Greening the fleet: A technological innovation system (TIS) analysis of hydrogen, battery electric, liquefied biogas, and biodiesel in the maritime sector

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ABSTRACT

The maritime shipping sector (MSS) is coming under increasing pressure to reduce its greenhouse gas (GHG) emissions. For Norway, emission reductions in the MSS are furthermore crucial for meeting the national 40% emission reduction obligations in accordance with EU and the Paris agreements. Using a technological innovation systems (TIS) approach, this report analyses four low- and zero-carbon (LoZeC) energy solutions (biodiesel, liquefied biogas, hydrogen, battery electric (BE) storage) that can replace or supplement fossil fuels in the MSS. Based upon this analysis the report provides both general and technology-specific policy recommendations.

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Executive summary

The maritime shipping sector (hereafter abbreviated as MSS) is coming under increasing pressure to reduce its greenhouse gas (GHG) emissions. For Norway, emission reductions in the MSS are furthermore crucial for meeting its 40% emission reduction obligations in accordance with EU and the Paris agreements. This report analyses four low- and zero-carbon (LoZeC) energy solutions (biodiesel, liquefied biogas, hydrogen, battery electric (BE) storage) that can replace or supplement fossil fuels in the MSS.

The report is an outcome of WP1 (technological innovation systems (TIS) analysis) in the research project 'Greening the fleet – Sustainability transitions in the maritime shipping sector' (GREENFLEET). The overall aim of the project is to analyse the systemic, contextual and actor-level drivers and barriers affecting a transition from fossil-based energy technologies to LoZeC technologies in the Norwegian MSS. In this report we assess the status and development of the four LoZeC TISs through TIS structural and functional analysis. The structural analysis describes the actors, networks and institutions shaping the development of different technologies, including battery electric storage. The functional analysis assesses the performance of the four TISs in terms of key functions or processes that are seen as crucial for technological development and diffusion.

Our findings reveal that development and implementation of the four LoZeC energy solutions share the same drivers to some extent. National and international climate policies and emission targets have directed attention to alternative energy solutions also in maritime transport and ship technologies, and have clearly influenced the direction of research, as indicated by Norway's frontrunner position within sustainable shipping. Furthermore, knowledge development and diffusion of all technologies takes place within national and local knowledge networks, as well as through participation in EU-funded research and development (R&D) projects.

Especially BE technology within the Norwegian MSS has developed rapidly in the last five years and has already achieved high legitimacy (particularly within the ferry segment). Strong resource mobilization with available funding from several public institutions, as well as investments by shipowners, have enabled experimentation with technology applications and business models. Maritime applications of hydrogen technology are beginning to emerge and are currently imbued with expectations regarding their maritime application. Both Statens Vegvesen's development contract for a new hydrogen road ferry and Trøndelag County Municipality's development contract for a high-speed ferry will contribute to increased entrepreneurial experimentation as well as knowledge development and diffusion, which in turn will increase legitimacy and spark the currently non-existing market formation.

The maritime use of biodiesel and LBG (liquefied biogas) is currently very limited. The development of the biodiesel TIS has stagnated during the last years and the fuel is mainly seen as a temporary solution. Given the rapid development of other LoZeC technologies, the future maritime use of biodiesel (especially based on current technologies and biomass feedstock) in Norway appears to be uncertain. Following public funding support, LBG – which is interchangeable with LNG (liquefied natural gas) – has recently been introduced into the maritime fuel market. Influence from the more mature LNG and LBG for heavy road transport TISs creates spillover effects from entrepreneurial experimentation and both knowledge development and diffusion in technology

development and production of LBG, which in turn may have a positive influence on the legitimacy of LBG in the maritime sector. The greatest weakness of the LBG TIS is the limited fuel availability, and there is an urgent need for development of sustainable production of biogas in Norway.

For future policy implementation, it is important to acknowledge that the respective LoZeC technologies have advantages and disadvantages that make them suitable for different segments within the Norwegian MSS. Clear political goals and public funding possibilities are vital for shipowners, ship designers and shipyards to invest in LoZeC technology. Additionally, continuous development and updating of the regulatory framework for the new LoZeC technologies is crucial to achieve legitimacy. Through implementation of our suggested policy measures, the Norwegian MSS has excellent possibilities to transition into LoZeC technologies and achieve a green fleet.

Table of contents

1 Introduction

This report is an output from the research project 'Greening the fleet – Sustainability transitions in the maritime shipping sector' (GREENFLEET). **The primary objective of GREENFLEET is to analyse the systemic, contextual and actor-level drivers and barriers affecting a transition from fossil-based energy technologies to low- and zero-carbon (LoZeC) technologies in the Norwegian maritime shipping sector** (hereafter abbreviated as MSS). The empirical scope of the GREENFLEET project, and therefore also this report, is Norwegian coastal maritime transport.

GREENFLEET is financed for the period 2017–2020 by the Research Council of Norway through the ENERGIX programme, with co-financing from Kystverket (Norwegian Coastal Administration). Research partners include SINTEF Digital, Department of Technology Management (project owner and management); NTNU, Department of Industrial Economics and Technology Management; University of Oslo, TIK Centre for Technology, Innovation and Culture; Lund University, Department of Human Geography; and Chalmers University of Technology, Department of Technology Management and Economics. User partners include Kystverket (the Norwegian Coastal Administration), NCE Maritime CleanTech (a cluster organization), the Maritime Branch of Norsk Industri (Federation of Norwegian Industries), Norges Rederiforbund (Norwegian Shipowners Association), DNV GL (Maritime classification society), Statens vegvesen (Norwegian Public Roads Administration), Sjøfartsdirektoratet (Norwegian Maritime Authority), Enova (a state agency for new energy solutions), and Bellona (an NGO for sustainable climate solutions).

Maritime transport is arguably a neglected empirical field within sustainability transitions research, despite the global importance of reducing greenhouse gas (GHG) emissions and other pollutants from this sector. Accordingly, this report contributes to filling an important research gap. More specifically, the aim of this report is to present the main findings from GREENFLEET WP1 (technological innovation system (TIS) analysis). In brief, the purpose of a TIS analysis is to assess the strengths and weaknesses associated with particular technologies – in this case a set of pre-defined energy technologies that may contribute to improving the environmental footprint of shipping. Similar to many other sectors, maritime transport is facing a transition with the introduction of several types of LoZeC fuels and energy carriers that can replace fossil fuels. In this report we focus on four such alternative energy solutions (fuels and energy carriers): battery electric (BE), hydrogen, biodiesel, and liquefied biogas (LBG).

The new energy solutions can all be seen as 'niche technologies'. Their further development and implementation will require adaptation of existing new infrastructure and development of new infrastructure and new value chains, as well as changes in regulations and institutions. Furthermore, the speed and scale of any sustainability transitions in shipping will be contingent on the ability and willingness of existing industry to experiment with and invest in new solutions.

1.1 Maritime transport and Norway's emission reduction targets

In order for Norway to meet its obligations in terms of GHG emission reductions in accordance with EU strategies and the Paris Agreement (30% by 2020, 40% by 2030, and 80–95% by 2050, all compared with 1990), substantial reductions need to be made in the sectors that are not covered by the EU Emissions Trading Scheme (EU ETS),[1] which includes both road and maritime transport. Norway has committed to a 40% reduction in GHG emissions by 2030 (Klima- og miljødepartementet, 2015). As shown in Figure 1, CO_2 emissions in Norway have increased since 1990, but the increases have been counterbalanced by reductions in other emission types. Hence, total emissions in Norway have remained stable and have not declined.

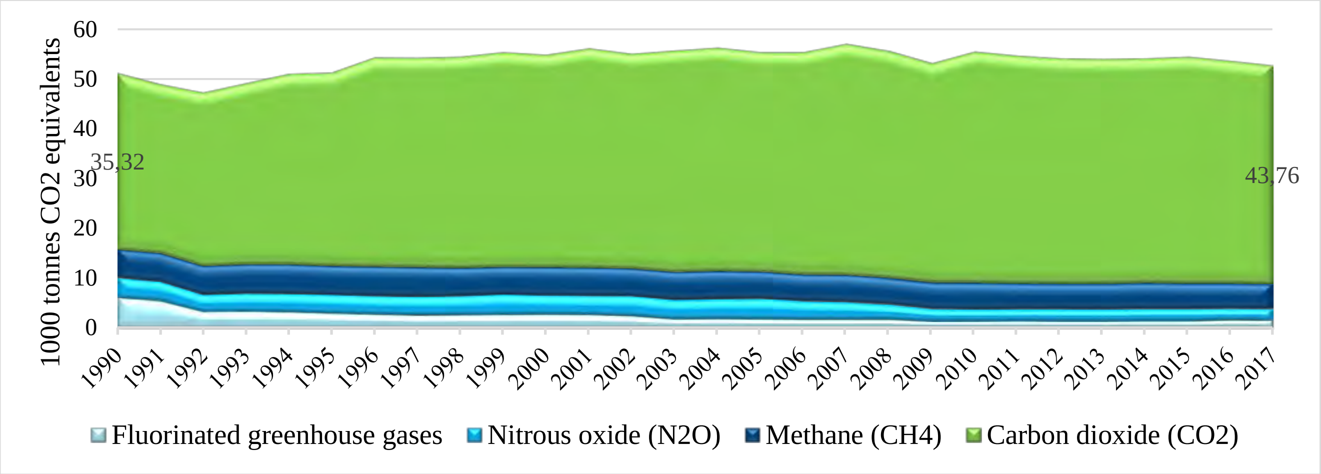

Figure 1 Greenhouse gas emissions in Norway 1990–2017 by gas type. Source: Miljødirektoratet (2019b)

To date, the majority of emission reductions from transport in Norway have been in the personal vehicle segment of land-based transport, due especially to various incentives to stimulate the introduction of battery electric vehicles (BEVs). However, GHG emission reductions in maritime transport will also be needed for Norway to meet its obligations. Shipping in domestic waters accounts for c.10% of GHG emissions in Norway (Mellbye et al., 2016). The development and implementation of new LoZeC energy solutions is seen as key to reducing emissions from shipping. The current Government’s maritime strategy emphasizes the need for research and development (R&D), pilot and demonstration projects, and commercialization of new solutions in order to achieve emission reductions (Nærings- og fiskeridepartmentet, 2015). The most recent White Paper on Norway’s climate strategy defines shipping as a prioritized area for emission reductions (Meld. St. 41 (2016–2017)). Several initiatives and policy instruments have been introduced to stimulate a technological shift, including changes in public procurement of passenger and road ferry services. As shown in Figure 2, shipping in Norwegian waters in 2018 accounted for an accumulated 7977 tonnes of CO_2, with passenger, fishing, offshore supply, and general cargo as the four largest shipping segments.

Figure 3 shows that emissions from the maritime sector (shipping and fishing) represent a substantial share of GHG emissions from domestic transport in Norway (18,7% in 2017, whereas the EU average in 2015 was 13% (European Commission, n.d.)). Additionally, Figure 3 shows that emissions from maritime transport declined between 2012 and 2017, and according to the Norwegian Environment Agency this was ‘*probably a result of lower activity levels for offshore supply ships, the transition to less emission-intensive fuels, and use of new technology. The decline*

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[1] Sectors covered by EU ETS are energy-intensive industries, petroleum and aviation, whereas sectors not covered include agriculture, transport, heating, and waste.

can also be a result of a higher share of ships bunkering abroad' (Miljødirektoratet, 2019a, our translation).

