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Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis

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ABSTRACT

Maritime transport faces increasing pressure to reduce its greenhouse gas emissions to be in accordance with the Paris Agreement. For this to happen, low- and zero-carbon energy solutions need to be developed. In this paper we draw on sustainability transition literature and introduce the technological innovation system (TIS) framework to the field of maritime transportation research. The TIS approach analytically distinguishes between different innovation system functions that are important for new technologies to develop and diffuse beyond an early phase of experimentation. This provides a basis for technology-specific policy recommendations. We apply the TIS framework to the case of battery-electric and hydrogen energy solutions for coastal maritime transport in Norway. Whereas both battery-electric and hydrogen solutions have developed rapidly, the former is more mature and has a strong momentum. Public procurement and other policy instruments have been crucial for developments to date and will be important for these technologies to become viable options for shipping more generally.

1. Introduction

Having been subject to tightening regulations on emissions of pollutants such as nitrogen oxides (NO_x) and sulphur oxides (SO_x) for several years, maritime transport now faces increasing pressure to reduce its emissions of greenhouse gases (GHG) in accordance with the Paris agreement. This became especially clear when the International Maritime Organization (IMO) in April 2018 adopted a strategy, focusing on energy efficiency measures, that aims to reduce GHG emissions from shipping as soon as possible, and to phase out emissions completely by the end of this century (IMO, 2018a). Globally, shipping accounts for approximately 3% of all anthropogenic GHG emissions. In the coming decades, these emissions are expected to increase further due to global economic growth, increasing international trade, and hence the need for more shipping. Whereas a range of technical and operational energy efficiency measures both on ships and in ports can contribute to reducing emissions (Bjerkan and Seter, 2019; Bouman et al., 2017; Lindstad et al., 2011; Mosgaard and Kerndrup, 2016), the introduction and use of alternative energy solutions to conventional marine fuels (diesel or crude oil) is needed in order for shipping to meet its emission reduction targets (DNV GL, 2016). Thus, it is necessary to develop and implement new low- or zero-carbon (LoZeC) energy solutions, such as liquefied natural gas (LNG), biofuels, battery-

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electric, and hydrogen.

Through applying LoZeC solutions, either as stand-alone technology or hybrids, maritime transport can preserve its ability to provide fundamental societal functions while reducing emissions. The environmental benefits from the LoZeC technologies differ, as do the challenges that they face (e.g. accessibility, phase of technological development, investment costs, “fit” with existing solutions and infrastructure) connected to their implementation and competition with conventional technology (Sandén and Hillman, 2011). Although these energy solutions are largely novel to shipping, they are not necessarily new to the world or to other sectors, and they also differ considerably in maturity and appropriateness for different segments within shipping (Bergek et al., 2018). In the words of Bouman et al. (2017, p. 418), “*no single measure is sufficient by itself to reach considerable sector-wide reductions*”, and the rate of implementation and level of commitment demonstrated so far seem suggest that “*more policies and regulations are needed to achieve high emission reductions.*”

Research on sustainability in maritime transport and shipping is a relatively new and growing interdisciplinary research field. Earlier studies have addressed the potential of different technologies to contribute to emissions reductions (e.g. Burel et al., 2013; Gabina et al., 2016; Talluri et al., 2016), life-cycle assessments of single (e.g. Jeong et al., 2018; Ling-Chin and Roskilly, 2016) or several technologies (e.g. Hua et al., 2017; Nanaki and Koroneos, 2012), as well as assessment methods for technology choice decisions (e.g. Ren and Liang, 2017; Ren and Lutzen, 2015). Substantial attention has also been devoted to the role of governance for more sustainable shipping (e.g. Lister et al., 2015; Stevens et al., 2015; Sys et al., 2016) and stakeholders' perceptions (e.g. Hansson et al., et al., 2019; Vieira et al., 2016). This article takes a different approach by conceptualizing the shift away from fossil fuels towards LoZeC energy solutions in shipping through a sustainability transition lens (Pettit et al., 2018; Steen, 2018). This research field – socio-technical or sustainability transitions – emphasizes how transformation of sectors such as transport is difficult due to the complex intertangling of technologies, regulations, infrastructures, markets, institutions, practices, and policies (Markard et al., 2012). In this literature, transition challenges have been discussed and analyzed for decades, with primary empirical focus on energy and onshore transport. Pettit et al. (2018, p. 293) argue that “*unlike other transport realms within which sustainable socio-technical transitions interventions may be achieved, the global shipping industry is far more likely to be immune to the usual prescriptions of this theoretical perspective*.” According to Pettit et al. (ibid.), this is due to shipping being “*embedded in global production systems*” and characterized by “*the combination of path dependency and fragmented governance structures*”, which “*reduce the scope for socio-technical developments at a ‘niche’ level*”.

Whereas this may be true for international deep-sea/long-haul shipping, numerous niche developments are visible within coastal shipping around the world. In Norway, for example, there has been a surge in the uptake of battery-electric energy storage on ships in recent years, and several pilot and demonstration projects for hydrogen fuel cells are underway (Steen et al., 2019). However, our point of departure is that development and implementation (i.e. innovation) of these new technologies does not simply happen. Rather, innovation in complex settings such as the maritime sector relies on engagement of various actors and the formation of 'innovation systems' around these new technologies. Thus, the main research questions addressed in this article is what are the joint and individual challenges and opportunities of new energy solutions in Norwegian coastal maritime transport?

This article focuses on two LoZeC technologies that are considered highly relevant (DNV GL, 2016) for achieving GHG emission reductions from domestic near-shore or coastal shipping in Norway: battery-electric (BE) and hydrogen. We furthermore limit the empirical context to Norwegian coastal shipping, which mainly comprises coastal ferry, freight, offshore supply and fishing vessels. Because our aim is to contribute to a better understanding of 'niche level developments' in the context of shipping, we apply the technological innovation system (TIS) framework (Bergek et al., 2008; Hekkert et al., 2007). This framework allows for a comprehensive (comparative) assessment of key innovation system functions, including knowledge development, entrepreneurial experimentation, legitimation, and market formation, for specific technologies in general or within particular application domains. Based on this assessment, technology-specific policy recommendations can be developed.

The TIS framework therefore adds a new dimension to the maritime transportation research literature, connecting several aspects of the prerequisites for technology development, and allows for identification of system strengths and weaknesses to be addressed by policy interventions. Furthermore, the analysis presented in this paper contributes with a systems perspective of the socio-technical challenges and opportunities for implementing BE and hydrogen technology in the coastal shipping sector, adding to the existing literature on governance of sustainable shipping and environmental assessments of alternative fuels.

The remainder of the article is structured as follows. In Section 2, we present the technological innovation systems function approach. In Section 3, we describe our research design, methods and data. In Section 4, we analyze the two technologies in order to identify specific system weaknesses. In Section 5, we discuss what policy makers – considering policy leverage – could do to solve these problems, in order to promote a shift towards more sustainable maritime transport. The final section concludes.

2. Theoretical framing: A sociotechnical perspective on sectoral change

The term ‘sociotechnical transitions’ refers to fundamental structural rearrangements of sectoral systems that fulfil certain societal functions, for example energy or transport, (Geels, 2002, 2004, 2005). In a *sustainability* transition, the changed system fulfils its societal function in a more sustainable way, considering ecological and/or social performance in addition to – or instead of – traditional economic performance. Such transitions normally require interconnected changes in sociotechnical systems, actor networks and regulations, norms and values (Geels, 2004; Geels and Kemp, 2007), but they can take different paths that imply different degrees of change in these three dimensions (Geels et al., 2016).[1]

While transitions thus involve more than just technological change (Geels et al., 2017), the emergence of new technologies (or innovations in a broader sense) is still an important part of the process. Indeed, for a transition of an entire societal sector to be realized, a number of different technologies normally have to be developed and diffused at a large scale (Jacobsson and Bergek, 2004). This is an evolutionary and iterative process characterized by considerable uncertainty, cumulative learning and feedback loops, and increasing returns to adoption (Jacobsson et al., 2017). It involves parallel and interacting advances in R&D, demonstration, niche market development and mass market formation, which can eventually result in a restructuring of existing production and consumption systems at the sectoral level (Hellsmark, 2014; Hellsmark et al., 2016b). Understanding how such processes unfold is in focus in the literature on 'technological innovation systems'.

2.1. The technological innovation systems approach

The technological innovation systems (TIS) concept refers to problem-solving networks of actors that are involved in the development, diffusion and utilization of new technology within a certain industrial-economic area and influenced by industry- and technology-specific rules, norms and perspectives (Bergek et al., 2008c; Carlsson et al., 2002; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Jacobsson and Johnson, 2000). It both acknowledges that actors drive technological change forward and that their efforts to do so are conditioned by other actors and the institutional framework that surround them (Bergek et al., 2008a).

For a transition of a sectoral system such as shipping to take place, the dynamics of existing or emerging technological innovation systems have to be supportive of the development and diffusion of alternative technological solutions. The structural configuration of relevant innovation systems has to come together or be adapted to new conditions through entry of firms and other organizations throughout and beyond the value chain, (re-)formation of different types of networks and other relationships between these actors (e.g. learning and political networks as well as a division of labor and mechanism for coordination), and institutional change or alignment (Bergek et al., 2008d; Jacobsson and Bergek, 2004; Jacobsson et al., 2017). The systems also have to function properly in order to generate innovation. This implies that the right kind of processes have to be set in motion, either as a consequence of the systems' internal workings or as a result of external influences from other technological, sectoral, regional, or national innovation systems or other contextual structures (Bergek et al., 2015; Bergek and Jacobsson, 2003; Jacobsson and Bergek, 2004; Jacobsson et al., 2017).

For new technologies to break through, TIS dynamics have to be matched with changes at the sectoral level. Indeed, existing sociotechnical systems, actor structures and institutions might have to be destabilized or even phased out to provide a "window of opportunity" for emerging innovations (Geels, 2002, 2004, 2005). This could happen due to internal conflict or tension or because of external pressures for change.

