[58] D. Loorbach, N. Frantzeskaki, W. Thissen, Introduction to the special section: Infrastructures and transitions, Technological Forecasting and Social Change 77 (8) (2010) 1195–1202.

[59] J. Farla, F. Alkemade, R.A.A. Suurs, Analysis of barriers in the transition toward sustainable mobility in the Netherlands, Technological Forecasting and Social Change 77 (8) (2010) 1260–1269.

[60] H. Hellsmark, T. Hansen, A new dawn for (oil) incumbents within the bioeconomy? Trade-offs and lessons for policy, Energy Policy 145 (2020), 111763.

[61] X. Lin, B.K. Sovacool, Inter-niche competition on ice? Socio-technical drivers, benefits and barriers of the electric vehicle transition in Iceland, Environmental Innovation and Societal Transitions 35 (2020) 1–20.

[62] A. Leitch, B. Haley, S. Hastings-Simon, Can the oil and gas sector enable geothermal technologies? Socio-technical opportunities and complementarity failures in Alberta, Canada, Energy Policy 125 (2019) 384–395.

[63] N. Bento, C. Wilson, Measuring the duration of formative phases for energy technologies, Environmental Innovation and Societal Transitions 21 (2016) 95–112.

[64] P. Johnstone, P. Newell, Sustainability transitions and the state, Environmental Innovation and Societal Transitions 27 (2018) 72–82.

[65] D. Kushnir, T. Hansen, V. Vogl, M. Åhman, Adopting hydrogen direct reduction for the Swedish steel industry: A technological innovation system (TIS) study, Journal of Cleaner Production 242 (2020), 118185.

[66] Norwegian Government, Regjeringens handlingsplan for grønn skipsfart [The Government's Action Plan for Green Shipping], Ministry of Climate and Environment, Oslo, 2019.

[67] J. Corbett, M. Ruwet, Y.-C. Xu, P. Weller, Climate governance, policy entrepreneurs and small states: explaining policy change at the International Maritime Organisation, Environmental Politics 29 (5) (2020) 825–844.

[68] K.P. Andreasen, B.K. Sovacool, Hydrogen technological innovation systems in practice: comparing Danish and American approaches to fuel cell development, Journal of Cleaner Production 94 (2015) 359–368.

[69] NEA, Klimakur 2030. Tiltak og virkemidler mot 2030, Norwegian Environment Agency, Trondheim, 2020.

[70] I.E.A. Bioenergy, Biofuels for the Marine Shipping Sector, International Energy Agency, Paris, 2017.

[71] J. Heiberg, Bibliographic Analysis Within Biofuels, Fuel Cells, and Electricity Storage Related to the Norwegian Maritime Shipping Sector, Lund University, Lund, 2017.

[72] J. Heiberg, Patent Analysis Within Biofuels, Fuel Cells, and Electricity Storage Related to the Norwegian Maritime Shipping Sector, Lund University, Lund, 2017.

[73] M. Tsouri, Analysis of the European Funded R&D Projects Within Biofuels, Fuel Cells, Hydrogen Fuel, and Electricity Storage Related to the Norwegian Marine Shipping Sector, University of Oslo, Oslo, 2018.

[74] M. Steen, H. Bach, Ø. Bjørgum, T. Hansen, A. Kenzhegaliyeva, Greening the Fleet: A Technological Innovation System (TIS) Analysis of Hydrogen, Battery Electric, Liquefied Biogas, and Biodiesel in the Maritime Sector, SINTEF, Trondheim, 2019.

[75] J. Markard, The life cycle of technological innovation systems, Technological Forecasting and Social Change 153 (2020), 119407.

[76] IMO, Sulphur oxides (SOx) –, Regulation 14 (2020).

[77] H. Ma, K. Steernberg, X. Riera-Palou, N. Tait, Well-to-wake energy and greenhouse gas analysis of SOX abatement options for the marine industry, Transportation Research Part D: Transport and Environment 17 (4) (2012) 301–308.

[78] F. Burel, R. Taccani, N. Zuliani, Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion, Energy 57 (2013) 412–420.