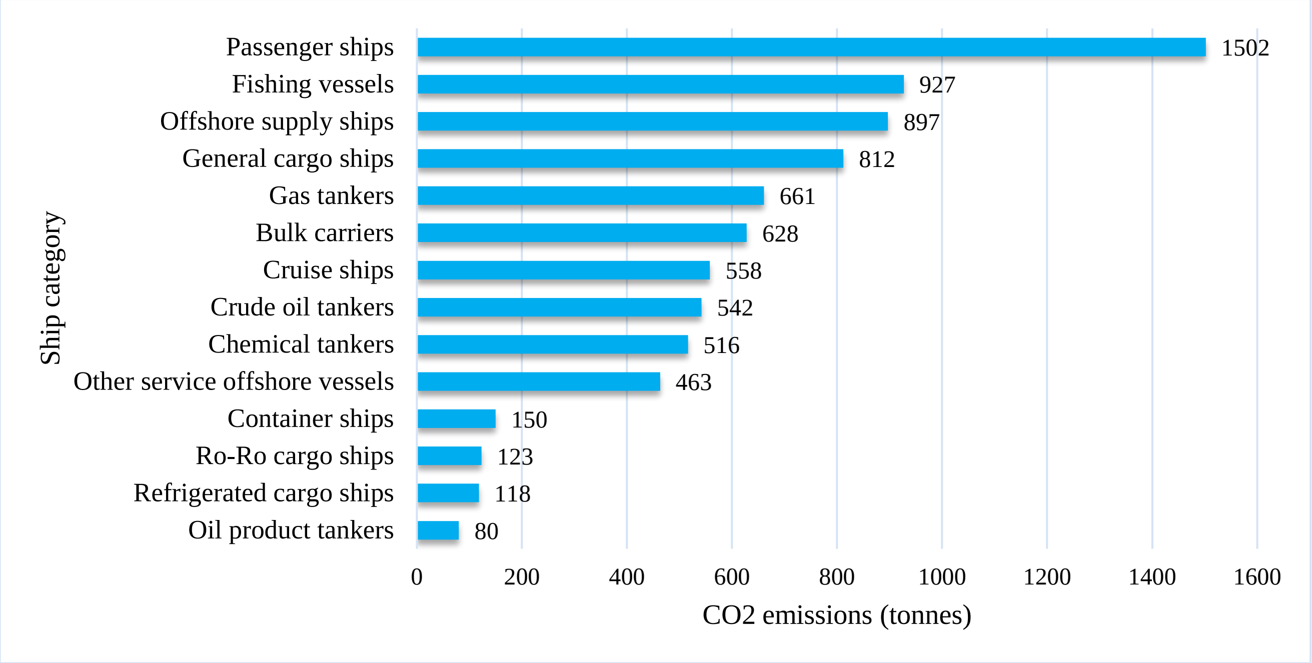

Figure 2 CO_2 emissions from ships in Norwegian waters, 2018. Source: Kystverket/Havdata[2]

Globally, shipping accounts for c.3% of CO_2 emissions, but unless new technologies are introduced this share is expected to increase in coming years as a result of economic growth and increases in global trade (IMO, 2015). Although shipping is the most environmentally and energy efficient form of transport, it is important that new LoZeC energy solutions are developed and implemented also in this sector. Therefore, also the maritime sector beyond Norway is challenged in terms of its environmental sustainability. In recent years, stricter environmental regulations have been introduced in international shipping. The most important regulations are those established by International Convention for the Prevention of Pollution from Ships (International Convention for the Prevention of Pollution from Ships), prepared by the International Maritime Organization (IMO), but the sector is also subject to EU regulations and other regulations. However, current international regulations are not in line with the scale of emission reductions that are needed in order to meet the 2 degrees Celsius target set by the Paris Agreement in 2015 and therefore more stringent regulations are expected in the years ahead. In April 2018, the IMO adopted an initial strategy to '*reduce GHG emissions from international shipping, and phase them out, as soon as possibly in this century*'(IMO, 2018). More specifically, and in order to be consistent with the Paris Agreement temperature goals, the IMO (2018) aims to '*reduce total annual GHG emissions by at least 50% by 2050 compared to 2008.*'

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[2] As of early July 2019, the data were not publicly available.

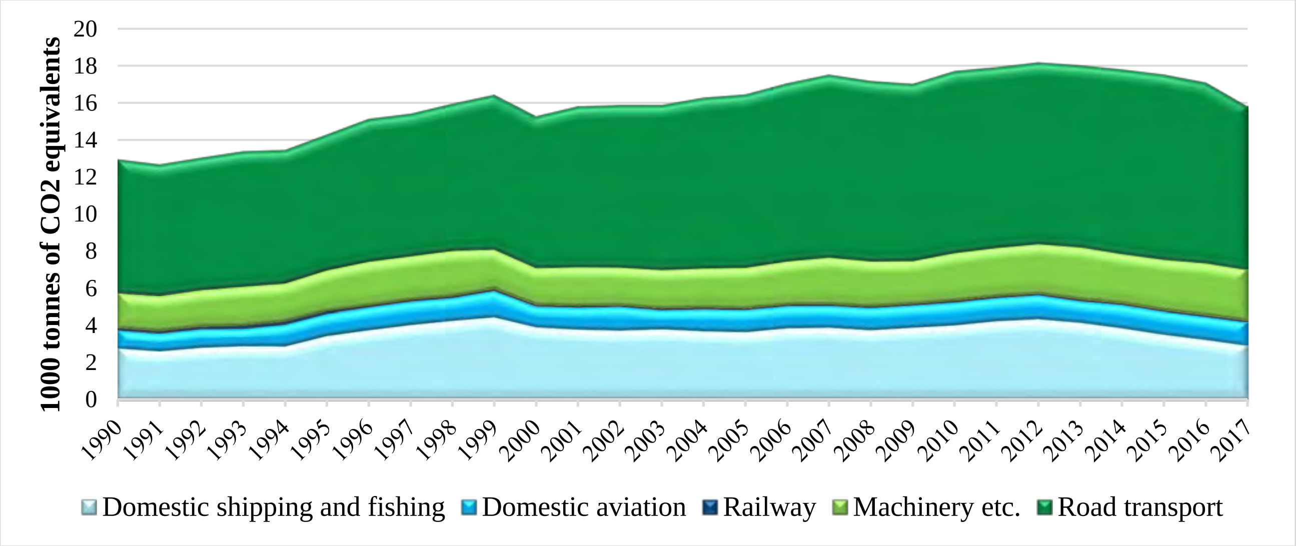

Figure 3 Greenhouse gas emissions from transport in Norway, 1990–2017. Source: Miljødirektoratet (2019a)[3]

According to the most recent outlook report by the Norwegian Shipowners Association (Rederiforbundet, 2019, 7), '*shipping is the most energy efficient means of transporting goods, but it nevertheless constitutes a major source of greenhouse gas emissions. […] The Norwegian maritime industry is uniquely positioned to meet this challenge.*' The maritime sector is one of Norway's strongest and most dynamic industries, covering the entire value chain from research, technological development and design to shipbuilding, equipment, control systems, operations, and knowledge-intensive services (Reve and Sasson, 2012). Norway is currently seen as a pioneer in terms of development and especially the implementation of low- and zero-carbon energy solutions for shipping. As such, the development and implementation of new technological solutions for short sea and coastal shipping in Norway may provide opportunities for exports of products and services to an expected growing global market demand for 'green solutions'.

1.2 Green energy solutions for maritime transport

To date, incremental innovations in the design and engineering of maritime vessels and equipment has contributed to energy efficiency gains (Rusten, 2010), but most ships still run on fossil fuels (diesel or crude oil), as they have done for more than a century (Geels, 2002, Endresen et al., 2007). The implementation of LoZeC energy solutions – including battery electric storage systems, biofuels, hydrogen, fuel cells, and various hybrids of these and/or conventional fuels and technologies – would enable the maritime shipping sector (MSS) to maintain its various functions while achieving decarbonization. However, LoZeC technologies currently play minimal roles in the MSS, provide different environmental benefits and their application faces different challenges (e.g. availability, technological development, investment costs) that need to be overcome in order for them to compete with conventional fuels. These challenges relate to different factors, such as stage

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[3] Data on GHG emissions from shipping have several shortcomings and limitations (e.g. see https://energiogklima.no/blogg/utslippene-fra-skipsfarten-er-bade-lavest-og-hoyest-pa-seks-ar/). The main issue is that emissions are calculated on the basis of domestic fuel sales (in Norway). Therefore, fuels that are purchased abroad but used domestically are not included.

of technological development, ‘fit’ with existing solutions and infrastructure, and need for, for example, large-scale investments in fuel production.

In this report we focus on the four LoZeCs that have been classified as most relevant for domestic shipping in Norway: battery electric (BE), hydrogen, liquefied biogas (LBG), and biodiesel (DNV GL, 2015). Liquefied natural gas (LNG) has not been included (as a focal technology) because it is a fossil fuel, although its use can reduce CO_2 emissions by c.20% compared with conventional fuels. Furthermore, it is important to note that the various LoZeCs can be seen as competitive or complementary, as is typical for technologies (Sandén and Hillman, 2011). BE systems can, for example, be full or hybrid. A full BE system can be seen as competitive with all other energy solutions, whereas hybrid BE systems complement all other solutions. Similarly, the use of both LBG and biodiesel now and in the foreseeable future appears to be as an add-on to conventional fossil fuels, due to the limited production capacities of biofuels.

Table 1 Evaluation of fuel alternatives (current status) compared with conventional marine diesel. Sources: Nærings- og fiskeridepartmentet (2015), DNV GL (2015), Dahl et al. (2013), Steen (2018))

	Biogas[b]	Biodiesel[b]	Electric (full)	Electric (hybrid)[c]	Hydrogen[d]
Reduction of GHGs[a]	High	High	Very high	Moderate–High	Very high
Reduction of NO_x[a]	High	Low	Very high	Moderate	Very high
Reduction of SO_x[a]	Very high	Very high	Very high	Moderate	Very high
Investment cost (on vessels)	Low[e]	Low	High	Moderate–High	High
Fuel cost	High	High	Low	Moderate	High
Availability (including infrastructure)	Low	Low	Moderate	Moderate	Low
Vessel adaptation	Low	Very low	Very high	Low–Moderate	High
Infrastructure adaptation (including fuel production and energy conversion)	High		Moderate–High	Low–High	Very high
Market segment suitability	All	All	Vessels – short routes (e.g. ferries)	All – especially variable energy demand	All
Importance of regularity[f]	Low	Low	High	Low–high	Low

[a] Environmental benefits of electric power (battery) and hydrogen depend on the source of electricity used

[b] Environmental benefits of biogas and biodiesel (and other biofuels) depend to large extent on the source of the biomass

[c] Electric hybrid refers to a combination of, for example, a conventional (fossil-fuelled) engine and a BE propulsion system

[d] Hydrogen produced by electrolysis from renewable energy source

[e] Provided dual-fuel/LNG engine, i.e. engines that can run on both gaseous and liquid fuels.

[f] Also contingent on fuel or energy availability

Biodiesel is produced from organic waste from agriculture, forestry or agriculture, as well as from designated energy crops. Biodiesel is compatible with conventional marine diesel engines and can therefore be used as a drop-in fuel, even if engine performance may be affected for parameters such as efficiency and brake power (Mohd Noor et al., 2018). Similar to biodiesel, *biogas* can also be produced from multiple forms of organic waste, including organic household waste and sewage sludge. Following liquefaction, *liquefied biogas* (LBG) is fully interchangeable with liquefied natural gas (LNG) and can be used in the same engines. Ships with *BE* solutions can be fully electric, thereby requiring charging infrastructures in harbours, which are connected to the electricity grid. Alternatively, ships may have a *hybrid* system and be equipped with other engines, too, such as conventional diesel engines, which can then be used for charging the batteries. *Hydrogen* can be produced in multiple ways, but today most hydrogen is produced from natural gas. Hydrogen from natural gas is labelled grey (without carbon capture and storage) or blue (with carbon capture and storage). By contrast, green hydrogen refers to hydrogen produced from water using renewable energy. The use of hydrogen for propulsion of ships relies on the use of fuel cells, such as proton exchange membrane fuel cells or solid oxide fuel cells, which convert hydrogen fuel into electricity (Tronstad et al., 2017). It should be noted that all technologies also exist in hybrid versions, wherein they are combined with each other or with conventional fossil fuel-based propulsion technologies.