However, neither the structural (re-)formation and performance of technological innovation systems, nor the destabilization of existing structures tend to come easy. At the TIS level, there are many potential obstacles both at the actor and system level for the development and diffusion of new technologies (Hansen and Coenen, 2017; Johnson and Jacobsson, 2001; Mignon and Bergek, 2016; Negro et al., 2012). In addition, there tend to be many sources of inertia and path dependency at the sectoral level. For example, established technical systems are often characterized by interdependencies and self-reinforcing mechanisms such as economies experience and network effects (Arthur, 1988, 1994; Geels, 2004; Klitkou et al., 2015; Onufrey and Bergek, 2015); actor structures are stabilized by established relationships, mutual expectations and commitments between actors (Adner and Kapoor, 2010; Geels, 2004; Geels and Kemp, 2007); and the institutional structure tends to reward actors that conform to current laws, rules, norms, values and expectations. It is because of such obstacles and inertia that innovation and transition policy could be needed.

2.2. The role of policy for innovation and transition

Considering the large challenges involved in achieving sustainability transitions, it is not surprising that policy makers are interested in finding ways to enable or facilitate innovation and transition processes where not enough is happening to meet societal goals and expectations (Chaminade and Edquist, 2010). Historically, innovation policy has for example targeted stagnating industries and sectors that are perceived to have a too low rate of innovation (Dodgson et al., 2011; Edquist et al., 2004; Gustafsson and Autio, 2011; Hart, 2009; Jacobsson and Bergek, 2004; Laranja et al., 2008; Tödtling and Trippl, 2005). More recently, "transformative" innovation policy has been suggested to address societal "grand challenges" or achieve certain "missions" (Diercks et al., 2018; Grillitsch et al., 2019; Mazzucato, 2016; Schot and Steinmueller, 2018; Weber and Rohracher, 2012). Indeed, it is commonly argued that only the state has enough power to push for the kind of transformative changes needed to solve complex issues such as climate change (Johnstone and Newell, 2018). A transition of the maritime sector fits well into both these discourses, as it could potentially strengthen its innovative ability and address several of the UN sustainable development goals (e.g. goal 7 "affordable and clean energy" and goal 13 "climate action").

However, regardless of the general merits of such a transition, two basic conditions must be met for policy intervention to be justified. First, there has to be a problem that the market or innovation system cannot be expected to handle on its own, either because it is out of reach of individual actors or because there are conflicts between the individual goals and interests of the actors

[1] In brief, a *substitution* or *de-alignment and re-alignment* pathway implies that new ones replace existing technologies and that established actors (the "incumbents") are outcompeted by new entrants (although the mechanisms behind these two pathways differ and they are associated with different degrees of institutional change). In contrast, a *transformation* or *reconfiguration* pathway involves a reorientation of incumbent actors. In the former, incumbents improve their existing technologies and/or develop incremental or radical innovations that complement or substitute these technologies. In the latter, they collaborate with new entrants to develop modular and, later, architectural innovations (Geels et al. 2016).

and what is needed for the innovation or transition process as a whole to work well (Aghion et al., 2009; Bergek, 2014; Bergek et al., 2010). At an overall level, such problems can be expected to be abundant as far as sustainability transitions are concerned, since the sociotechnical changes required to handle societal challenges are not necessarily in line with the established actors' interest. However, more specific policy-relevant issues still have to be identified. Much of the previous and current policy debate centers on the need to correct different types of 'market failures', which limits innovation by firms in general. Such failures include, for example, positive and negative externalities, information asymmetries, economies of scale and capital market failures that all can result in an inefficient distribution of resources from a socio-economic point of view (Jacobsson et al., 2017).

The innovation systems literature has for a long time argued that the market failures approach is too static to use as a basis for stimulating innovation, which as described above is an inherently dynamic process.[2] It instead argues that policy makers should focus on strengthening the structure and performance of relevant innovation systems, in line with the discussion on TIS dynamics above (Carlsson and Jacobsson, 1997; Jacobsson and Bergek, 2004; Metcalfe, 2005; Nelson, 2009). This implies a substantial shift in focus both with regard to the problems policy makers identify and the solutions they will put forward to solve those problems (Jacobsson et al., 2017).

Second, policy makers should only intervene if they have a reasonable chance to solve the identified problems (Chaminade and Edquist, 2010). This raises the issue of policy "leverage" (or autonomy) (Johnstone and Newell, 2018), where a particular important question is to what extent key innovation processes, markets and actor networks are within reach of public administrations (cf. Chaminade and Edquist, 2010). In the case of shipping, a challenge might for example be that the multi-national character of this sector implies that national regulations and governance mechanisms might not be very effective (Pettit et al., et al., 2018).

2.3. A framework for identifying functional system weaknesses

In previous literature, two main approaches to identify innovation system problems have been suggested. The first targets failures or weaknesses in the structural composition of innovation systems, such as actor failures, networks failures and institutional failures (for an overview, see Klein Woolthuis et al. (2005)). These emerge for example when networks are too weak to allow for knowledge exchanges and collaboration or too strong to allow for experimentation with new approaches and relationships.

However, as argued by Jacobsson and Bergek (2004, p. 819), *"… there is no reason to expect a particular system structure to be related to the performance of a technological [innovation] system in a clear and unambiguous way."* Their advice is, instead, that policy makers should focus their attention on whether relevant innovation systems work well or not and identify the strengths and weaknesses that determine their performance (Bergek et al., 2008a, 2008c, 2010; Jacobsson and Bergek, 2004; Wieczorek and Hekkert, 2012). In line with this, the second approach uses the so-called "functions of technological innovation systems" framework (Johnson, 1998, 2001; Johnson and Jacobsson, 2001) to identify weaknesses in a number of key processes that contribute to the development, diffusion and utilization of new technologies. This analysis also includes identifying the determinants of those weaknesses, often referred to as "blocking mechanisms" (cf. e.g. Jacobsson and Karltorp, 2013; Johnson and Jacobsson, 2001).

Functions can be described as emergent and interlinked sub-processes of the overall innovation process (Bergek, 2019; Jacobsson and Jacobsson, 2014). They capture what is achieved in terms of innovation by the system and as a consequence of external influences from, e.g., related sectors, technologies, regions and countries (Bergek et al., 2008a, 2015; Bergek and Jacobsson, 2003; Jacobsson and Bergek, 2004). In this paper, we apply an adapted version of the TIS functions (see Table 1) defined by Bergek et al. (2008a).

Functions can be mapped empirically, as evidenced by over 160 studies covering for instance renewable electricity and heating technologies, electric and hybrid vehicles, and hydrogen direct reduction in steelmaking (Bergek, 2012, 2019; Kushnir et al., 2020). While the interconnectedness between functions implies that influences cannot always be unambiguously assigned to a particular function, a complete analysis of all functions and the mechanisms influencing them makes it possible to identify how the structural composition of the TIS – together with external influences – enable or hinder the innovation process (Jacobsson and Bergek, 2004). This implies that functional strengths (e.g. development of relevant knowledge) and weaknesses (e.g. lack of market formation) can be identified, which can be considered by policymakers (or other actors) as potential points of intervention (Bergek et al., 2008a, 2008c, 2010).

Policy makers can then design and implement instruments that aim at weakening blocking mechanisms and/or providing or strengthening inducement mechanisms (Johnson and Jacobsson, 2001). Considering the varying nature of the functions, such instruments do not only involve traditional science and technology policy instruments, such as R&D support, but a much wider variety of instruments including those directed at stimulating entrepreneurial experimentation and market formation (Bergek and Norrman, 2015).[3] It is common for several functional system weaknesses to co-exist and for several instruments to be needed to stimulate individual functions. This implies a need for 'systemic' instruments (Smits and Kuhlmann, 2004) and more complex 'policy mixes' (Kivimaa and Virkamäki, 2014; Rogge and Reichardt, 2016). These for the most part have to be technology-specific, since functional

[2] It should be noted, though, that more modern approaches to market failures acknowledge the existence of 'dynamic market failures' related to learning-by-doing and learning-by-using (see, e.g., Gawel et al., 2017; Lehmann and Gawel, 2013).

[3] Support for experimentation could for instance be funding for pilot projects and testbeds (Hellsmark et al., 2016a). Market formation instruments could include public procurement (Edquist and Zabala-Iturriagagoitia, 2012; Guerzoni and Raiteri, 2015) An interesting example from Norwegian coastal shipping is the innovative tendering process by the Ministry of Transport and the Public Roads Administration that led to the introduction of the world's first full-electric battery-powered car and passenger ferry *M/F Ampere* in 2014 (Sjøtun, 2019).

Table 1
TIS functions.

Function	Description
Knowledge development and diffusion (KDD)	Broadening and deepening of the knowledge base of a TIS, sharing of knowledge between actors within the system and new combinations of knowledge because of these processes.
Entrepreneurial experimentation (EE)	Problem-solving and uncertainty reduction through real-world trial-and-error experiments at different scales with new technologies, applications and strategies.
Market formation (MF)	The opening up of a space or an arena in which goods and services can be exchanged in (semi-)structured ways between suppliers and buyers, including e.g. articulation of demand and preferences, product positioning, standard-setting and development of rules of exchange.
Influence on the direction of search (IDS)	Mechanisms that influence to what opportunities, problems and solutions firms and other actors apply their resources, incentivizing and pressuring them to engage in innovative work within a particular technological field and determining what strategic choices they make within that field.
Resource mobilization (RM)	The system's acquisition of different types of resources that for the development, diffusion and utilization of new technologies, products and processes, most notably capital, competence and manpower and complementary assets (e.g. infrastructure).
Legitimation (LEG)	The process of gaining regulative, normative and cognitive legitimacy for the new technology, its proponents and the TIS as such in the eyes of relevant stakeholders, i.e. increasingly being perceived as complying with rules and regulations, societal norms and values and cognitive frames.
Development of positive externalities (PE)	The creation of system-level utilities (or resources), such as pooled labor markets, complementary technologies and specialized suppliers, which are available also to system actors that did not contribute to building them up.

Source: Bergek (2019) (adaptation of Bergek et al., 2008a, 2008b, 2008c).

weaknesses tend to differ between technologies (Jacobsson et al., 2017). If possible, policy makers should try to exploit current system strengths (Hellsmark et al., 2016b), including the innovative capabilities of firms and other actors, but they might also have to strengthen the system through other channels if the internal structure is too weak.