[79] A.T. Furtado, M.P. Hekkert, S.O. Negro, Of actors, functions, and fuels: Exploring a second generation ethanol transition from a technological innovation systems perspective in Brazil, Energy Research & Social Science 70 (2020), 101706.

[80] S. Bengtsson, E. Fridell, K. Andersson, Environmental assessment of two pathways towards the use of biofuels in shipping, Energy Policy 44 (2012) 451–463.

[81] Norwegian Government, Regjeringens handlingsplan for grønn skipsfart, 2019.

[82] K. Grjotheim, M. Nordum, L.C. Espenes, Kunskapsgrunnlag for omsetningskrav i skipsfart, Department of Environment, Oslo, 2018.

[83] T. Mäkitie, J. Hanson, M. Steen, T. Hansen, A.D. Andersen, The sectoral interdependencies of low-carbon innovations in sustainability transitions, FME NTRANS Working paper 01/20, 2020.

[84] A.M. Fevolden, A. Klitkou, A fuel too far? Technology, innovation, and transition in failed biofuel development in Norway, Energy Research & Social Science 23 (2017) 125–135.

[85] NEA, Kunnskapsgrunnlag for omsetningskrav i skipsfart, Norwegian Energy Agency, Trondheim, 2018.

[86] Norwegian Government, Økning i salget av avansert biodrivstoff i fjor [Growth in sale of advanced biofuels last year], (2019). https://www.regjeringen.no/no/aktuelt/okning-i-salget-av-avansert-biodrivstoff-i-fjor/id2627163/. (Accessed November 24th 2020).

[87] K. Andersson, S. Brynolf, J. Hansson, M. Grahn, Criteria and decision support for a sustainable choice of alternative marine fuels, Sustainability 12 (9) (2020) 3623.

[88] A. Florentinus, C. Hamelinck, A. van den Bos, R. Winkel, M. Cuijpers, Potential of Biofuels for Shipping, Ecofys, Utrecht, 2012.

[89] DNV GL, Grønt Skipsfartsprogram. Norge blir verdensledende på miljøvennlig og effektiv skipsfart, (n.d.). https://www.dnvgl.no/maritime/gront-skipsfartsprogram/pilotprosjekter.html. (Accessed November 24th 2020).

[90] T. Stensvold, Hurtigruten skal kjøre på biogass og LNG - spår ny vår for biogass, Tu.no, 2018.

[91] Kystverket, Status 2018, Kystverket, Ålesund, 2018.

[92] B. Lahn, Norwegian Petroleum Policy in a Changing Climate, CICERO, Oslo, 2019.

[93] T. Stensvold, Nesodden-fergene blir elektriske i løpet av 2019, Tu.no, 2018.

[94] M. Forbord, L. Hansen, Enacting sustainable transitions: A case of biogas production and public transport in Trøndelag, Norway, Journal of Cleaner Production 254 (2020), 120156.

[95] E24.no, Hurtigruten avbestiller grønne motorer på grunn av coronakrisen, E24.no, 2020.

[96] Sund Energy, Biogass kan blandes inn i LNG til skip i Norge: Potensiale for doble utslippskutt, Sund Energy, Oslo, 2019.

[97] VANytt.no, VEAS mottar hele 37,5 millioner kroner i støtte fra Enova, VANytt.no, 2018.

[98] Biokraft, Biokraft leder an i det grønne skiftet, 2016. http://www.biokraft.no/pressemelding-biokraft-leder-an-i-det-gronne-skiftet/. (Accessed November 20th 2020).

[99] J.J. Cadillo-Benalcazar, S.G.F. Bukkens, M. Ripa, M. Giampietro, Why does the European Union produce biofuels? Examining consistency and plausibility in prevailing narratives with quantitative storytelling, Energy Research & Social Science 71 (2021), 101810.

[100] A. Goetz, L. German, J. Weigelt, Scaling up biofuels? A critical look at expectations, performance and governance, Energy Policy 110 (2017) 719–723.

[101] M. Aldenius, Influence of public bus transport organisation on the introduction of renewable fuel, Research in Transportation Economics 69 (2018) 106–115.