Table 1 shows that the LoZeC solutions differ not only in terms of environmental benefits, investments costs and so forth, but also in the extent to which they ‘fit’ the needs within particular market segments within maritime transport. The two main factors are vessel size and operational patterns. This mirrors how the MSS is a mature and multisegmented sector that, similar to road transport, is highly heterogeneous in that it includes vessels ranging from massive intercontinental freight and bulk carriers to small passenger vessels. In an assessment of various policy instruments to promote more environmentally friendly fuels and energy carries in maritime transport, DNV GL (2015) distinguishes 273 different vessel segments based on type of ship, ship size, and time spent in domestic waters.

Different ships and vessels vary considerably in their size and operational patterns, they have different types of owners and customers, and they are part of or linked to different sectors and value chains. The conditions for implementing new energy solutions thus vary substantially within maritime shipping (Bergek et al., 2018). In addition, substantial parts of the Norwegian shipping fleet operate primarily in international waters or in traffic between Norway and Europe. With regard to technology implementation, this report focuses on the part of the Norwegian fleet that primarily operates in domestic and near-shore or coastal waters. The dominant vessel types are freight ships, fishing vessels, passenger vessels, and offshore supply vessels.

1.3 Technological innovation systems

A sustainability transition in maritime transport hinges on two main interrelated mechanisms. First, new LoZeC technologies need to be developed in order to constitute realistic alternatives to conventional fossil fuels. Second, the maritime shipping sector needs to start implementing these new energy solutions. In recent years, we have seen many examples of these two mechanisms working in tandem. A well-known example from the Norwegian maritime sector is the BE road ferry Ampere, which began operating on the Lavik–Oppedal route in Sogn og Fjordane county in 2015.

This report focuses on the first of the above-described two mechanisms (i.e. the development of new energy solutions), albeit also paying attention to the second mechanisms (i.e. in terms of market demand for new solutions). We employed the TIS functions approach (Bergek et al., 2008) in our analysis. The TIS framework is one of the main approaches used in the field of sustainability transitions research, where it is most often applied to analyse the early development phases of, for example, new renewable energy technologies (Markard et al., 2012, Bergek et al., 2015).

Most innovations require considerable time to adapt to conditions in user sectors. Environmental innovations have the added challenge that whereas risks and costs are borne by the innovators, the benefits (e.g. less pollution) are reaped by society. This reduces incentives for firms to invest in environmental innovation (Beise and Rennings, 2005). Green technologies therefore require policy interventions in the form of, for example, pilot studies or demonstration programmes, subsidized markets, and R&D support that give them opportunities to develop and compete with existing technologies (Smith and Raven, 2012). Moreover, technological innovation systems have to form around new energy technologies in order for them to develop and diffuse successfully, especially in early phases of development (Jacobsson and Johnson, 2000). The successful introduction of LoZeC energy solutions in the MSS will require, for example, the development of new value chains or adaptation of existing value chains, infrastructures, business models, and regulations.

The TIS approach emphasizes inter-organizational interaction spanning public and private sectors, knowledge creation and dissemination, and the establishment of infrastructure and institutions[4]. A first step in TIS research is to map the actors, networks and institutions associated with a particular focal TIS (e.g. the hydrogen TIS). Emerging TISs often face challenges, which can be identified as system weaknesses. These challenges in technology development and diffusion can be identified by studying key processes or functions in an emerging TIS (Bergek et al., 2008). Such functions are (with key aspects) listed in Table 2.

By identifying *system weaknesses* (e.g. lack of market formation) and *system strengths*, TIS analysis provides the basis for policy recommendations and interventions (see Section 4.5). Such recommendations can leverage on system strengths (Hellsmark et al., 2016), such as firm innovative capabilities or proactive public procurement policies. TIS analyses generally highlight the need for a portfolio of policy instruments, rather than assuming that single policies will suffice to develop and diffuse technologies.

Table 2 TIS functions. Adapted from Bergek et al. (2008)

Function	Description
Knowledge development and diffusion	Broadening and deepening of the knowledge base of a TIS, sharing of knowledge between actors within the system and new combinations of knowledge as a result of these processes
Entrepreneurial experimentation	Problem-solving and uncertainty reduction through real-world trial-and-error experiments at different scales and with new technologies, applications and strategies

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[4] Institutions are commonly described as the rules of the game and they comprise formal (e.g rules and laws) and informal (e.g. norms and habits) '*humanly devised constraints that shape human interaction*' (NORTH, D. C. 1992. Institutions, Ideology, and Economic-Performance. *Cato Journal*, 11**,** 477-488.

Function	Description
Market formation	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 articulation of demand and preferences, product positioning, standard setting, and development of rules of exchange
Influence on the direction of search	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	The system's acquisition of different types of resources 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	The process of gaining regulative, normative and cognitive legitimacy for the new technology, its proponents and the TIS 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	The creation of system-level utilities (or resources), such as pooled labour markets, complementary technologies and specialized suppliers, which are available also to system actors that did not contribute to building them up

1.4 Methods and data

This report is based on a mixed-methods research design, reflecting the diverse data requirements for conducting a TIS functions analysis (Bergek et al., 2008). The main source of data for this report is interview data produced through semi-structured interviews in the period 2015–2019. In total, the analysis in this report is based on c.70 interviews held mainly with senior-level managers in various companies (e.g. shipowners, shipyards, ship designers, technology suppliers, and fuel producers), public agencies, interest organizations, research institutes, universities, and non-governmental organizations (see Appendix A.3). Most interviews were conducted by at least two researchers and lasted 60 minutes on average. In this report, references to interviews are given by the following abbreviations: NGO (NGO), industry association (IA), classification society (C), public authority (PA), shipyard (SY), public support agency (PSA), R&D (R&D), technology supplier (TS), shipowner (SO), fuel producer (FP), cluster organization (CO), ship design (SD), technology-specific interest group (TIG), and other (O).

The following GREENFLEET project team members were involved in interviews for this report:

Anna Bergek (Chalmers University of Technology), Øyvind Bjørgum (NTNU), Jens Hanson (UiO), Teis Hansen (Lund University), Assiya Kenzhegaliyeva (SINTEF), Tuukka Mäkitie (UiO), Lone Slettbak Ramstad (SINTEF), Markus Steen (SINTEF), Tyson Weaver (NTNU), and Olav Wicken (UiO).

In addition to interview data, the report is based on the following data sources:

- Literature review and document studies: including other research articles, industry reports, government documents media, web pages
- Patent analysis: national (Norwegian) data from the European Patent Office's comprehensive PATSTAT (Heiberg, 2017b).
- Bibliographical analysis: data obtained from the Science Citation Index Expanded (SCIE) database available through ISI Web of Knowledge (Heiberg, 2017a).
- Research data: data from the CORDIS database, which contains all EU-funded R&D projects (including FP5 (1998–2002), FP6 (2002–2006), FP7 (2007–2013), and H2020 (2014–2020) (Tsouri, 2018)
- Data on financial support awarded by support agencies (e.g. Enova, Innovasjon Norge), obtained from publicly available websites and via personal communication.
- Events: we have participated in various events hosted by, for example, Enova, ZERO, SINTEF Energy, and the Maritime Battery Forum.
- As part of the project, we organized several project workshops with GREENFLEET user partners and external actors. At these events, research designs and preliminary findings were presented and discussed, and user partners and external partners also gave presentations.

Conducting research on ongoing innovation and development processes can be challenging. However, our substantial interview data (triangulated with other data sources) over a period stretching more than four years provide detailed insights into why, for example, some technologies gain momentum whereas others do not. Workshops with project user partners helped us keep track of important developments in the maritime sector, including less visible ones, and were very useful for discussing interpretations of findings with industry (both private and public actors) insiders. In assessing the level of development of TIS functions (Section 3), the authors have triangulated data and arrived at a consensus, scoring each function on a three-point ordinal scale from weak to intermediate to strong. Finally, it should be noted that our data on the BE TIS are more comprehensive than on the other TISs, which merely reflects differences in the momentum (experiments, pilots, commercial application) of the BE TIS in the Norwegian MSS to date.

1.5 Structure of report

In line with the TIS framework, the report is structured as follows. In the next section (Section 2) we present the structural analysis, including descriptions of value chains, actors, networks, and institutions, and we provide an assessment of the different technologies in terms of their development phase. Section 3 comprises the TIS functions analysis, which is structured by function rather than by TIS. Section 4 provides a summary assessment of the TIS functions analysis, and Section 5 provides policy recommendations.

2 Structural analysis

This section explains the structural components of the four TISs: value chains, central actors and networks for the respective technologies, as well as institutions shaping the Norwegian MSS. It also describes the Norwegian position in the global sustainable shipping context and Norwegian actors' participation in EU-funded R&D programmes. The purpose of the structural analysis is to identify the components that define the way the TISs function and describe the actors involved, which in turn provides the foundation for the subsequent functional analysis.

In this report, and in line with TIS analysis, the term 'actors' refers to individuals or organizations, and the term 'institutions' relates to rules and regulations as well as informal aspects (such as social norms) that shape the 'rules of the game' for the TIS. The value chains for the respective technologies refer to the different stages of production of fuels and energy carriers, and identify the different actors involved in different value chain segments. Regional, national and international networks are important for the development and sharing of knowledge between involved actors, which is of central importance for innovation and technological development. By looking, for example, at participation in EU-funded R&D projects, it is possible to identify central actors and their connections with each other.

2.1 Value chains

The Norwegian maritime industry is strong and covers the entire shipping value chain and ship building, from suppliers of technical components to ship designers, shipyards and shipowners. In this section we describe the value chains for the TIS that constitute the upstream part of a LoZeC energy solution implemented on a ship or other vessel type. This upstream value chain for each technology describes the technical components and services needed for the TIS, such as production of fuel, batteries, engines, and power trains. The upstream part differs considerably between the different TISs. By contrast, the downstream parts of the value chain include the same type of actors for all four technologies and are described in Section 2.1.4.

2.1.1 Biodiesel and liquefied biogas (LBG)

The upstream part of the value chain (Figure 4) for the two biofuels consists of the production of biomass followed by processing of biomass into different types of biodiesel or LBG and the construction of engines. Norwegian production of both biodiesel and LBG is currently very limited, as is the use of biofuels within the MSS. Since it is possible to use biodiesel in conventional diesel engines and LBG is interchangeable with LNG for gas engines, the engine production is the same (with some modifications) as for diesel and LNG.

Figure 4 The upstream part of the value chain for biodiesel and LBG

2.1.2 Battery electric

The BE sector's value chain (Figure 5) in the context of the Norwegian MSS takes its starting point in Norway's unique access to cheap, renewable energy, which provides good conditions for both electrification of the shipping fleet and the manufacturing of batteries. Norwegian technology suppliers, shipyards and shipowners are increasingly interested in BE technology, and the national production/assembly of batteries, components for electric powertrains and charging infrastructure is growing. International companies focusing on BE solutions are establishing themselves in Norway; for example, Siemens opened a maritime battery factory in Trondheim in January 2019, and Corvus who will do the same in Bergen in September 2019 (Stensvold et al., 2019).

Figure 5 The upstream part of the value chain for BE technology

2.1.3 Hydrogen

As shown in Figure 6, the value chain for maritime use of green hydrogen in Norway starts with electricity generation, which is needed for the production of hydrogen by electrolysis, similar to the BE TIS. Current Norwegian production of sustainable hydrogen is limited to local production connected to pilot projects on hydrogen ferries, and widespread bunker infrastructure is lacking. A small number of fuel cell manufacturers are already established in Norway and shipyards and shipping companies have shown a growing interest in hydrogen propulsion, which is likely to develop business opportunities for specialized suppliers of technical components.