In a transition context, it has been argued that an analysis of innovation system weaknesses should be supplemented by dimensions that capture aspects such as the “creative destruction” of established system structures (Kivimaa and Kern, 2016) and increased directionality and reflexivity (Weber and Rohracher, 2012). The former is related to the sources of sectoral inertia described in Section 2.1, which in this paper is captured through its influence on the functionality of the analyzed technological innovation systems. The latter highlights the importance of on the one hand priority-setting and on the other hand policy assessment and learning. While this is not in focus in this paper, a functional analysis of several technologies can be used to determine which technologies to prioritize and it can also be used as an assessment tool to follow up and learn from the impact of specific policy instruments (Janssen, 2019; Kivimaa and Virkamäki, 2014).

In the analysis of this paper, we use the functions framework to examine the Norwegian technological innovation systems for BE and hydrogen in the context of coastal maritime transport. For each technology, we analyze the TIS structure, level of maturity and functional pattern, including the determinants of each function, i.e. inducing and blocking mechanisms. Subsequently, the achieved functional pattern is assessed and potential policy interventions needed to improve the functionality of the TIS(s) are discussed.

3. Research setting, methods and data

The empirical scope of our analysis[4] is coastal shipping in Norway, i.e. ships that primarily operate between or out of ports (or quays) domestically. While technological innovation systems in principle can be global (Andersson et al., 2018; Carlsson, 2006), the national delimitation used here is justified considering that Norway has a unique geographical context and prerequisites for energy production, in combination with a strong maritime industry investing in innovation in LoZeC technologies. In this study we have chosen the two LoZeC technologies BE and hydrogen because they have a high emission reduction potential, and have been identified as appropriate technologies for Norwegian coastal shipping (DNV GL, 2015). Additionally, the two respective technologies are applicable to different segments within coastal shipping, which justifies the inclusion and comparison of both technologies. Furthermore, the size and complexity of the maritime sector, political focus and support, and early implementation of different LoZeC technologies in several market segments make the Norwegian maritime shipping sector highly relevant for studying these technologies' innovation systems.

As discussed in Section 2.2, conducting a TIS analysis requires attention to both structural dimensions and functions of the respective innovation systems. To generate the necessary data to analyze these different aspects, we employed a mixed-methods approach. The primary source of data is 72 semi-structured interviews with senior level representatives of various firms, public agencies and other organizations (see Table 2). Interviews were carried out in the period 2015–2019. Our firm informants were typically CEOs, CTOs or managers responsible for R&I and/or business development. For R&D organizations and knowledge-intensive business services (e.g. consultancy), we interviewed experts on specific technologies, or representatives responsible for particular services, such as standardization. For public actors we interviewed managers of public support programs or public transport services while for NGOs and industry associations, the representatives were mainly directors and/or managers responsible for the maritime

[4] [Blinded for submission].

Table 2
Overview of interviews.

Type of organization	No. of interviews
Maritime sector firms (e.g. ship owners, shipyards, designers, equipment developers/suppliers)	37
Adjacent sector firms (e.g. fuel producers, infrastructure developers, ports)	7
Public agencies/actors (e.g. coastal administration, road administration)	11
R&D, KIBS	6
NGOs, associations, networks and coalitions (e.g. environmental NGOs, ship owners' associations, regional maritime cluster organizations)	11

sector or a specific technology.

The interviews were conducted face-to-face or via telephone/video conference, usually by two to three project team members, and typically lasted 60–80 min. For all interviews, we followed semi-structured interview guides based on the TIS framework (see Appendix 2 for an exemplary interview guide). These guides were tailored to different actor types, such as ship owners, technology developers, public actors, and NGOs, and the questions were further adapted as new insights were gained during the duration of the project.

Transcribed interviews were coded (using manual NVivo software), according to TIS functions (following the definitions in Table 1). This made it possible to connect and analyze each specific technology according to the TIS framework. Representative quotes from the interviews for each technology and function are compiled in Appendix 1. The interview data was complemented with literature review and document studies, bibliographical analysis (Heiberg, 2017a), patent analysis (Heiberg, 2017b), analysis of EU-funded R&D projects (1998–2020) (Tsouri, 2018) and data on financial support from Norwegian support agencies. All these methods shed light on both TIS structural dimensions and functions (see Fig. 1). The exception is the analysis of patent and bibliometric data, which primarily sheds light on two structural dimensions (actors and networks) and two functions ("Knowledge Development and Diffusion", and "Influence on the Direction of Search").

When judging the current status of the different TIS functions, the authors have combined the different data sources for each specific TIS, and arrived at a consensus, appointing each function with a score on a three-point ordinal scale (weak – intermediate – strong). These types of analyses are quite comprehensive due to the amount of data and different data sources, and it is consequently not feasible to elaborate in full detail in this paper due to length restrictions. Instead, an example of the functional analysis 'Knowledge development and diffusion' of the hydrogen TIS illustrates the logic behind our analysis and how different data sources are combined in the analysis. Based on findings briefly presented in Table 3, the 'Knowledge development and diffusion' function of the Hydrogen TIS is assessed as *intermediate*. This is because the strengths (R&D and collaboration) are partly offset by limited practical knowledge and experience with hydrogen in the maritime sector.

Conducting research on currently developing innovation and development processes is a complex endeavor (Steen, 2016). We have, however, carefully designed the study to increase the credibility of the research. Foremost by triangulation of researchers (at least two researchers during coding and (most) of interviews), triangulation of interview data (several organizations within different organization types), and by using different qualitative and quantitative methods. Finally, the data-gathering period stretched over more than four years (2015–19), enabling comprehensive insight into e.g. why a technology may gain or lose momentum.

4. Findings

In the following sections we present the main findings of our study. First, we introduce the empirical background and structural components of the Norwegian maritime sector and the BE and hydrogen TISs, followed by the functional analysis of the respective TISs.

4.1. Introducing the case

The Norwegian maritime sector has historically been fundamental to the Norwegian economy and is still one of Norway's largest

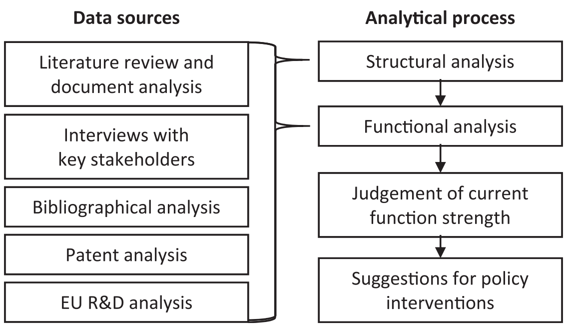

Fig. 1. Overview of data sources and the analytical process.

Table 3
Example of functional analysis of 'Knowledge development and diffusion' of Hydrogen TIS.

Strengths	Weaknesses
Norwegian actors are central within the EU R&D network, as well as actively patenting fuel cell technology (Data sources: EU R&D analysis, patent analysis)	Further development and large-scale testing of hydrogen technology needed (Data sources: Interviews with researchers, public agencies, firms)
Good collaboration between several types of actors within national and regional networks (Data sources: Interviews with firms, public agencies, network associations)	Need for education of on-board personnel for operation and maintenance of new hydrogen systems (Data sources: Interviews with university, firms)

industries. In 2018, the maritime sector employed approx. 85,000 people and represented around 17% of Norway's export earnings (Helseth et al., 2019). Furthermore, the maritime sector is characterized by a high number of advanced vessels, and the maritime service and supplier industry holds a prominent position globally. Maritime service and product suppliers are engaged in technology development for maritime application of LoZeC solutions (Mellbye et al., 2018). The main segments are freight (300 vessels), fishing (5000 vessels), offshore supply (600 vessels), and coastal passenger transport (500 vessels). Coastal shipping stands for 19% of the GHG emissions from domestic transport and 10% of Norway's total GHG emissions, and for Norway to meet its obligations within the Paris Agreement there is an urgent need for emission reductions within the shipping sector.

The Norwegian coast winds along the fiords for 20,000 km, and coastal shipping, in terms of public transportation, plays an important role connecting the towns along the coast. This implies that public administrations, such as the Norwegian Public Roads Administration and County Council Administrations, are responsible for public procurement of a large number of the 500 coastal passenger vessels. National and regional CO_2 emission policies have driven public administrations to include emission standards in specifications for public procurement contracts. In addition, so called "development contracts", where a ship-owner and/or shipyard receives extra funding for developing new solutions in combination with winning a tender, have been implemented for both BE and hydrogen technology. The state also controls the licenses to operate for aquaculture and petroleum producers, which may include emission standards. This provides a rather unique setting for the implementation of LoZeC technologies.

Constructing LoZeC ships is a complex process depending on collaboration between various actors. The Norwegian maritime sector covers the entire value chain and includes the necessary actors for the respective TISs. Norway's abundance of electricity from hydropower can enable the production of fossil free hydrogen, and provide electricity (onshore power supply, charging) of ships. Actors providing these services are included in the upstream parts of the value chains for both TIS. Actors involved in the downstream part of the development and construction of LoZeC ships include R&D actors, technology suppliers, consultancy firms, ship designers, shipyards, classification societies, and public agencies and funding bodies.

The technologies in focus of this analysis can be implemented either as total BE or hydrogen solutions or as hybrid solutions, where they are combined with each other or with conventional engines. Fully electric ships depend on charging infrastructure in harbors, which requires access to the electricity grid. Currently, hydrogen is mainly produced from natural gas. There is however potential for extensive Norwegian production of fossil free hydrogen through electrolysis of water (using renewable energy). Hydrogen propulsion solutions include fuel cells, which convert hydrogen fuel into electricity. As many technologies that can fulfil similar needs (Sandén and Hillman, 2011), such as energy, the various BE and hydrogen solutions can be either complementary to each other, or competitors.

Different versions of BE and hydrogen solutions have particular advantages and disadvantages regarding emission reductions, fuel and investment costs and so forth (see Table 4). In addition, the respective solutions are applicable to different market segments within shipping, mainly depending on vessel size, energy demand and operation area.

The two technologies also differ in terms of their maturity level in relation to different market segments. In the following section

Table 4
Evaluation of hydrogen and battery electric (full/hybrid) fuel alternatives (current status).

	Electric (full)	Electric hybrid[b]	Hydrogen[c]
Reduction of GHG[a]	Very high	Moderate-High	Very high
Reduction of NOx[a]	Very high	Moderate	Very high
Reduction of SOx[a]	Very high	Moderate	Very high
Investment cost (on vessels)	High	Moderate-High	High
Fuel cost	Low	Moderate	High
Availability (incl. infrastructure)	Moderate	Moderate	Low
Vessel adaptation	Very high	Low-moderate	High
Infrastructure adaptation (incl. fuel production/energy conversion)	Moderate-high	Low-high	Very high
Market segment suitability	Vessels – short routes (e.g. ferries)	All – esp. variable energy demand	All
Importance of regularity	High	Low-high	Low

[a] The environmental benefits of electric power (battery) and hydrogen depends on the source of electricity used

[b] Electric hybrid refers to a combination of e.g. a conventional (fossil) engine and a BE propulsion system.

[c] Hydrogen here refers to hydrogen produced via electrolysis from renewable energy. *Sources:* Nærings- og fiskeridepartmentet (2015), DNV GL (2015) and Steen (2018).

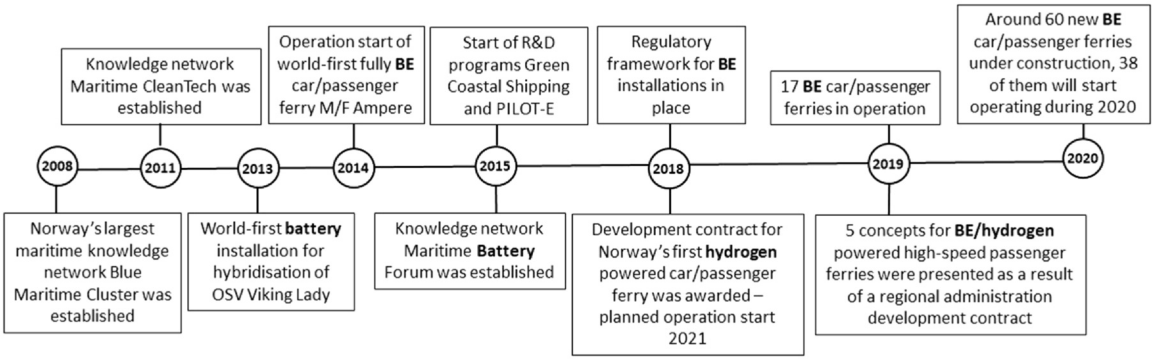

Fig. 2. Timeline of important milestones for the development of the BE and hydrogen TISs in Norway. Boxes that do not include a description of the technology in focus cover both technologies. *Sources:* Øystese (2019) and Steen et al. (2019).

we present the development of the structural components, such as important actors and institutional frameworks, and give an overview of the current maturity level for the respective technologies.

4.1.1. *Structural analysis of the BE TIS*

Many different actors are involved in the development of the BE TIS, such as ship-owners, technology suppliers, shipyards and classification societies. R&D projects and local initiatives have formed national and international knowledge networks, and standards and regulations for maritime BE applications are being established both at Norwegian and EU levels.

EU legislation regarding public procurement of public transport has enabled the state and local authorities to include emission requirements in tenders for ferries (The European Parliament and the Council of the European Union, 2014a,b). Following the operation start of the world's first BE car/passenger ferry in 2015, *M/F Ampere (in Norway)*, the Norwegian BE segment is maturing fast and public procurement has resulted in ordering of 70 BE ferries in the last five years (Stensvold et al., 2019) (see Fig. 2). The accelerating market expansion within the Norwegian road ferry segment has resulted in an *advanced niche market*, following the achievement of a high legitimacy. Hybrid propulsion and hybrid solutions for other segments than car ferries, such as peak-shaving technology for the offshore supply vessel segment, still have a slower market development but are progressing steadily within a *demonstration phase*.

Considering hydrogen, solutions for the maritime sector are currently immature even though Norway has previous experience of fuel cell production. However, a growing interest in hydrogen as a maritime fuel (or energy carrier), by both public authorities and individual ship-owners, has emerged (see Fig. 2). This indicates that the hydrogen TIS currently is in an *early demonstration phase*. Norwegian actors, mainly ship-owners, suppliers, R&D institutions and the classification society DNV GL are active in EU research networks on fuel cell technology and hydrogen. Furthermore, hydrogen is in focus for several national knowledge networks within the maritime sector, and standards and regulation are under development.

4.2. *Functional analysis of the BE TIS*

In the following sections we present the current performance of the BE and hydrogen TISs following the structure of the TIS-framework's functional analysis and identify the main system weaknesses for each technology.

4.2.1. *Knowledge development and diffusion*

Norwegian actors perceive themselves as being at the global forefront of BE ship technology, which is confirmed by their central position within EU R&D networks, active development and patenting of technologies, and strong contribution to publications on the topic. Knowledge development and diffusion primarily occurs within the strong national networks, where sub-divisions of international companies, research institutions, local ship-owners and yards are important contributors and often collaborate on technological development. This has resulted in increased knowledge about for example maritime battery installations, charging infrastructure solutions and required capacity and effect for different vessels. The interviewed actors expressed that competition between technology developers and suppliers drives innovation and knowledge development.

However, more knowledge is needed to achieve further advancements in battery and powertrain production and charging infrastructure solutions. In addition, there is a continued need for upscaling of marine BE applications, in particular within other segments than smaller chargeable car/passenger ferries operating along the coast. Representatives from technology suppliers, ship designers and shipyards expressed that there is a need for co-operation with research institutions and ship-owners, as well as dialogue with on-board personnel to collect insights on the operation of the BE systems in order to improve further system development.

To sum up, considering the continued need for upscaling and knowledge diffusion the function is assessed as intermediate, although knowledge networks within Norway are strongly developed.

4.2.2. Influence on the direction of search

Together with the unique access to non-expensive, renewable electricity in Norway, ambitious national climate and emission policies have influenced the direction of search towards BE technology. Initiatives from public administrations and state-owned institutions, for instance the Norwegian Public Roads Administration and the Norwegian Maritime Authority, have provided incentives for other actors to enter the BE TIS. Especially the state-initiated “development contract”, aimed at sparking development around new ship technologies, for a BE road ferry in 2013 (which resulted in M/F Ampere), gave a clear direction of search. Furthermore, a few ambitious ship-owners and shipyards have acted as first-movers inspiring others to explore BE solutions.

Implementation of full BE propulsion is currently restricted to smaller vessels with short routes, focusing on ferries, which is seen as a stepping-stone towards implementation of BE technology onboard larger vessels. Given the current focus on BE technology for car/passenger ferries within public procurement, most interviewed actors believed that the focus will most likely remain on electrification of ferries in the near future. Although this is mainly positive for the development of the TIS, there is a risk for application of outdated technologies and technological lock-in (both in terms of charging systems etc., but also in relation to alternative technologies such as hydrogen) if procurement requirements are not sufficiently updated parallel to technology development.

To conclude, the influence on the direction of search function is judged as strong, considering the policy support for BE, the fact that well-established actors are acting as first movers, and the accelerating market and technology development.

4.2.3. Entrepreneurial experimentation

Elements in focus for entrepreneurial experimentation are chargeable BE ferries, various hybrid solutions (including peak-shaving and dynamic positioning (DP) operation) and onshore power supply. Testing is performed in laboratories as well as on ships, and fully electric and hybrid ships have been in full operation since 2014. Following the initial implementation, experimentation has focused on solving problems with charging infrastructure and shortages of power supply. A need for new roles for suppliers has also been identified, and experimentation with business models has led to the rise of system integrators. These actors (e.g. Siemens, Wärtsila) provide complete systems for ship-owners and contribute to a holistic management of the installation, which reduces the risk for investors. Actors in forefront of experimentation are often ship-owners with a particular interest in keeping technology up to date. Others taking initiatives are technology suppliers and system integrators. Considering that experimentation is initiated by several types of actors and includes laboratory testing, pilot studies on operating ships as well as experimentation with business models, the function is assessed as strong.

4.2.4. Market formation

Over the last ten year (and especially during the last two years), the market for maritime batteries and electrical installations has expanded rapidly, both nationally in Norway and globally (see Fig. 3). Currently, approximately 40% of the global maritime battery installations are onboard Norwegian ships. The battery suppliers Corvus and Siemens have recently invested in Norwegian battery module factories (with a total capacity of c. 800 MWh), indicating continued market growth.

Investments in BE ship technology has been induced by rapidly increased battery capacity and price reductions. In addition, the success of front-runners drives new actors to invest in BE ship technology, particularly in the case of the road ferry segment, which is the dominating segment regarding both number of battery installations and installed battery capacity (followed by offshore supply vessels).

Incentives to invest in BE technology, apart from emissions regulations, appear to be quite individual. Some examples are rapid return on investment, lower fuel costs, ambitions to be a technological front-runner, and social norms. There are also some segment-specific incentives. For offshore supply vessels, alterations of contract details regarding fuel costs, where ship-owners gradually are taking over the fuel cost from the companies chartering their vessels, are initiating market formation for battery technology aimed at peak-shaving and decreasing fuel consumption. In the passenger segment, state-initiated development contracts and requirements in

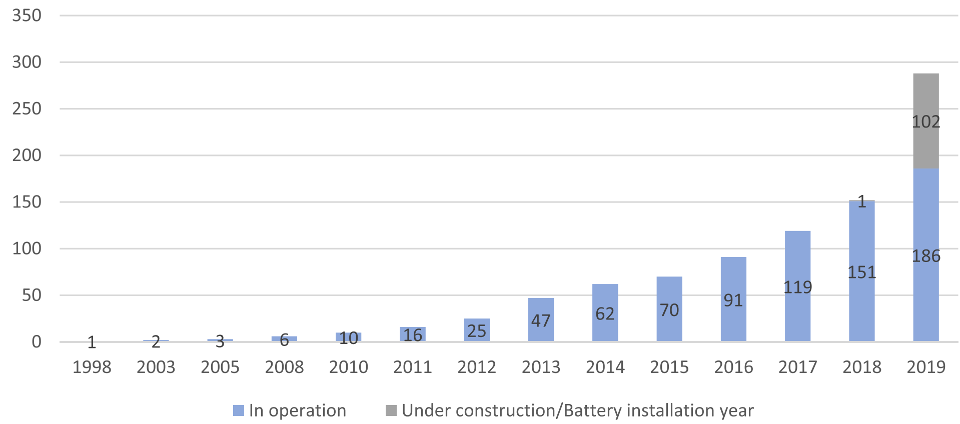

Fig. 3. Development in total number of vessels with installed battery (globally). (Source: Adapted data from DNV GL’s Alternative Fuels Insight platform (DNV GL, n.d.).)

public procurement tenders are two crucial drivers of market formation. However, when signing long-term contracts, ship-owners and shipyards take substantial risks, since their suppliers cannot always promise longstanding deliveries of spare parts and repair services.