Figure 6 The upstream part of the value chain for hydrogen technology based on electrolysis

2.1.4 Downstream part of the value chain

The downstream part of the value chain includes the same actors for all four TISs (Figure 7). However, construction of LoZeC ships is not a linear process but requires collaboration between actors in varying constellations. Public regulators such as Sjøfartsdirektoratet and private classification companies such as DNV GL provide rules and legislations to guide the development process. Norwegian ship designers and shipyards are world leaders within sustainable shipping and shipowners are increasingly investing in alternative technologies to decrease fuel consumption and emissions. Suppliers of different kinds of systems and components for LoZeC technologies, such as system integrators for BE powertrains, is a growing sector within the Norwegian industry. Consultancy firms often have unique competencies and participate in the development of new technology and its components. Public organizations such as Statens vegvesen and local governments are public procurers with responsibility to provide transport for certain routes. They do not own any vessels themselves, but state demands regarding emissions and which technology should be used for the ships operating on their behalf, and they are therefore important drivers of the development of LoZeC ships. Port actors contribute to the creation of LoZeC ships by providing either charging infrastructure for BE ships or other necessary infrastructure.

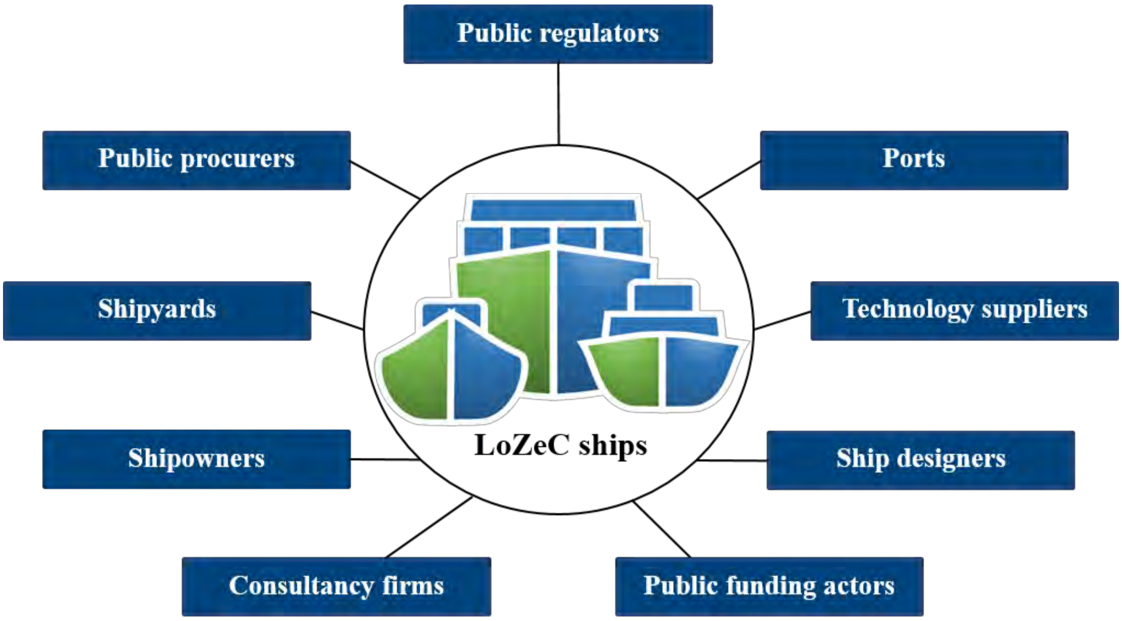

Figure 7 Actors involved in development and construction of LoZeC ships

2.2 Central actors and networks

By examining important actors and knowledge networks for the Norwegian MSS, it is possible to identify structures for knowledge development and sharing. The Norwegian green energy technology network in the MSS consist of a wide range of actors, from technology suppliers, ship designers and shipyards to shipowners, ports and classification societies, as well as public authorities and R&D institutions. Most actors have a maritime profile, but some non-maritime actors such as technology suppliers for infrastructure and local and regional governments are also part of the network. On the Norwegian west coast, an industry cluster for the MSS has developed over a long time and, in combination with national funding, R&D programmes and the formation of national and regional networks for sustainable shipping, it has become a hotspot for green technology innovation. In the following subsections 2.1.1–2.1.3 we present three important types of networks – regional and national network organizations, joint ventures and international knowledge networks – that facilitate information sharing, pooling of resources, and knowledge development and diffusion among actors in the Norwegian LoZeC TISs.

2.2.1 Regional and national network organizations

Five large networks are important for the development of the Norwegian sustainable shipping sector and focus especially on hydrogen and BE technology (Table 3). Participation in networks is seen as an advantage when applying for R&D funding, both nationally and within the EU: '*Maritime CleanTech helps bringing different actors together, and if we are applying for funding, we often find partners within the network. MCT [Maritime CleanTech] are also very good at driving development and put it on the agenda*' (R&D4, 2017).[5]

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[5] Code refers to the overview of interviewees, see Appendix A.3.

Table 3 Networks and organizations – size and technology focus. Data adapted from Mäkitie (2018)

Network	No. of members	Biodiesel	Hydrogen + fuel cells	Battery electric
GCE Blue Maritime Cluster	141		X	X
Grønt Kystfartsprogram	26	X	X	X
Norsk Hydrogenforum	44		X	
Maritime Battery Forum	45			X
NCE Maritime CleanTech	74		X	X

Note: The data were compiled in 2018 and the numbers may have changed since then.

GCE (Global Centre of Expertise) Blue Maritime Cluster is the largest network, with members from the whole value chain (see Appendix A.4 for an overview). It is a regional maritime industry network (centred on Ålesund Municipality in the county of Møre og Romsdal) and specializes in advanced offshore vessels and does not focus entirely on LoZeC technologies. NCE (National Centre of Expertise) Maritime CleanTech, the second largest network, similarly has representatives from the entire value chain, and during the interviews it was highlighted a number of times that it was especially important to be part of that network. The network is centred in the region of Sunnhordland, which spans the counties of Hordaland and Rogaland. NCE Maritime CleanTech focuses on supporting its members in the development of energy-efficient and environmentally friendly technologies. Key areas of activities in the network are to establish innovation projects within clean technologies and to seek to influence relevant policy frameworks (see also Sjøtun, 2019 regarding the battery electric ferry Ampere). The more than 70 members in the network include various technology providers, shipowners and research organizations, but also companies with specific competences in low-carbon technologies such as energy storage systems. Both NCE Maritime CleanTech and GCE Blue Maritime are part of the Norwegian Innovation Clusters programme (Norwegian Innovation Clusters, n.d.), which aims to trigger and enhance collaborative development activities in geographically concentrated clusters, increase cluster dynamics and attractiveness, and increase individual companies' innovativeness and competitiveness.

Grønt Kystfartsprogram, which is administered by the classification and consultancy company DNV GL, has an overall focus on LoZeC solutions and has conducted various pilot projects and scoping activities. It is the only network with a focus on biofuels and it has carried out a pilot project on a biodiesel ferry. The network, which mainly consists of shipowners, suppliers and county municipalities, is also involved in projects on hydrogen-powered and BE-powered passenger vessels.

Norsk Hydrogenforum is an industry association that specializes in promoting hydrogen as an energy carrier, particularly in the transport sector, both on land and at sea. The network seeks to support R&D and commercialization of hydrogen technologies, as well as to spread information about hydrogen and influence industrial policy that would support the development of the hydrogen value chain in Norway. The network has developed quickly in recent years: '*From being a small group of friends telling each-other about hydrogen, now all the politicians are talking about it and bringing it up. There are more and more actors seeing the bigger picture and it is easier to work with hydrogen now than a few years ago*' (R&D4, 2017).

The Maritime Battery Forum seeks to support the development of electric and battery-hybrid vessels and related value chains. The network has c.45 members, including various maritime technology providers, battery and electric power system suppliers, and research organizations and public authorities. The forum reported increasing interest in its activities in 2018 and rapid growth in participation in its annual conference (personal communication).

2.2.2 Joint ventures

Only three new joint ventures directly relevant to the biodiesel, LBG, BE, and hydrogen TISs have been identified in the Norwegian MSS. Hyon, which was established in April 2017, is a joint venture between NEL, Hexagon Composites and PowerCell. NEL delivers various solutions to produce, store, and distribute hydrogen, while Hexagon Composites is developing and delivering composite pressure cylinder technology. The Swedish company PowerCell develops and produces fuel cell stacks and systems powered by hydrogen. By utilizing its owners' technologies and competences, Hyon is able to offer integrated solutions for the complete hydrogen value chain from production, storage and distribution to fuel cell technology that supplies energy.

Clean Power is a joint venture between the Norwegian companies Prototech and Norwegian Electric Systems (NES), and was established in 2016. NES is a total system integrator of diesel electric and hybrid electric system for maritime markets, whereas Prototech provides technical solutions related to fuel cells applications. Since March 2019, the status of Clean Power AS has been somewhat uncertain, but the initial joint venture was established to deliver comprehensive propulsion system packages using fuel cells.

Høglund Power Solutions, established in April 2019, is a joint venture between Høglund Marine Automasjon and ACEL. Høglund Marine Automasjon has delivered power management systems to electrical ship suppliers for more than 25 years. ACEL is an electrical supplier for vessels and oil rigs. The joint venture, Høglund Power Solutions, focuses on delivering energy-efficient electrical power systems for maritime vessels using electric hybrid systems.

2.2.3 International knowledge networks

In the global context, Norway is one of the world leaders in sustainable shipping. Given the country's relatively small population, Norwegian actors have been very active in generating knowledge and patenting technologies related to the application of hydrogen and fuel cells, as well as BE technology (see also Section 3.1). Although co-patenting technologies with actors of other nationalities does not seem to be a tradition, a number of Norwegian actors have collaborated in EU-funded R&D programmes in the past 20 years. Norwegian actors repeat collaborations over time, which is crucial for knowledge transfer, and new actors from Norway constantly join the EU knowledge networks. Although Norway is not one of the dominant countries within the EU knowledge network of green shipping, Norwegian actors are important in terms of both their participation and the intensity of their collaboration.

2.2.3.1 Biodiesel and biogas

Regarding biodiesel and biogas, there is very little Norwegian participation in EU-funded R&D programmes. Since 1998, Norwegian actors have only participated in one biodiesel project and nine biogas projects, all during the FP7 research-funding framework that ran from 2007 to 2013. However, the combined number of projects related to biofuels within the EU R&D network is clearly lower than the number of projects on fuel cells, hydrogen and BE solutions, and has not increased over the years (see Figure 8). With regard to Norwegian patents, Norsk Hydro holds one patent for biogas technology together with the University of Newcastle, and Statoil (now Equinor) acquired six biodiesel patents during the period 2000–2007.