In conclusion, the market formation for BE technology is assessed as strong and the base for further market formation is good, provided that policy support will continue to provide incentives for installation of batteries.

4.2.5. Legitimation

The historical success rate of diesel electric engine solutions[5] has opened up for a variety of electric solutions including battery hybrid propulsion. Additionally, successful pilot tests, demonstrating the technology's functionality, have increased interest in BE technology. The increasing number of chargeable ferries operating on the fiords further strengthens the legitimacy, as the interviewed new entrants expressed that the success rate of early movers increased their trust in the new technology. Furthermore, lobbying by the Norwegian networks Maritime CleanTech (MCT), Maritime Battery Forum, as well as by BE technology suppliers and system integrators is important for the legitimation process. After successful implementation of chargeable ferries, BE solutions are diffusing to segments such as coastal fishing and workboats for the aquaculture industry. However, uncertainties regarding the life length of batteries and power supply capacity for charging infrastructure are barriers that need to be overcome for further increased legitimacy.

For several R&D projects, certain funding was set aside to create regulations and standards for BE technology within the maritime sector. Consequently, the institutional framework is relatively complete, increasing the legitimacy of the TIS. However, while ship-owners and shipyards find this framework reassuring, as security is of high importance, they express some frustration over the extensive regulation development process.

To sum up, the legitimation function is assessed to be strong, considering the increasing acceptance of BE technology and the relative completeness of the institutional framework.

4.2.6. Resource mobilization

In the last decade, Norwegian public support agencies have offered financial support for BE solutions and there has been an increase of allocated funding to BE technology since 2006. The main funders are public support agency Enova (1.5 billion NOK for ship technology, 665 million NOK for charging infrastructure and 518 million NOK for onshore power supply) and the NOx-fund (119 million NOK). According to the NOx-fund, they prioritize BE and hydrogen technology over other LoZeC technologies when allocating funding. The four public financial support agencies offer various levels (40–100%) of investment support. Access to funding has both enabled knowledge development and entrepreneurial experimentation and, later, resulted in construction of infrastructure.

However, while shipyard representatives argue that public funding is particularly important during financial recession, since it allows maintaining of development and innovation, funding applications are experienced as lengthy and demanding processes. Moreover, since public funding is focused on new innovations, firms struggle with project continuation without external funding.

Overall, many big companies within the maritime industry have a designated internal budget for developing and experimenting with BE technology, resulting in less dependency on external funding. Extensive firm-internal investments in BE solutions have been made by established companies in the Norwegian maritime sector, for example investments in hybrid laboratories (Stensvold, 2019) and Siemens' 100 million NOK investment in a battery module factory in Trondheim (Larsen, 2019). In addition to internal investments, large established companies and informal investors have provided new firms with considerable (venture) capital.

Regarding human resources, the competence base for diesel-electric systems is transferable to BE propulsion. However, recruitments from other sectors, such as electrical engineers, are needed to meet the demand for increased knowledge within battery and powertrain production and to handle increased uptake of maritime BE applications. Moreover, there is a need for user-side education of the on-board personnel to optimize the operation of the new systems.

Overall, the resource mobilization function is assessed as strong, due to the access to public funding, the considerable internal as well as external investments and the solid supply-side human capital applicable to the new technology.

4.2.7. Development of positive externalities

Through having strong national and regional networks, the Norwegian BE segment has developed numerous positive externalities. Pilot testing by first movers accelerates processes for latecomers and is a crucial driver of technological diffusion. A growing number of specialized suppliers for BE solutions are entering the market. Although Norwegian actors' knowledge is spread over multiple BE applications and solutions, the knowledge base is strong. Sharpening standards and classifications for maritime BE technology would create common competencies among installers and on-board personnel. Implementation of charging infrastructure or onshore power supply could benefit various ships but requires standardization of charging solutions and plugs to make the infrastructure available to different types of ships. Therefore, the current state of the development of positive externalities is assessed as intermediate.

4.2.8. Summary and overall assessment

Taking all functions into consideration, the BE TIS seems to function relatively well, with most functions being strong (see Table 5). Its core system strengths are the strong legitimacy, distinct direction of search, solid market formation and resource mobilization, and the varied entrepreneurial experimentation. However, there are also several system weaknesses that work against

[5] The first ship with diesel-electric transmission was launched in the early 1900s (Wärtsilä, 2020).

Table 5
Sum-up of functional analysis for the BE TIS.

Function	Assessment	Strengths	Weaknesses
KDD	Intermediate	• Strong collaboration in national and regional knowledge networks • Competition that drives innovation	• Need for further development of battery and powertrain production and charging • Continued need for upscaling • Need for increased user involvement
IDS	Strong	• Clear political goals and emission regulations • Access to renewable electricity • Public incentives for BE development • First movers that inspire others	• Risk of technological lock-in due to specifications in public procurement
EE	Strong	• Wide range of experiments initiated by several types of actors	
MF	Strong	• Emissions regulations and other (segment-specific and individual) incentives to invest	• High risk involved in signing long-term public procurement contracts
LEG	Strong	• Success rate of implemented battery installations and pilot tests • Relatively complete regulatory framework	• Technological uncertainty • Lack of standardization
RM	Strong	• Substantial public and private investments	• Complicated funding application process • Lack of public funding for project continuation • Need for education of on-board personnel
PE	Intermediate	• Late mover advantages • Entry of specialized suppliers	• Lack of standards for maritime BE applications and charging infrastructure

the further development and diffusion of BE technology, most notably the need for further development and upscaling of the technology and the lack of standards and other positive externalities.

4.3. Functional analysis of the hydrogen TIS

4.3.1. Knowledge development and diffusion

Currently, the hydrogen knowledge base in Norway is limited, indicating that extensive technology development and trials of marine applications throughout the entire value chain is required. Cooperation between different actors is seen as crucial to speed up processes at this early stage of technology development, and Norwegian actors hold a central position within EU R&D networks for fuel cells and maritime hydrogen technology. In the Norwegian hydrogen TIS, collaboration between various actors in the form of R&D projects and pilot studies have been initiated by ship-owners and technology developers. National and regional networks, such as the Norwegian Hydrogen Forum and NCE Maritime CleanTech, further enable knowledge sharing and collaborative partnerships.

To sum up, the function is assessed to be of intermediate strength, due mainly to network collaborations and the increasing number of R&D projects, although further technology development and large-scale testing is still required.

4.3.2. Influence on the direction of search

As renewable energy is a requirement for fossil-free hydrogen production, the Norwegian capacity to produce renewable electricity provides a central incentive for the maritime sector to implement hydrogen technology. Common to the BE TIS, the direction of search for hydrogen is also guided by political ambitions and goals and public procurement policies, especially the Norwegian Public Roads Administration's ordering of a new road ferry to be built with hydrogen powered fuel cells (estimated to start operating in 2021). There are also clear positive expectations regarding the future development of the TIS.

However, the interest in hydrogen technology is heavily influenced by the development of other technologies, most notably by biofuel availability (since biofuels are a low-carbon alternative to hydrogen on longer routes) and the restrictions of BE technology. Currently, hydrogen is mainly seen as complementing BE solutions, as hydrogen and fuel cell systems allow electrification of various type of ships operating on larger distances and without charging infrastructure.

According to our interviewees, coastal high-speed passenger ferries' high energy demand and their obligation to comply with more stringent emission regulations make them a suitable entry point for the transition to hydrogen technology. Absence of bunker infrastructure, low fuel availability, and high fuel prices were mentioned by several actors as barriers for investments in development of hydrogen technology, although they believe the technology has potential once it becomes more advanced and regulations have been implemented. Furthermore, regardless of consensus on BE being insufficient as the sole LoZeC technology, there is some unwillingness among ship-owners and shipyards to simultaneously perform testing of multiple technologies (including hydrogen), especially considering lack of resources and the financial risk. This provides an additional barrier for the implementation of maritime hydrogen solutions.

To conclude, the influence on direction of search is assessed to be of intermediate strength, considering on the one hand the direction provided by goals, ambitions and expectations for hydrogen technology and on the other hand its dependence on the status of other technologies.

4.3.3. Entrepreneurial experimentation

The current main experimentation activity is pilot projects focusing on hybrid technology integrating hydrogen powered fuel cells with battery modules for BE propulsion. Initial application of hydrogen technology is concentrated to smaller high-speed ferries, mainly driven by development contracts initiated by the Norwegian Public Roads Administration and some of the County Council Administrations. Due to the limited access to fossil-free hydrogen combined with public procurement requirements to use fossil-free fuels, experimentation activities also include the development of methods for sustainable production. Furthermore, the potential for lowering fuel prices through local fuel production by ship-owners is explored.

However, so far experimentation within the hydrogen TIS is limited to a few actors, mostly ship-owners and shipyards. Moreover, suppliers and ship-owners have criticized the rules of the state initiated development contract for being too strict too early, as they fear that the immaturity of the technology will create high risks since the suppliers cannot give the same 10-year operating commitment that the ship-owners are obliged to guarantee the Norwegian Public Roads Administration.

Overall, the function is assessed as intermediate since experimentation activities span over a wide range of maritime hydrogen solutions, despite the low number of actors currently carrying out pilot testing and R&D projects.

4.3.4. Market formation

The Norwegian hydrogen fuel market is still very small, especially for fossil-free hydrogen. Development contracts and zero emission requirements in public procurement contracts are expected to spark an upscaling of the means of production and control, which in turn will decrease hydrogen fuel prices to competitive levels and drive market formation for hydrogen in the future. The Norwegian Public Roads Administration's call for a hydrogen car/passenger ferry has been an important driver, since the state promises to cover the higher operating costs. This is seen as crucial to decrease hydrogen fuel prices, which is needed to compete with conventional fuels. Nevertheless, there is generally hesitance towards implementing maritime hydrogen technology, as it is perceived that high fuel prices entail a great risk and it is difficult to receive compensation for increased fuel or operation costs.

At the same time as interest in maritime hydrogen solutions is growing, hydrogen technology for road transport is developing rapidly. Positive synergies between onshore and maritime transport are therefore expected for hydrogen. In the present conditions, however, the function is assessed as weak.

4.3.5. Legitimation

Increasing legitimacy was observed during data collection. Investments have been initiated by several important actors across the value chain, indicating increased acceptability of hydrogen technology. The Norwegian Government has pointed out hydrogen as a promising sustainable fuel, which will probably increase interest in hydrogen as a maritime fuel. The state-initiated development contract is expected to reinforce the legitimation of maritime applications of hydrogen technology further, by adding to the development of the institutional framework. Furthermore, lobbying regarding implementation of hydrogen within both maritime and road transport from the Norwegian Hydrogen Forum, as well as the parallel development process of the hydrogen road transport TIS furthermore positively influences the legitimation process.

However, although some of the previous safety concerns have been reduced, hydrogen ships are automatically rated at the strictest security level because of insufficient rules and regulations for maritime applications. This makes the construction process complex and financially demanding.

Following this, the legitimation function is assessed as intermediate to reflect the increasing acceptance of hydrogen technology as well as the remaining safety regulation issues.

4.3.6. Resource mobilization

Despite the low level of technology development and the TISs' early formative phase, there are several funding possibilities for hydrogen technology. Public financial support has been available through (and prioritized) by the same funders as for BE technology, but in smaller numbers. Since 2016 four pilot projects (three in the passenger segment and one in the freight segment) have been awarded public financial support. However, the NOx-fund's criteria for disbursing funding requires that a project has been successfully implemented, and the interviewed ship-owners and shipyards emphasized that the financial risk for hydrogen projects is still too high for the NOx-fund's funding to be applicable.

Private investments are limited but increasing. For example, the young company Greenstat has successfully obtained investments in the range of 8–12 million NOK from c. 400 investors through numerous crowdfunding rounds. In addition, there are signs that larger companies are initiating internal investments, such as ABB (in collaboration with SINTEF) and Kongsberg Maritime's financing of laboratories for developing hybrid fuel cell technologies. Smaller businesses are however regularly relying on external investments, which may be challenging to obtain.

Regarding human resources, the competence base for maritime applications of hydrogen powered fuel cells is not very mature, but Norwegian actors believe they have the capability to develop the required knowledge. The abovementioned need for education of on-board personnel about BE technology should be relevant for hydrogen as well.

All in all, resource mobilization is assessed as intermediate because of the increasing access to public and private funding.

4.3.7. Development of positive externalities

Considering the TISs early phase of development, no strong positive externalities can be expected, and the function is also assessed to be weak. However, the coming hydrogen car/passenger ferry may presumably advance the development of positive externalities – similar to how implementation of the first BE ferry paved way for rapid expansion of the BE ferry segment, as early-movers create free-riding for late comers in terms of technology development and increased legitimation.

The most notable weakness at present is the lack of an accessible bunker infrastructure. Early entering ship-owners suggested two

Table 6
Sum-up of functional analysis for the hydrogen TIS.

Function	Assessment	Strengths	Weaknesses
KDD	Intermediate	● Collaboration between several types of actors in regional, national and international networks ● Increasing number of R&D projects	● Weak knowledge base ● Need for further development and upscaling of technology
IDS	Intermediate	● Political goals, ambitions and expectations ● Access to renewable electricity	● Attention dependent on status of other technologies ● Hesitance among ship-owners towards parallel development of ships with different LoZeC technologies
EE	Intermediate	● Increasing experimentation including pilot testing in relation to public development contracts ● Public procurement requirements	● Few actors involved in experimentation ● High risk related to public development contracts
MF	Weak	● Possible synergies with road transport	● High fuels prices and limited availability imply high risk
LEG	Intermediate	● Important actors starting to invest ● Lobbying ● Developments in road transport	● Lack of rules and regulations, including safety classification, for maritime applications
RM	Intermediate	● Increasing access to public and private capital (especially for larger firms)	● Lack of external investors ● Need for education of on-board personnel
PE	Weak	● Newly implemented development contracts	● Early phase of development ● Non-existent maritime sector fuel infrastructure

possible main directions for establishing fuel infrastructure: either local production in connection to harbors or large-scale production. Centralized, large-scale production will depend upon extensive transport infrastructure, which is resource intensive but would create positive externalities and incentives for new actors unable to make investments on their own to join the TIS.

4.3.8. *Summary and overall assessment*

Hydrogen appears to be a promising fuel for various segments and is one of few viable solutions for energy intensive vessels operating on longer routes. Taking all functions into consideration, the hydrogen TIS so far seems to function less well than the BE TIS, with all functions being weak to intermediate (see Table 6). The core system strengths are the increasing involvement of actors in knowledge development and entrepreneurial experimentation, the relatively clear political direction and legitimacy, and the increasing availability of funding. However, there are also a number of system weaknesses that work against the further development and diffusion of hydrogen technology in the maritime sector, most notably the still immature actor network and institutional framework and the high perceived risks, which have a negative influence on all functions but especially on market formation and the development of positive externalities.

5. Recommendations for policy

The preceding empirical analysis suggests that the more mature BE TIS is the stronger of the two TISs, but an increasingly rapid development of the hydrogen TIS was noted during the investigation period (see Fig. 4). Whereas our evaluation refers to their current state, previous research has shown that, for example, legitimacy may increase very rapidly but also be lost fast (Ruef and Markard, 2010).

In addition to their specific strengths and weaknesses, the Norwegian BE and hydrogen TIS also share some challenges. In the

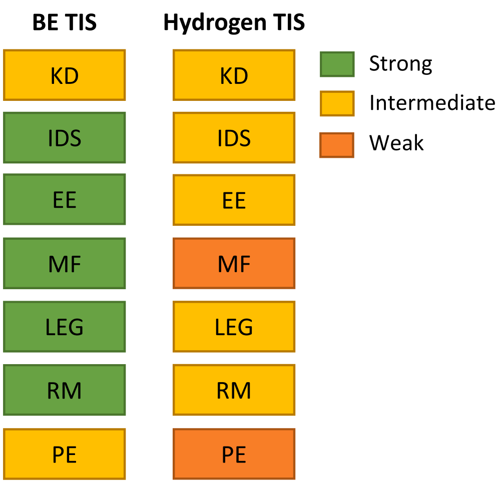

Fig. 4. Overview of the current status of the respective TISs functions.

following sections, we will first discuss some of the joint aspects that can warrant policy attention and then turn to the system-specific policy needs of each of the two TISs.

5.1. Shared support needs and suggested policy interventions

To enable a successful sustainability transition within the Norwegian maritime sector further policy interventions are required. These measures, i.e. the policy mix, should be designed to encompass policies and initiatives for market-pull as well as technology-push (Rogge and Reichardt, 2016). In addition to addressing system weaknesses with suitable policy interventions, it is also important to consider how system strengths can help addressing system weaknesses (Hellsmark et al., 2016b).

With regard to strengths, both TISs benefit from national and international collaboration (KDD), clear political goals and emission regulations guiding development and access to renewable electricity (IDS), increasing experimentation with technologies and applications (EE), and increasing public and private investments (RM). To further improve the functionality of both TISs, it is important for policy makers to maintain these strengths, for example by further sharpening national as well as international climate and emission policies.

The two systems share five main system weaknesses. First, the need for further development and upscaling of technology remain for the BE TIS as well as the hydrogen TIS. The main policy intervention to ensure further innovation and implementation is to maintain funding possibilities and innovation support, which apart from knowledge development will strengthen entrepreneurial experimentation and resource mobilization. Second, ship owners and operators perceive that there is a high risk connected to investments in novel technology. To accelerate implementation of BE and hydrogen technology, it is important to implement market stimulation measures such as removing subsidies for fossil fuels and implementing a CO_2 tax. The tax incomes could favorably be used to fund a LoZeC bonus, or to create a CO_2 fund (similar to the Norwegian NO_x fund). Third, focusing on one specific technology in development contracts and public procurement specifications creates risk for technological lock-in and de-legitimization of other LoZeC technologies. Considering that both technologies are in early development stages, it is crucial to design public procurement requirements in ways that minimize negative lock-in effects (see Fig. 5).

Fourth, although the two technologies partly share technological components and it is noteworthy that increasing interest in one of the technologies usually sparks interest in other LoZeC solutions too, there is very limited interaction between the two TISs. Policies aimed at creating further synergies between the BE and hydrogen TISs (for example specific R&D and pilot programs designed for encompassing both technologies) would strengthen the development of positive externalities as well as knowledge development and diffusion. It is especially beneficial to implement policy measures for facilitating learning and knowledge exchange between the TISs, which could further reduce lock-in effects. Last, the identified need of education of ship personnel should be addressed by educational policies for on-the-job-training and updates of curricula for vocational education in order to improve the common knowledgebase that can be shared within and between the TISs.

5.2. The BE TIS

Despite the recent rapid implementation of BE technology in the passenger segment, the BE TIS would benefit from further policy support, since preserving the system strengths identified in Section 4.2.8 is essential for successful further expansion of BE technology in the Norwegian maritime sector.