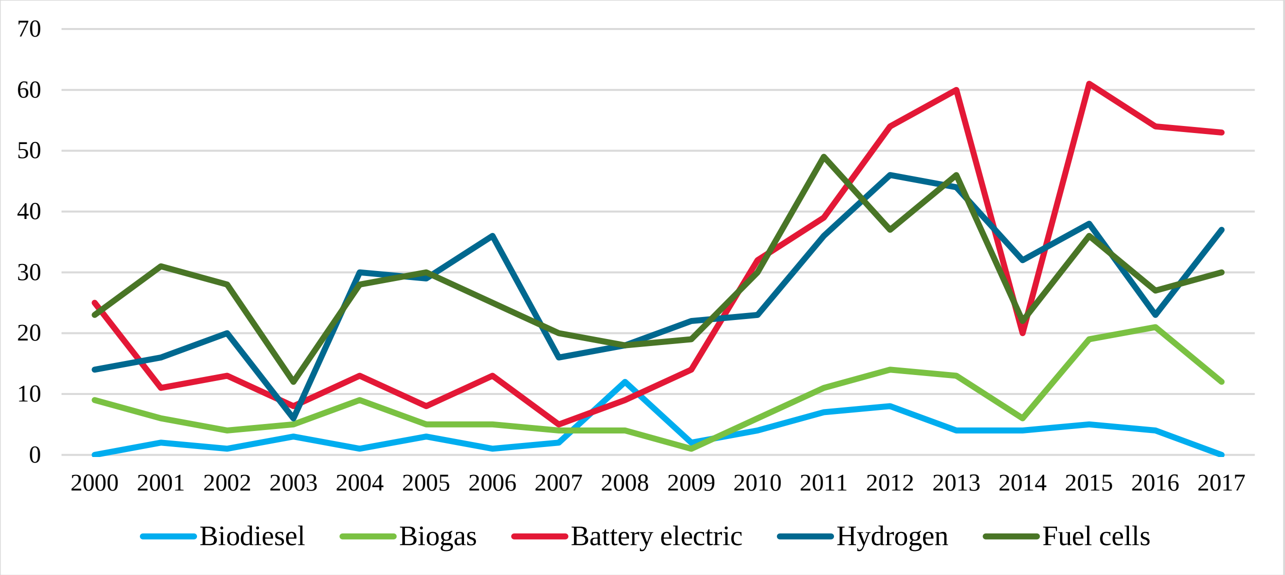

Figure 8 Number of EU-funded R&D projects related to biofuels, hydrogen and BE technology per year. Data adapted from Tsouri (2018).

2.2.3.2 Battery-electric

BE and hydrogen solutions are the most developed fields within EU-funded research (Figure 8). In the EU-funded R&D context for BE technology, Norwegian actors are important players but have a peripheral role in working in different projects that are isolated from each other. This can be seen in Figure 9, in which the Norwegian actors are placed in different nodes representing particular projects and the networks around them. The most central actor within the EU-funded R&D network for electric ships is the University of Newcastle, which participates in a high number of projects and acts as a knowledge broker between different projects and parts of the network. DNV GL appears to be the most central Norwegian actor within the EU-funded R&D network for the BE TIS (Table 4); it participates in one of the bigger projects and has achieved a strong network with many connections with various international actors. Other important actors within the international knowledge network are Rolls Royce Marine in Ålesund and IFE because they are involved in research on and patenting BE and hybrid technology (Table 4).

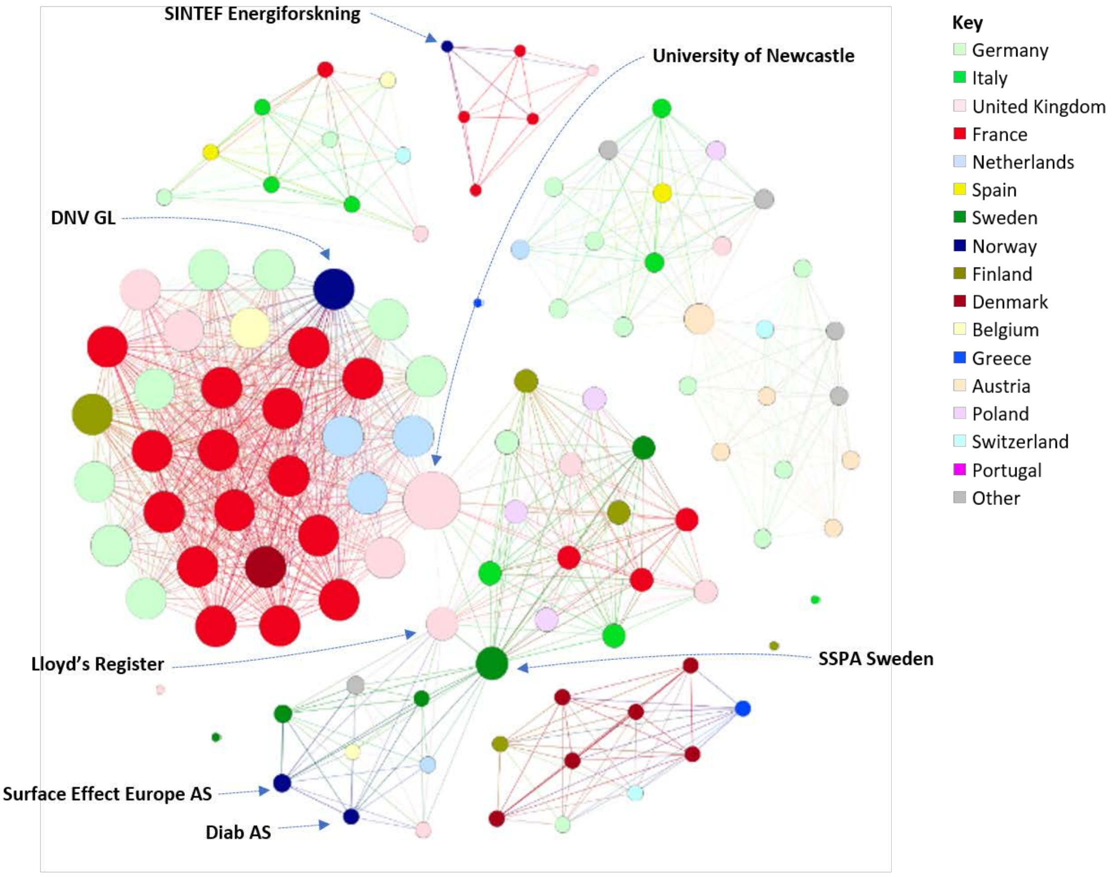

Figure 9 Norwegian and central actors within the EU R&D network for electric ships. Data adapted from Tsouri (2018)

In addition to the above-mentioned actors, the interviews pointed to the central importance of the national divisions of Wärtsilä, Siemens and ABB as partners for technological development. Although Norway is not a dominant country within the EU R&D network for BE ships and it does not have a high number of patents, it has a prominent role in the global context due to its very well-developed national innovation networks (as described in Section 2.2.1). During the interviews, both NTNU and SINTEF Ocean/MARINTEK were pointed out as very important R&D partners and collaborating with suppliers, shipowners and shipyards. National funding comes mainly from Innovasjon Norge, Enova, and NOx-fondet. Innovasjon Norge is owned by the Ministry of Trade, Industry and Fisheries (51%) and the county authorities (49%). Enova is controlled by the Ministry of Climate and Environment. NOx-fondet was founded in 2008 and operates in agreement (the most recent of which is 2018–2025) with the same ministry.

Table 4 Important Norwegian actors within the EU sustainable shipping network

Actor	Technology	R&D[a] (1998–2017)	Patents[b] (1980–2014)	Publications[c] (1980–2017)
DNV GL AS	Fuel cells	X		
	Hydrogen	X		
	Battery electric	X		
Eidesvik	Fuel cells		X	

Actor	**Technology**	**R&D**[a] **(1998–2017)**	**Patents**[b] **(1980–2014)**	**Publications**[c] **(1980–2017)**
IFE	Fuel cells			X
	Hydrogen	X		
	Battery electric			X
MARINTEK	Fuel cells	X		X
	Hydrogen	X		
Norsk Hydro AS	Fuel cells	X	X	
	Biogas		X	
Equinor	Biodiesel		X	
	Biogas		X	
Prototech	Fuel cells		X	X
Rolls Royce Marine AS, Ålesund	Hybrid electric	X	X	

[a] R&D refers to participation in EU-funded R&D programmes in the period 1998–2017 (Tsouri, 2018)

[b] Patents obtained from national patent offices (information obtained from EPOs PATSTAT database) during the period 1980–2014 in the following patent classes: green shipping, biogas, synthetic natural gas, biodiesel, bioethanol, fuel cell, and electricity storage (Heiberg, 2017a)

[c] Published academic articles in journals indexed in the ISI Web of Knowledge (Heiberg, 2017b)

2.2.3.3 Hydrogen

Norway has an especially influential role in the EU-funded R&D projects on fuel cells and hydrogen fuels, in which it has participated since the early years of research in the field. Several Norwegian actors hold patents for fuel cell technology (see Table 4). However, initial research on fuel cells was not exclusively aimed at hydrogen technology and therefore fuel cells are listed separately from hydrogen in Table 3. DNV GL appears to be the most influential Norwegian actor in both the hydrogen sector and the BE sector. Furthermore, it is among the most central actors in the entire EU green shipping knowledge network, as it has the role of broker in connecting different projects, as indicated by its central positions and many connections to other actors in Figure 10. DNV GL researches both fuel cells and hydrogen fuel, and it cooperates especially with the Italian companies Ansaldo Fuel Cells S.P.A and Fincantieri S.P.A. Through EU-funded R&D programmes, DNV GL also cooperates with other central Norwegian actors, among which Norsk Marinteknisk Forskningsinstitutt AS (MARINTEK) is especially active.

DNV GL is also an important actor for the national and regional networks, as it is the project manager for Grønt Kystfartsprogram and hosts the secretariat for the Maritime Battery Forum. Other important actors involved in EU-funded R&D projects and/or patenting technologies for fuels cells and hydrogen are the shipowner Eidesvik, and the suppliers Norsk Hydro AS and Prototech (see Table 4 for more details).

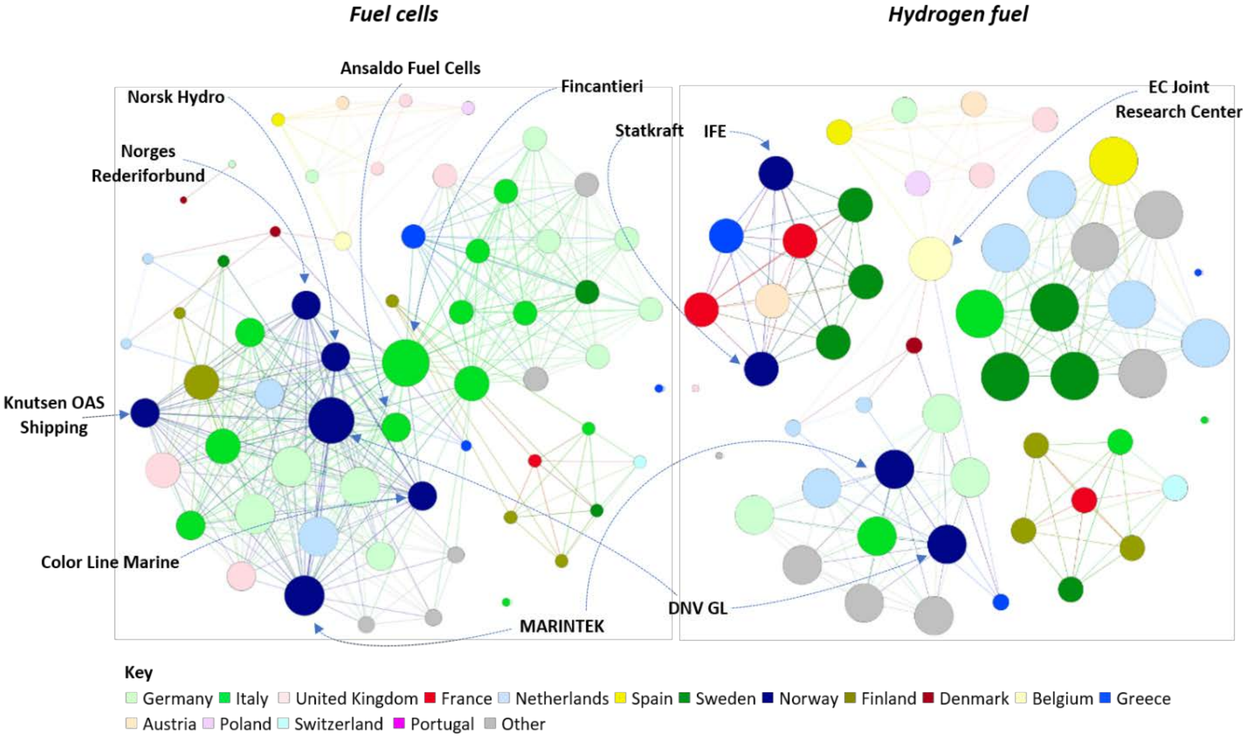

Figure 10 Central Norwegian actors and their relation to other central actors within the EU R&D networks for fuel cells and hydrogen fuel between 1998 and 2017. Data adapted from Tsouri (2018)

2.3 Institutions

The shift towards a LoZeC MSS in Norway is taking place under the influence of various formal and informal institutions. Formal institutions comprise, for example, rules and regulations, support policies and procurement practices. Informal institutions are norms, values and beliefs that guide actors' cognition and practices.

2.3.1 Rules and regulations

2.3.1.1 Generally applicable rules and regulations

With regard to rules and regulations, the Norwegian maritime shipping sector is subject to a multiscalar governance system that includes international and national regulations, and public and private regulations. Norway has introduced several excises (special taxes) that apply to the maritime shipping sector. A CO_2 tax on mineral oil (introduced in 1991) is one of the most important instruments for ensuring lower GHG emissions. Its purpose is to contribute to cost-effective reductions of CO_2 emissions (Regjeringen.no, 2018). However, the fishing segment is subject to reduced CO_2 tax (Finansdepartementet, 2018). Furthermore, it is possible to apply for CO_2 tax refund (Altinn.no, 2018). The NOx tax was introduced in 2007 with the aim to contribute to NOx reductions. This special tax applies to emissions in Norway and on the continental shelf. For actors from the maritime shipping sector, it applies to their emissions from operations within Norwegian territorial waters and domestic traffic, although some parts of the operations may be outside Norwegian territorial waters (NHO, 2019).

Several acts are generally applicable to the MSS, such as the *Lov om sjøfarten* (Shipping Act) and *Lov om skipssikkerhet* (the Ship Safety Act). In addition, a number of regulations have been developed for conventional fuels that might apply to specific TISs (see A.1 for an overview). At the same time, some regulations relating to conventional energy sources may apply to the MSS.

In addition to maritime guidelines and regulations, a number of regulations concern infrastructure (e.g. fuel containers and bunkering equipment). The process of developing regulations for new fuels can therefore be complex, as a number of actors are responsible for different aspects. For example, different public regulatory actors are responsible for seaside and landside regulations, implying that no single regulatory actor has 'full control'.

2.3.1.2 Technology-specific rules and regulations

Rules and guidelines for specific technologies are at different development stages and are issued both at Norwegian and European levels. The existing rules and guidelines for conventional fuels also apply to liquefied biogas and biodiesel. These rules and guidelines are complemented by TIS-specific regulations, such as European standards addressing minimum requirements for biodieseldiesel (EN14214 and EN590 respectively) and *Temaveiledning om tilvirkning og behandling av farlig stoff - prosessanlegg og biogassanlegg* (Norwegian guidelines on the manufacturing and treatment of hazardous substances – process plants and biogas plants). The battery framework is relatively complete. The last updates were adopted by DNV-GL in January 2018.

Sjøfartsdirektoratet developed *Veiledning om kjemiske lager for energi-maritime batteri systemer* (Guidelines for chemical energy storage - maritime battery systems). According to these guidelines, a company has three ways to satisfy the provisions of *Lov om skipssikkerhet* (the Ship Safety and Security Act). The first way is by following the *Veiledning om kjemiske lager for energi-maritime batteri systemer*. The second option is to carry out a technical analysis based on MSC.1/Circ.1455 Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments. Sjøfartsdirektoratet would closely follow the process in this case. The third option allows to use the *Veiledning om kjemiske lager for energi-maritime batteri systemer* in combination with rules on battery systems from a recognised classification society where the rules must be accepted by Sjøfartsdirektoratet. Independent of which option the company chooses,a recognised classification society should certify or approve the battery systems (Sjøfartsdirektoratet, 2016).

While the most recent rules for fuel cells applicable to hydrogen were adopted in January 2018 (DNV-GL), there are still some gaps in the hydrogen framework (DNV GL, 2019).

The role of the established rules is perceived by industry actors as important, as the lack of them can cause insecurities. However, in general, the role of the regulatory bodies in the Norwegian MSS, whether private or public, is assessed as positive by industry actors. One of our interviewees (a technology supplier) stated the following about the development of regulatory frameworks: '*It has been very positive. DNV GL has been very active. A close dialogue took place with Sjøfartsdirektoratet and early involvement [of the companies] was part of the projects*' (TS2, 2017). Sjøfartsdirektoratet is also a part of several PILOT-E consortia, which allows it to follow the development of new technologies very closely.

2.3.2 Support policies

In addition to the rules and regulations described in the preceding section, formal institutions also include support policies for LoZeC technologies. From the interviews, we identified the most relevant support mechanisms as the programmes of NOx-fondet, Enova, Innovasjon Norge, and PILOT-E, as well as Grønt Kystfartsprogram. These mechanisms aim at the reduction of NOx or GHG emissions by providing support to environmentally friendly solutions. Although some of the agencies have technology-specific support programmes (e.g. Enova's support programme for batteries within the maritime sector, the existing support mechanisms are primarily technology neutral. Most of these support schemes or instruments are available to actors in all MSS segments. However, there are also some segment-specific programmes, such as NOx-fondet's programme for the fishing segment.

Since the support mechanisms have different goals, the preconditions for obtaining support differ too. NOx-fondet's primary task is to reduce NOx emissions, and therefore members of the organization (i.e. companies that contribute to the fund) can apply for financial support for NOx reductions as well as energy optimization measures, insofar as they entail reduced NOx emissions in Norwegian waters (NHO, 2019).

Enova provides support for the implementation of emission-reducing solutions in vessels (maritime transport) and in infrastructure (industry and plants or constructions).[6] In the case of vessels, Enova's programmes are primarily intended to support vessels with significant operations in Norway's economic zone and/or regular calls in Norwegian ports and/or that are registered in the Norwegian Ship Registers (NOR/NIS). Financing can be provided to ships sailing under other flags, provided one-third of their ports of call are Norwegian ports or if they spend at least one-third of their operation time in Norway and/or the Norwegian exclusive economic zone (Enova, n.d.-a). Enova currently has three programmes available for GHG emissions-reducing technologies (piloting, demonstration and full-scale application) and two programmes for infrastructure support (onshore power supply in ports and municipality or public infrastructure) (Enova, n.d.-b).

Innovasjon Norge provides support services to start-ups and established companies. Ocean related equipment and technology, clean energy development and sustainability are identified focus areas. Projects intended to contribute to more environmentally friendly domestic shipping can receive financial support, which covers investments in the use of climate and environmental technologies and in other measures that potentially lead to emissions reduction. It is assumed that the projects are based on a real customer need. The presence of a final user in the applying consortia is considered advantageous (Innovasjon Norge, n.d.).

Enova, Innovasjon Norge and Forskningsrådet have created a common support programme: PILOT-E. This programme is intended to contribute to faster development of new environmentally friendly solutions and their introduction to the market. An important requirement for application for support from PILOT-E is the presence of a final user in the applying consortia (Enova, n.d.-c). Grønt Kystfartsprogram (literal translation: 'The green coastal shipping programme') was set up in 2015 as a cooperation programme between public and private sector, and is coordinated by DNV GL. The programme has four phases: (1) assessing the potential for battery-based and gas-based

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[6] In some cases, it is possible to apply for support from both the NOx-fondet and Enova, although the organizations have different goals.

transport in Norway; (2) assessing the respective business cases; (3) removing barriers to the green maritime shift; and (4) an implementation and upscaling phase between 2019 and 2030). Both vessels and infrastructure can obtain support from Grønt Kystfartsprogram. An overview of projects is given in Appendix A.2.

2.3.3 Procurement practices

Procurement practices both shape the institutional context for the green transition of the Norwegian maritime sector and drive technology development. The development contract established in 2012 by Statens vegvesen's (Norwegian Public Roads Administration), which resulted in the first BE road ferry (M/F *Ampere*), specified CO_2 and NOx emission levels among the award criteria. The agency continued to set requirements for low- and zero-emission ferries for subsequent tenders. Statens vegvesen has also awarded a development contract to a hydrogen-electric road ferry project, which is expected to begin operating in 2021. The goal of the project is to enable the use of zero-emissions technology on long sailing routes where a full BE solution is not feasible.

Additionally, Norwegian municipalities and county municipalities are important procurers. Among their procurements are road ferries from the county municipalities in the former county of Sør-Trøndelag (now part of Trøndelag) and the county of Hordaland.

2.3.4 Informal institutions

Informal institutions, such as norms and values, are considered important for the changes happening in the Norwegian MSS. The reputation of the maritime industry, vision and current sustainability trends in the industry, and the values of individuals in different organizations and their willingness or lack of willingness to consider new technologies all seem to play an important role in supporting the green transition. For example, one of our interviewees (SO3, 2017) stated, '*our owner sends me links to articles on new technology that he finds interesting. He thinks green solutions are important, and as the owner he is a driver of such processes within the company.*' Furthermore, Norwegian working culture, with its focus on collaboration and flat organizational hierarchies, was mentioned by some interviewees as a factor that contributes positively to identification and potential implementation of LoZeC solutions.

2.4 Assessment of the phase of development

In this section we assess the phase of development for the different TISs in the context of the Norwegian MSS. This assessment is intended to provide a brief account of current TIS status, whereas the functional analysis that follows in Section 3 provides an overview of the status of different aspects of the respective TISs.

2.4.1 Biodiesel

The biodiesel technology reached maturity in the early 2000s, but never experienced proper market formation or achieved high legitimacy. The current market for biodiesel is stagnating and only a few actors are involved. There is little activity in the form of new investments or R&D projects, indicating that the maritime biodiesel TIS is retracting from the niche market phase it achieved about ten years ago.

2.4.2 LBG

LBG was introduced to the Norwegian road transport market quite recently and is on the verge of entering the maritime fuel market. The LBG TIS for the Norwegian MSS is therefore still in an early formative phase. However, since LBG is interchangeable with LNG, it is possible to implement it without large investments in infrastructure or new vessels. Furthermore, the introduction of LBG as a heavy road transport fuel will add to the development of LBG production, and therefore there is potential for rapid maturation of the technology. The cruise company Hurtigruten is currently retrofitting six of their ships by installing gas engines and has invested in the use of LBG in combination with LNG from the operation start of the first converted ship in 2020 (TU.no, 2019). Apart from Hurtigruten, there are few clear signs of other actors investing in the maritime application of LBG and there is a need for incentives to push the development of the LBG TIS.

2.4.3 Battery electric

Following the introduction of the world's first BE road ferry, M/F *Ampere*, on the route between Lavik and Oppedal (Norway), the BE propulsion technology within the road ferry segment is maturing rapidly and has experienced an accelerating market expansion, as more than 70 BE ferries have been ordered during the last five years (Stensvold et al., 2019). Hybrid solutions for other sectors, such as peak-shaving technology for the offshore segment and hybrid propulsion, have not experienced the same rapid maturation process or market development but are advancing steadily. Knowledge networks, both national and international, have formed through R&D projects and local initiatives, and standards and regulations are coming into place. A large number of successful pilot tests have resulted in the emergence of an advanced niche market within the Norwegian road ferry segment, as the technology has reached high legitimacy and has been requested by a number of actors.