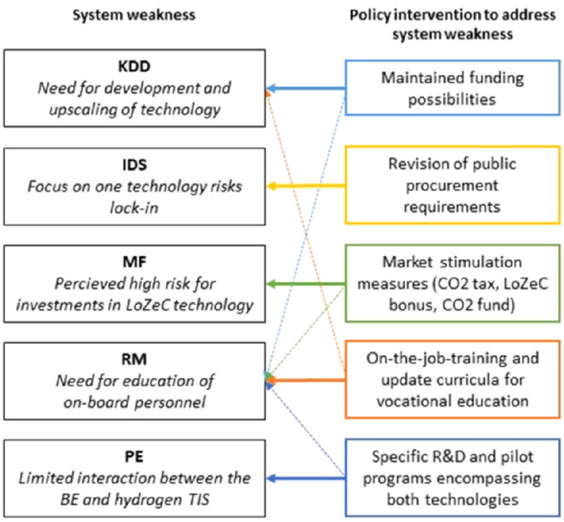

Fig. 5. Proposed policy interventions to address shared system weaknesses. Dotted lines represent additional interaction between the specific policy intervention and other functions than the targeted system weakness.

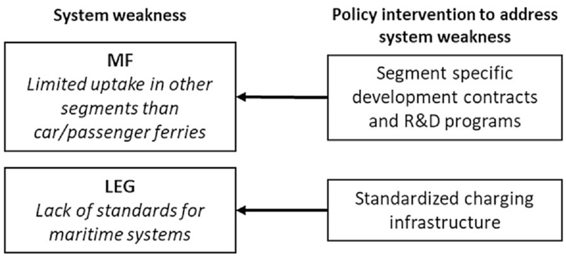

Fig. 6. Policy interventions to address system weaknesses within the BE TIS.

With regard to the main system weaknesses specific for the BE TIS, establishing standardized charging infrastructure would advance the development of positive externalities and reinforce the BE TIS legitimation process. However, this requires that present capacity issues concerning the development and upgrading are resolved. It is furthermore necessary to promote uptake of BE technology for additional types of vessels (e.g. fishing and freight), for example through development contracts and segment specific R&D programs (see Fig. 6).

5.3. The hydrogen TIS

Since the hydrogen technology and its maritime applications are immature, the hydrogen TIS require additional technology specific policy support to succeed with large-scale implementation. To achieve a rapid introduction of hydrogen powered ships, it is critical that public funding prioritize hydrogen technology and offer financial support to fuel production, construction of infrastructure, as well as drive train development. The state-initiated development contract for a BE car/passenger ferry had crucial influence on the rapid development of the BE TIS. This suggests potential for similar improvements of the hydrogen knowledge development and entrepreneurial experimentation functions following the development contracts for hydrogen car/passenger ferries.

Additionally, to ensure advancement of the regulatory framework, particularly with regard to safety aspects, it is important to continue the development of rules and regulations in connection to the development contracts, to strengthen legitimation. It is specifically vital to attain a classification of hydrogen ships, to decrease the high cost of designing hydrogen vessels. In combination with the activities within the development contracts, this could positively affect market formation (see Fig. 7).

Initially allowing fossil-based hydrogen within public procurement contracts for LoZeC ships would rapidly increase available volumes and initiate market formation. However, to avoid non-compulsory use of fossil-based hydrogen and to drive upscaling of production of fossil-free hydrogen, permission for use of fossil-based hydrogen should only be granted for a limited period. Considering the restricted fuel availability, one option is initiating implementation in fuel intensive segments, for example high-speed passenger vessels.

5.4. Implications for supranational policymaking

Following our analysis it is clear that public development contracts is the most prominent policy measure driving development of LoZeC-technologies in Norway (see also (Sjøtun, 2019)). Additionally, green public procurement has been crucial for the car/passenger ferry segment to facilitate the development and diffusion of initially BE technology, as well as shifting the market from fossil fuel ferries to LoZeC-ferries (Bergek et al., 2018). Furthermore, through green public procurement (i.e. by requiring LoZeC transport of goods), public actors can support transition processes in additional segments such as cargo ships.

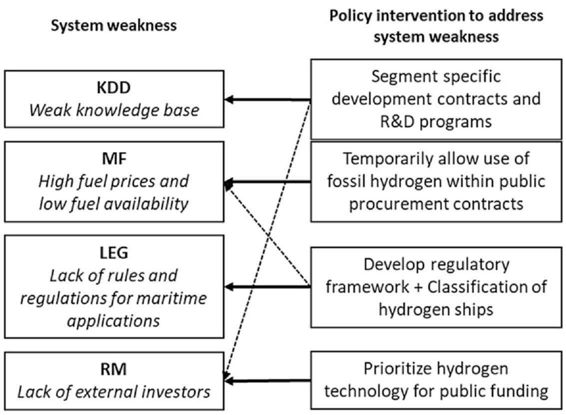

Fig. 7. Policy interventions to address system weaknesses within the hydrogen TIS. Dotted lines represent additional interaction between the specific policy intervention and other functions than the targeted system weakness.

Given that shipping (neither in terms of public transport or merchant shipping) is not included in EU policy around green public procurement or procurement for innovation (European Commission, 2018; The European Parliament and the Council of the European Union, 2014b), a first step towards an attempt to replicate the Norwegian success would be to include ships in the existing guidelines for green public procurement of transport (European Commission, 2016). Furthermore, EU have leverage to sharpen regulations around emission criteria for public procurement, and develop their initiatives around procurement for innovation to include sustainable shipping.

However, considering the trans-nationality of the shipping sector, national and regional measures will not be sufficient. As current international legislations focus on measures for energy efficiency and regulation of NO_x and SO_x (IMO, 2018a, 2019), there is a clear need for international policy favoring innovation around LoZeC technologies. Following Norway's example, it is evident that national emission regulation for coastal areas has an impact on the transition to LoZeC shipping. It is therefore our recommendation that IMO includes CO_2 in the already implemented coastal emission control areas for NO_x and SO_x (IMO no date-a,b), to further create incentives for implementation of sustainable technologies. To reduce the overall carbon footprint of shipping, further measures to ensure a decrease in GHG emissions from deep-sea shipping will also be needed.

6. Conclusions and implications

Although the maritime sector currently only contributes to 3% of global GHG emissions, there is an urgent need to decrease emissions to comply with the Paris agreement. The aim of this article was to identify the joint and individual challenges and opportunities of new energy solutions in Norwegian coastal maritime transport, specifically battery-electric and hydrogen solutions, by means of a functional analysis of their respective technological innovation system.

6.1. Conclusions

As revealed by our findings, the BE TIS has matured rapidly in the last years and is clearly the stronger one of the two TISs, although the hydrogen TIS is currently developing at a high speed. The two TISs share some challenges and opportunities for large-scale implementation, such as the requirement for further development and uptake of technology, lack of standards and regulations as well as education of on-board personnel. However, their individual challenges generally differ depending on the maturity of the TIS. Although the BE TIS has developed rapidly, technology adoption has mainly been in the car/passenger segment, and wider diffusion in other market segments remains a challenge. In addition to the need for development of technology and a regulatory framework, the hydrogen TIS struggles with a very limited supply of fossil-free hydrogen leaving potential investors hesitant.

6.2. Implications for policy

It should be noted that to date, public policy has been of crucial importance for the development of the two TISs. Most notably, state-initiated development contracts and the opportunity to include emission standards in public procurement contracts have been strong leverage points, as they force ship-owners to be innovative to comply with the requirements. Indeed, the technology development connected to green public procurement and development contracts have strengthened most functions of the BE TIS, and similar effects are expected for the hydrogen TIS following the newly implemented development contracts for hydrogen ferries. Overall, these development contracts and green public procurement in combination with national climate policies and emission standards, have proven to be a promising starting point for the Norwegian sustainability transition to fossil free coastal shipping, although some adjustments in the requirements might be needed in order to avoid future lock-in to BE technology.

Moving forward, our assessment is that Norway has several means to give policy the leverage to address the identified innovation system weaknesses. As the discussion in Section 5 shows, the required policy mix (Rogge and Reichardt, 2016) needs to include policies and initiatives for market-pull as well as technology-push to be able to drive the required transformation processes. Most notably, there is a need for further funding possibilities, market stimulation measures, development of educational policies, and creation of further synergies between the BE and hydrogen TIS. In addition to addressing system weaknesses with suitable policy interventions, policy makers also have to consider how system strengths can be maintained and mobilized to help addressing system weaknesses (Hellsmark et al., 2016b). In particular, it is important to maintain and further sharpen climate and emission policy, and to advance development contracts and green public procurement, to create incentives for implementation of LoZeC technologies.

As Norwegian actors' hold a prominent position within global sustainable shipping, the national maritime sector has fertile conditions to accelerate the implementation of LoZeC alternatives to conventional fossil fuels. However, we recognize that Norwegian national level policies are insufficient on their own. It is therefore important that Norway as a frontrunner continues lobbying towards the IMO and additional international actors to implement firmer emission regulations and more ambitious targets for the shipping sector.

6.3. Implications for further research

In order to achieve a sustainability transition within the maritime sector there is a need for a portfolio of LoZeC-technologies. BE and hydrogen solutions are suitable for certain segments within coastal shipping (Bergek et al., 2018), however, there is still a need for continued research on additional alternative technologies and the challenges and opportunities of their implementation. Future research could also investigate the current state of the national BE and hydrogen TISs in other countries to gain new insights about the global development. Furthermore, coastal shipping is a small part of the maritime sector, and extensive research on fossil-free offshore shipping is still needed.

CRediT authorship contribution statement

Hanna Bach: Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Anna Bergek:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Øyvind Bjørgum:** Investigation, Writing - original draft. **Teis Hansen:** Conceptualization, Investigation, Writing - original draft. **Assiya Kenzhegaliyeva:** Investigation, Writing - original draft. **Markus Steen:** Conceptualization, Investigation, Writing - original draft.

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.