Figure 11 The battery electric ferry M/F Ampere. Source: Fjellstrand

2.4.4 Hydrogen

The maritime application of hydrogen technology is currently relatively immature. However, an increasing interest in hydrogen as both road transport and maritime fuel has resulted in Norwegian production of fuel cell technology and pilot testing on-board ships, indicating that the hydrogen TIS is in an early demonstration phase. Norwegian actors have been active in EU research networks for more than 20 years, and several national maritime knowledge networks focus on hydrogen. Standards and regulation have not yet been formalized, which is hindering the implementation of extensive technology.

3 Functional analysis

The functional analysis builds upon the structural analysis and the assessment of the development phase of the respective TISs. The functional analysis covers seven functions – knowledge development and diffusion, direction of search, entrepreneurial experimentation, market formation, legitimation, resource mobilization, and development of positive externalities – and aims to map the drivers and barriers within each TIS. The analysis also includes an assessment of how well the TIS is performing with regard to the specific functions, which are evaluated as weak, intermediate or strong (see Section 1.3). In the following section, we assess the status of each technology with respect to the seven functions.

3.1 Knowledge development and diffusion

The function knowledge development and diffusion is often regarded as the core of the TIS, as it provides the knowledge base that the other functions build upon. Analysis of how knowledge is created and shared within a TIS allows identification of critical knowledge gaps (Bergek et al., 2008). Our investigation was carried out by using patent analysis, bibliometric analysis, an analysis of EU-funded research and innovations projects, and interviews with key actors.

3.1.1 Biodiesel

Knowledge development and diffusion activities relating to biodiesel within the Norwegian MSS are currently limited. Prior to 2007, Norway was one of the leading countries in the acquisition of biodiesel technology patents (see also Section 2.2.3.1), but since 2009 very few patents have been approved or applied for in Norway or globally, thus indicating the maturity of the technology. However, the number of publications on biodiesel has increased slightly over the last ten years, which may indicate a renewed interest in biodiesel. Currently, the main knowledge development focuses on the sustainability aspects of the fuel production, as research institutions are continually evaluating the environmental impacts of the production of and emissions from different types of biodiesel. This indicates that the main issue regarding knowledge development and diffusion is within the upstream part of the value chain (biomass feedstock for biodiesel production) and not directly related to the Norwegian MSS.

Although there has been strong early development and diffusion of knowledge regarding biodiesel and there has been a recent increase in publications, the function is assessed as weak due to the current lack of participation in R&D projects and limited knowledge network.

3.1.2 LBG

Knowledge development for maritime use of LBG takes its starting point in the maritime LNG sector, since LBG can either be mixed with LNG or used alone in LNG engines. Research institutions in collaboration with suppliers have taken the lead in developing gas-powered ship engines and the further development of them. Parallel to LBG's implementation as a maritime fuel, it has also been introduced as a renewable fuel for heavy road transport and buses, which currently is a more developed TIS. Knowledge development from the road transport sector will benefit the maritime LBG sector in the initial phase.

Currently, as LBG can be used with existing LNG ships, the focus for knowledge development and diffusion is, similarly to biodiesel, on the sustainable production and distribution of LBG, which is part of the upstream part of the value chain and not directly part of the Norwegian MSS. An important contributor to knowledge formation regarding LBG is R&D projects, and Norwegian actors have participated in a few EU funded R&D projects over the last ten years. Biokraft, the owner of the world's largest LBG factory which is located at Skogn north of Trondheim (Scandinavian Biogas, 2018), currently participates in several R&D programmes on LBG production. The two main ones are the EU-funded EffiSludge for Life[7] and the Forskningsrådet-funded COMPLETE[8]. These R&D projects include testing and research that will further increase knowledge development. Biokraft is collaborating with NTNU, NIBIO, SINTEF Ocean, and the Swedish actors Scandinavian Biogas and University of Linköping. Collaborations between different companies were mentioned during the interviews as important to build up valuable networks for knowledge sharing: '*We have called people, and asked questions, and been nagging at people, and we have gotten a lot of help and answers and have built up a network. We did not have a network from the beginning, it has developed over time*' (FP1, 2017). In the absence of a national network for maritime use of LBG, this Scandinavian network is important for the sharing of knowledge. In combination with knowledge sharing from the heavy road transport sector, the developing Scandinavian LBG network provides a solid basis for knowledge development and diffusion regarding LBG. However, given the small number of Norwegian actors involved and limited focus on maritime use of LBG, the function is considered weak.

3.1.3 Battery electric

Norwegian actors see themselves as global front-runners in BE ships technology, and this position is confirmed by the fact that Norwegian actors are central within EU R&D networks for BE propulsion, are developing and patenting technologies, and are contributing to publications on the topic. National divisions of some international companies are important contributors to technological innovation and often collaborate with national research institutions on technological development (see also Section 2.2.3.2). Furthermore, Norway's prominent global position is considered a result of both pressure from legislation regarding emissions and synergies within the great maritime cluster in Norway, which provides a strong national knowledge network. However, the latter is not exclusively through cooperation but also importantly because development is stimulated by competition among technology developers and suppliers: '*We push each other towards solutions. It is more competition than it is cooperation*' (TS2, 2017).

Although a number of Norwegian ferries include BE systems and further pilot testing is underway, there is a continued need for knowledge development as well as upscaling of marine applications. To achieve this, technology developers and suppliers claim it is important to co-operate with research institutions, shipowners and on-board personnel: '*We need input from those who are actually on-board and see things and components in operation*' (SO3, 2017). This indicates that the main need for knowledge development and diffusion is within the downstream part of the value chain, among the technology suppliers, ship designers and shipyards, as well as the shipowners. However, although the BE propulsion technology has matured rapidly, there is still a demand for increased knowledge within the upstream part of the value chain in order to develop battery and powertrain production further, as well as solutions for charging infrastructure. A number of interviewees pointed out that technological innovations alone are not enough to achieve a greener fleet and rather there is also a need for increased knowledge development among engine room staff regarding how to handle the new systems. Although knowledge networks within Norway are

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[7] See http://scandinavianbiogas.com/effisludge/
[8] See https://www.sintef.no/prosjekter/complete/

strongly developed, there is a continued need for education and knowledge diffusion, both within technology development and in the operative sector. Therefore, the function is assessed as intermediate.

3.1.4 Hydrogen

Currently in Norway, there is a basic knowledge base regarding hydrogen technology, but the focus is on cars and further development and large-scale testing of marine applications is required: '*We need a concrete project where we can learn more hands-on and get our hands dirty*' (TS3, 2017). Given the limited knowledge regarding maritime applications of hydrogen technology, there is a need for knowledge development and diffusion throughout the entire value chain, from fuel and fuel cell production to increased knowledge among all actors involved in the development of hydrogen ships. Following knowledge development in recent years regarding safe hydrogen operations, there is increasing interest and optimism in finding solutions for the maritime sector.

Knowledge has been developed mainly from collaboration between research institutions, technology developers, suppliers and shipyards, as well as shipowners, both through R&D projects, studies initiated by shipowners and though pilot studies by technology developers. Norwegian actors are among the most central actors within the EU R&D network for maritime hydrogen and fuel cell technology. Cooperation is seen as necessary and a way to move forward more quickly: '*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*' (SY4, 2018). The national and regional networks, such as Norsk Hydrogenforum and NCE Maritime CleanTech, provide good opportunities for knowledge sharing and finding partners for collaboration.

Collaborations and the development of regional and national hydrogen knowledge networks, and an increasing number of R&D projects all strengthen the knowledge development and diffusion, which is judged as intermediate, even though further development and large-scale testing of maritime hydrogen technology is still needed.

3.2 Direction of search

The direction of search indicates the route for the development of the TIS and is determined by the strategic choices that are made by actors involved in the TIS. This function is intended to investigate factors that are taken into consideration by actors within the TIS as well as those interested in joining the TIS, such as incentives for joining or remaining and what strategic choices are made regarding technological applications, and markets (Bergek et al., 2008). The direction of search for the respective technologies has been investigated through interviews with key actors.

3.2.1 Biodiesel

The direction of search for all LoZeC solutions covered in this report is driven by stronger regulations governing emissions and political climate goals globally, but primarily nationally, which have resulted in requirement for LoZeC solutions for new ships. Biodiesel, which has the advantage that it can be used in conventional diesel engines and does not require new infrastructure, is mainly seen as a temporary solution until other technologies are developed enough to achieve sustainable shipping: '*I do not think that biodiesel will be big in the future. I think it is just an attempt to prolong the lifetime of conventional diesel engines a little more, maybe ten years, and then I think it will be more or less over*' (SO1, 2017).

The current use of biodiesel is a direct result of emission regulations for coastal areas and specifications within public procurement contracts for inshore vessels. However, as it becomes much more expensive to operate ships on biodiesel, local governments are leaning towards technology-neutral public procurement contracts instead of specifying the minimum use of biodiesel: '*When we set these minimum requirements for biodiesel, the measure becomes very expensive. The current proposal under political consideration is that we cannot afford using biodiesel but that we will go for sustainable solutions whereby it is possible and where the politicians want to apply zero emissions solutions*' (PA4, 2017). Hence, the incentive to use biodiesel will further decrease.

The focus for the direction of search for biodiesel is divided between the very start of the value chain (concerning biomass production and conversion to biodiesel) and the downstream part, as emission regulations and political priorities drive the direction of search towards more sustainable fuels. However, biodiesel is seen as a temporary solution with small incentives for further development and the function is judged as weak.

3.2.2 LBG

With regard to knowledge development and diffusion, the direction of search for maritime LBG is highly influenced by the road transport sector and the existing infrastructure for LNG, which are the main incentives for actors to invest in LBG. Additionally, political goals and emission standards are directing attention to LoZeC solutions such as LBG. The Norwegian LBG producer Biokraft has recently signed its first contract within the MSS with Hurtigruten, and is looking to diversify its deliveries to other segments within the MSS.

Similar to the biodiesel TIS, the focus for the direction of search is split between the fuel production within the upstream part of the value chain, and the regulations of public authorities and procurers within the downstream part. Since it is possible to produce biogas from many different raw materials, much attention has been given to the sustainability of the production due to regulations relating to the sustainability certification within public procurement contracts. As production volumes currently are low, available LBG is mixed into LNG, which further decreases CO_2 emissions compared with pure LNG (see also Section 3.3.1). Given the political incentives that clearly steer the search for LoZeC solutions and the influence from the heavy road transport and LNG sectors, the function is assessed as intermediate, although so far little attention has been given to the maritime use of LBG. However, recent interviews suggest that there is potential in localized and low- to medium-scale production and use of LBG.

3.2.3 Battery electric

Norway's unique access to non-expensive electricity from renewable sources in combination with policy support has steered the search for sustainable shipping towards BE solutions, which are considered to have great potential. The direction of search has influence on the entire value chain, and there are two main parallel tracks within the BE sector: electrification of propulsion (fully electric or hybrid) and other BE solutions such as shore power, battery installations for peak shaving, energy efficiency, and decreased fuel consumption. The former track concentrates on smaller vessels operating in coastal areas, with a special focus on ferries, whereas the latter track concentrates on bigger ships. Focusing on smaller vessels is seen as a stepping stone towards electrical solutions for larger ships: '*I think the smaller ships operating near the coast will come first, and then the larger will come eventually*' (TIG1, 2018). After successful implementation of chargeable ferries operating on the fiords, the technology is now spreading to other segments such as workboats for the fish farming industry and coastal fishing vessels.

Figure 12 The electric fishing boat Karoline (left, source: Selfa Arctic) and the electric aquaculture workboat Elfrida (right, source: Enova)

Public bodies and state-owned institutions, such as Statens vegvesen and Sjøfartsdirektoratet, have taken the lead in providing incentives to other actors to use BE solutions. Furthermore, a few ambitious private shipowners and shipyards have taken the initiative to build fully electric-powered ferries and smaller ships. Rapidly increased battery capacity, recent economic benefits such as decreases in battery prices, and especially the success of front-runners have all led to increased incentives for new actors to join the TIS, especially in the case of the road ferry segment: '*I think that what was done at Lavik–Oppedal opened up the door for the rest of us to follow*' (PA4, 2017). New procurement demands from Equinor (within the offshore supply segment) have incentivized shipowners in that segment to install BE systems.