Appendix 1. Quote table

Battery-electric

Function	Quote	Type of actor	Year
KDD	'*We push each other towards solutions. It is more competition than it is cooperation.*'	Technology supplier 2	2017
	We need input from those who are actually on-board and see things and components in operation.'	Ship-owner 3	2017
IDS	*I think the smaller ships operating near the coast will come first, and then the larger will come eventually.*'	Technology specific interest group 1	2018
	'*I think that what was done at Lavik–Oppedal opened up the door for the rest of us to follow*' (PA4, 2017).	Public administration 4	2017
EE	'*It is often ship-owners who have some philosophies in the company that they are going to build new ships at certain time intervals to keep the technology up to date. There are some who do. These ship-owners are often working on-board the ships themselves, as engineers or captains.*'	Technology supplier 9	2018
	'*Right now most ship-owners are quite traditional in their mindset, so for now we have not met anyone who has said "yes, we want a performance agreement", but it is certainly those ship-owners that have their business set up in that way that makes this interesting.*'	Technology supplier 8	2018
MF	'*Previously, Statoil [now Equinor] paid for the fuel, and then there were no incentives for the ship-owners to introduce innovations, because the cost were already covered – but that has changed now.*'	Technology supplier 5	2017
	'*When it comes to energy-economic solutions and such, it is clear that it [wind farm supply ships] is basically a green industry. Therefore, they cannot allow anyone to see that they have not invested in technology that reduces fuel consumption.*'	Ship designer 1	2017
	'*The financial incentives the state provides is often directed to the ship-owner or cargo holder, but the shipyard does not benefit from that. The ship-owner does not have to pay a CO2 fee, so there is no reward for us, but we are taking a very high risk and it is difficult to protect patents, technology and get financial loans.*'	Shipyard 2	2017
LEG	*I think it is very important that one has seen what we actually get out of this. Suppliers are following because they have been shown that it is possible. That would not have happened if someone had not gone ahead and shown that it is actually possible*' (PSA1, 2017).	Public support agency	2017
	The Norwegian Maritime Authority has tried to find its own way of approaching this, within what makes sense to test so that you can make sure that safety is regarded when installing the systems. Also, it has not been necessary to wait and get a "no" right at the end, but we had a close dialogue along the way, which we find very positive.'	Technology supplier 2	2017
RM	'*A catalyst system that is relatively inexpensive and relatively mature, and has a low sustainability index, gets the lowest support rate. Full electrification, with battery or hydrogen technology, gets the highest support rate.*'	The NOx-fund	2017
	'*It is simply too demanding for us to apply to other funds than the NOx-fund. […] It is demanding to write the applications, to document our costs and to claim them back. The NOx-fund is much more standardized on what we are doing.*'	Ship-owner 7	2017
	We have employed persons with a background in power supply technology, who had competence we were lacking. And then those already employed who were keen on these new things have taken a step up.'	Technology supplier 5	2017
PE	*Someone has to take the overall control over this. It cannot be up to each port. We have flagged a lot for this and talked about that it is time for a port version of Avinor.*'	Industry association 3	2017
	'*All hydrogen ships will have batteries on-board, and the lighter these are, the better the total system becomes, and the easier it becomes to outcompete diesel. […] I think that the total solutions which are good enough to outcompete diesel are the ones that open up possibilities, and the development of batteries is positive for those total solutions, and also that fuel cells are developing.*'	R&D 4	2017

Hydrogen

Function	Quote	Type of actor	Year
KDD	'*We need a concrete project where we can learn more hands-on and get our hands dirty*'	Technology supplier 3	2017

	'From our project partners, we have probably received such good advice along the way that we have come faster towards what we think is a good solution.'	Shipyard 4	2018
IDS	*'The thing about hydrogen is that it allows electrical propulsion for all ships instead of just those on short routes or where you have charging infrastructure, etc. With hydrogen, you have the possibility for zero emissions on all vessels.'*	R&D 4	2017
	Batteries have obvious limitations, so we cannot only rely on BE technology for the green transition. We need other energy carriers as well, and hydrogen is coming, slowly but surely.'	Technology specific interest group 1	2018
	High-speed ferries is a much tougher case than [normal] ferries, but at the same time it is more difficult to do it with only BE propulsion and therefore it is very interesting with hydrogen technology.'	R&D 4	2017
EE	*'There are many types of fuel cell technology, but there is not one solution. There are various technologies that have their advantages and disadvantages.'*	Technology supplier 3	2017
	'In less than ten months we are supposed to commit to operating this ferry for ten years, without being able to develop the suppliers' competencies or the technology that will be on-board the ships. We think it is going too fast.'	Ship-owner 7	2017
MF	*'There is no use in producing hydrogen before there is a market. So, it is a bit like the chicken and the egg, but shipping could be a good addition to the market since it could be a rather large consumer of hydrogen.'*	R&D 4	2017
	'Previously, it was like we were the only ones saying it made sense with fuel cells, but now, suddenly, there are many interested. Wärtsilä has had to turn around and do things, which shows how important public purchasing power is.'	R&D 4	2017
LEG	*'She [prime minister Erna Solberg] believes in hydrogen, and she has shown examples of hydrogen ship projects in presentations, so they are keeping up and have faith in this.'*	Shipyard 4	2018
RM	*'Innovation Norway does not always have very good finances in their projects, and that is hampering us a bit. […] and I think that leads to [a situation] that when there is focus on impact, it is often the largest actors that gets funding. It is more difficult for smaller actors to try out technology at a larger scale.'*	R&D 4	2017
	'The operators have also communicated that they could be interested in being a co-owner, so that they have some control over the production. For example, the company who wins the development contract from the Norwegian Public Roads Administration.'	Fuel Producer 2	2017
	'There is a lot that we do not know now, but we have put together a lot of different technologies before, we are used to that. […] Now and then, we need support from the research environment which has the right competences.'	Ship Designer 1	2017
PE	*Everyone sees Ampere as very positive and that that is the reason that all these new ferries coming now are built with batteries. It [development contracts] is a strategy to bring out new technology and keep Norway's world leading knowledge, and as it is believed that batteries cannot cover all the needs, the next step is to take the same role for hydrogen.'*	R&D 4	2017
	We are working on two tracks. One is whether we ourselves should become an energy supplier and produce our own hydrogen. That is one way to go. Another way is to find the big actors within the energy sector. Large oil companies already claim that they want to enter the hydrogen market.'	Ship-owner 7	2017

Appendix 2. Exemplary interview guide

Notes:

- Semi-structured
- Bullet-points intended as pointers
- Original interview guide in Norwegian
- Tailored to different actors (e.g. technology developers, ship-owners, industry associations, R&D)

Purpose of interview

- Short presentation round, project info and interview background
- Clarification recording, anonymity, quote.

Short intro (informant)

- Background: informant and business
- What role in the business does the informant have, background?
- Business brief: location, size, turnover, products/services, market.
- Status of activities within the TIS

Search processes, motivation/incentive

- Motivation for entering the field/domain/activity?
- External factors, e.g.
  - o Politically driven?
  - o External expectations?
  - o Customer demand?
- Internal factors, e.g.
  - o Advantages (competences)

- o Economically motivated (winning tenders, savings etc)
- o “Green” motives
- How did you get into X?
  - o Via R&D, demo/pilot, or 'straight to' procurement?
  - o With others?
- When did you start considering the new technology, and when seriously?

Technology and knowledge

- How do you assess which (new) technologies/solutions you are investing in?
  - o Long term?
  - o Short term?
- What knowledge is required for this?
- Who do you work/collaborate with?
  - o If what, how/in what way?
- How quickly does technology X develop in terms of price and performance?
- What knowledge is needed to implement/apply new technology?
  - o How to develop /access knowledge/skills that are lacking?
- What are your expectations for further technology development?

Low- and zero-emission technologies

- How do you see the competition between different zero-/low-emission solutions?
  - o Pros/cons of the different technologies?
- Are they in competition or can they be complementary (incl. with conventional technology)?
- Do you envision different solutions/technologies for different segments (within shipping)?
- Have you used or tried to access support instruments for low- or zero-emission technology?
  - o Which?
  - o What/how do these contribute?
- What is good/less good about instruments?
  - o What is missing and why?
  - o Do you have an overview of relevant support instruments?
- What new products and services do you see emerging within this (technological) area?
- In what areas do you see the potential for introducing new business models?

Legitimation

- What laws/regulations affect the area?
  - o Are these adapted to uses, needs, requirements?
  - o Is the development/uptake hindered by legislation /regulations in any way?
- Are there standards for the technology/ies, products?
  - o Are standards needed?
- Do you do anything active to influence legislation/regulation/instruments and the like?
- Do you attend workshops, seminars and the like?
  - o Any benefits?

Market formation

- Who are your customers?
- Do you have different customers in different segments?
  - o What are their buying incentives?
  - o Competition?
- Who are your suppliers?
  - o Several?
- What kinds of relationships do you have with your customers and suppliers?
  - o Cooperation? In what ways?
- Describe the buying process
  - o Tender?
  - o Long processes?
  - o Complexity?
- Use of new energy technology/fuel – does that change…

o Supplier Relationships?
o Business model?
- What expectations do you have for future market developments?

Resource mobilization

- How is development/implementation of new energy solutions financed?
  o Challenges related to financing?
- What infrastructure is needed for you to use new energy solutions (e.g. battery electric, hydrogen, biofuels)
  o Demonstration or pilot plant?
  o Production plants?
  o Logistics system for distribution and filling/making available?
- Is there anything that hinders infrastructure development?
  o What drives/prevents it from being built?
- New energy solutions - does it require new skills/knowledge, for example by hiring new employees with specialized expertise?
  o Is this available?

Success criteria and barriers

- What are the critical criteria for success?
  o Technology, resources, policy support, market
- Circumstances that make you consider abandoning X?
- How about the sector /TIS as a whole?
- What are the biggest uncertainties?
  o Why and what are these?
  o How do you handle these uncertainties?
  o Technology, market, other?

Final questions (wrapping up)

- How do you view the long-term development of shipping and what role will you have?
  o What will be the role of technology X?
- Norwegian maritime industry has ambition for significant emission cuts in the years to come - What do you think it will take to make this happen?
- If you were to advise those who develop and implement regulations and legislation and (in part) can directly influence the framework conditions - what would your main message(s) be?
- Is there something we haven't touched upon that you think is important for the success of green transformation in maritime transport?
- Is it ok if we contact you later for a follow-up interview, workshop, etc.

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