Despite consensus on BE not being the only solution, there is reluctance among shipowners and shipyards to try out several technologies at the same time, mainly due to financial risk and lack of resources. Following the current surge on BE technology for ferries operating in the fjords, most interviewed actors believed it was likely that focus would remain on electrification within the ferry segment in the coming years. Given the clear political climate and emission policies, the fact that well-established actors are taking the lead, and the rapid technology and market development, the direction of search is judged as strong.

3.2.4 Hydrogen

The abundance of renewable electricity in Norway is an important prerequisite for the interest in hydrogen technology for the MSS and, as for the BE TIS, the direction of search influences the entire value chain. Currently, hydrogen is mainly seen as complementing BE solutions, either as hybrid technology in combination with BE propulsion or for ships not suitable for electrification: '*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&D4, 2017). Lack of infrastructure for bunkering, limited amounts of fuel, and high fuel costs were mentioned by a number of actors as reasons not to invest in hydrogen technology (see also Section 3.7.4), despite the belief in its potential once regulations are in place and the technology has been further developed.

The direction of search for hydrogen is driven by regulations and political goals in the same way as in the biofuels and BE sectors, especially by Statens vegvesen's request for a new road ferry with hydrogen propulsion with operation start in 2021. However, other important drivers are concerns regarding the availability of biofuels and the limitations of the BE technology: '*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*' (TIG1, 2018). High-speed ferries operating on relatively short coastal routes are considered the starting point for transitioning to hydrogen technology, due to strong emissions regulations in coastal areas: '*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&D4, 2017). These drivers, in combination with access to renewable electricity and positive expectations regarding the rate of development in hydrogen technology and the use potential the technology provide a solid basis for the direction of search, which is currently considered as intermediate but with potential to become strong.

3.3 Entrepreneurial experimentation

Development and maturation of new technologies depend on the testing of various applications and solutions, as the experimentation will develop new products and eliminate dysfunctional technology. Entrepreneurial experimentation is important in order to reduce uncertainties regarding the technology and its function, and the function aims to map the extent and type of experimentation taking place within the respective TISs (Bergek et al., 2008). In order to identify indicators of entrepreneurial experimentation, a research and innovation project analysis of EU-funded R&D projects was conducted and interviews were held.

3.3.1 Biodiesel

Given the maturity and limited use of the biodiesel technology, entrepreneurial experimentation within the Norwegian MSS is currently very limited (see also Sections 3.1.1 and 3.2.1). There has not been any Norwegian participation in EU-funded R&D programmes in the last six years. Additionally, there are no empirical data indicating experimentation regarding new business models, which thus further indicates that the Norwegian MSS has little interest in biodiesel. The function is therefore assessed as weak.

3.3.2 LBG

Technological innovations in gas propulsion are currently taking place within the LNG sector, since LNG is more mature than LBG (Stensvold, 2017) and the same technology can be used for both fossil and renewable gas. Entrepreneurial experimentation in LBG is therefore currently focused on the production side and he introduction of new sustainable raw materials for production, which is upstream in the value chain and not directly related to the Norwegian MSS. Biokraft is experimenting with producing LBG from waste from fish farms, as well as developing new products from the by-products from the biogas production. Within the energy gas sector, experimentation in blending LNG and LBG in order to decrease fossil-based CO_2 emissions is already in progress and showing positive results. For example, Hurtigruten has initiated the conversion of six of its ships to gas engines, and stated that it is planning to mix LBG with LNG from an operation start in 2020 and will eventually phase out the use of LNG (Stensvold, 2018a).

Biokraft originally signed a 10-year supplier contract with AGA[9] to ensure approval for bank loans and an innovation loan from Enova. However, Biokraft has very recently revealed that it will start delivering LBG to the Norwegian cruise company Hurtigruten in 2020, thus indicating the start of experimentation with business models within the MSS.

As current entrepreneurial experimentation in Norway is mainly focused on sustainable local production of LBG, and experimentation in the maritime use of LBG currently is limited, the function is assessed as weak. However, with Hurtigruten’s intention to blend LBG with LNG from 2020, there is potential for more extensive experimentation.

3.3.3 Battery electric

A number of actors drive entrepreneurial experimentation in the BE sector, which in turn influences the entire value chain, and shipowners, technology suppliers and system integrators (such as Siemens) take initiatives. With regard to which actors are at the forefront of developments, ‘*It is often shipowners 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 shipowners are often working on-board the ships themselves, as engineers or captains*’ (TS9, 2018). Elements in focus are battery ferries with charging infrastructure ashore, different hybrid solutions, onshore power supply in harbours, and hybrid battery solutions for peak-shaving or dynamic positioning (DP) operation. Previously, the starting point for experimentation was often in technology developments for the car industry, but currently the focus is on developing maritime solutions directly.

Testing is done both in laboratories and on-board ships, and since 2014 there have been BE and hybrid ships in full operation, such as the road ferry M/F *Ampere*, which was designed within a Statens vegvesen development contract. Since then, much attention has been given to solutions to problems regarding charging infrastructure and shortages of power supplies. It has also been discovered that shifting to BE systems requires new roles for suppliers, and implementation of a system integrator seems to help with the completion of installations and risk reduction for shipowners and shipyards.

Shipyards, suppliers and system integrators have expressed concerns about public procurement regulations for ferries. One such concern has been that specification of technology choices may lead to lock-ins and the implementation of outdated solutions in a time of rapid technological change. A possible solution would be to transition to performance contracts instead, thereby allowing the supplier to design and develop technology over time: ‘*Right now most shipowners 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 shipowners that have their business set up in that way that makes this interesting*’ (TS8, 2018). This indicates that the main issue regarding entrepreneurial experimentation is within the downstream part of the value chain, because as the technology is maturing, there is an increasing need for new solutions to be developed by technology suppliers, ship designers and shipyards, as well as for changes in traditional contracts and regulations to fit the new technology. Since entrepreneurial experimentation is initiated by several

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[9] Currently, AGA only supplies the road transport sector with LBG and dies ot have any official plans to expand into the MSS in the near future.

types of actors and since testing is performed in laboratories as well as on operating ships and covers both technologies and business models, the function is assessed as strong.

3.3.4 Hydrogen

Only a few actors, most of them shipowners and shipyards, are involved in entrepreneurial experimentation in hydrogen propulsion and currently the main activity is pilot projects. In the case of the hydrogen TIS, the focus of entrepreneurial experimentation is currently in the upstream part of the value chain, and experimentation in propulsion is concentrated around hybrid technology combining BE solutions with hydrogen and fuel cells: '*There are many types of fuel cell technology, but there is not one solution. There are various technologies that have their advantages and disadvantages*' (TS3, 2017).

The implementation of the technology is focused on small high-speed ferries and involves most actors within the downstream part of the value chain. Given the limited access to green hydrogen and specifications regarding the use of fossil-free fuels in public procurement contracts, entrepreneurial experimentation also directs attention to methods for sustainable production and exploring the possibility of lowering hydrogen prices if shipowners could produce their own fuel locally. Especially the competition around Statens vegvesen's contract for a new hydrogen road ferry drives technology development and experimentation, but suppliers also criticize the rules for the contract for being too strict: '*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*' (SO7, 2017). Since experimentation covers different areas of maritime hydrogen solutions, the function is assessed as intermediate, even though only a few actors are involved in pilot testing and R&D projects today.

3.4 Market formation

Market formation is an important part of the establishment of new innovations, but the market development takes place in different stages and is seldom an obvious success. To understand the market formation function, it is crucial to investigate the market development over time, incentives for buyers, and other drivers of the market formation (Bergek et al., 2008). In order to map incentives and drivers, interviews have been held with key actors, in addition to an analysis of the market size for the respective technologies.

3.4.1 Biodiesel

Pure biodiesel is a very limited division of the current Norwegian fuel market,[10] due to its varying availability and high cost. Subventions of marine diesel compared to diesel for road transport makes biodiesel additionally expensive for the MSS: '*Instead of comparing about 10 NOK per litre for road transport with 12 for biodiesel, the comparison is between 5 NOK contra 12 NOK. So, we are talking about 130% more expensive fuel if we are to demand sustainability-certified biodiesel for shipping*' (PA4, 2017).

A possible driver of the biodiesel and LBG markets could be state-initiated development contracts for ships with LoZeC technology and demands regarding emissions in public procurement

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[10] The total market for biofuels in Norway sunk from 659 million litres in 2017 to 496 million litres in 2018, while the sale of advanced biofuels grew from 138 litres to 196 million litres (https://www.regjeringen.no/no/aktuelt/okning-i-salget-av-avansert-biodrivstoff-i-fjor/id2627163/)

regulations, which are a direct result of stronger regulations relating to emissions. However, uncertainties regarding the availability of biodiesel and the fuel cost means buyers are hesitant to invest in biodiesel; instead, other LoZeC solutions such as hydrogen and BE are preferred: '*According to the contract, if you are going to use biodiesel, it must be documented that it is sustainable. That in itself is a limitation. At least, we experienced it like that. That, and to be sure to have a fuel supplier, and then the price*' (SO1, 2017). In the fish farming industry, the sustainability demands from international supermarkets that buy the fish is an incentive for a green fuel shift, in addition to emissions regulations. However, the potential market drivers have not yet resulted in a growth of the biodiesel market and the market formation is therefore assessed as weak.

3.4.2 LBG

The Norwegian biogas market is currently focused on road transport, but with the increasing interest in LBG as a fuel for heavy road transport there is opportunity for this market segment to be a driver for maritime use of LBG, especially given that the still high price are likely to decrease with upscaling of production. Norwegian biogas producer claimed that '*Even though liquefaction means an increased cost for the production, it is a very important strategic market choice, and not least because the vehicles [trucks] have now arrived*' (FP1, 2017). However, for biogas, there are uncertainties regarding the possibilities for large-scale production and fuel availability. Therefore, a probable future scenario is the continued mixing of biogas with natural gas rather than extensive use of pure LBG. The market development for maritime use of LBG has been initiated by Hurtigruten, the largest cruise company in Norway, which has signed a seven-year contract with Biokraft for delivery of LBG to their converted cruise ships. Biokraft is currently upscaling its production to 25 million Nm^3 LBG per year in order to meet the demand from Hurtigruten, as well as its delivery to AGA.

Currently, since the market for maritime use of LBG is limited to one actor, the function is assessed as weak. The parallel process of introducing LBG as a heavy road transport fuel could help with market formation also for the MSS, and the recently signed contract between Hurtigruten and Biokraft indicates hope for further development of markets for LBG.

3.4.3 Battery electric

The development of the global market for batteries and electric vehicles has escalated during the past few years, with rapidly decreasing prices. For the MSS, this reflects an unusually quick development and implementation of new technology with regard to BE solutions. The growth in battery installations on maritime vessels has been especially fast in the last two years, as shown in Figure 11. In addition, the size of the battery packages is growing fast. For instance, the largest ordered battery package in 2017 had a capacity of 4.7 MWh (Color Hybrid), while in 2018 Havila Kystruten ordered four 6.1 MWh batteries (a total order of 24.4 MWh) and Yara Birkeland ordered a 6.8 MWh battery. Corvus, the largest supplier of maritime batteries, increased its deliveries from 5.5 MWh in 2016, to c.70 MWh in 2018. However, in Q1 2019, Corvus had already sold more batteries (in MWh) than it did in total in 2018 (Stensvold, 2019b). Recent investments by battery suppliers indicate that this growth will continue, since both Siemens (battery assembly factory opening January 2019) and Corvus (battery assembly factory opening Q3 2019) have invested in battery module factories in Norway with a capacity of c.400 MWh each.

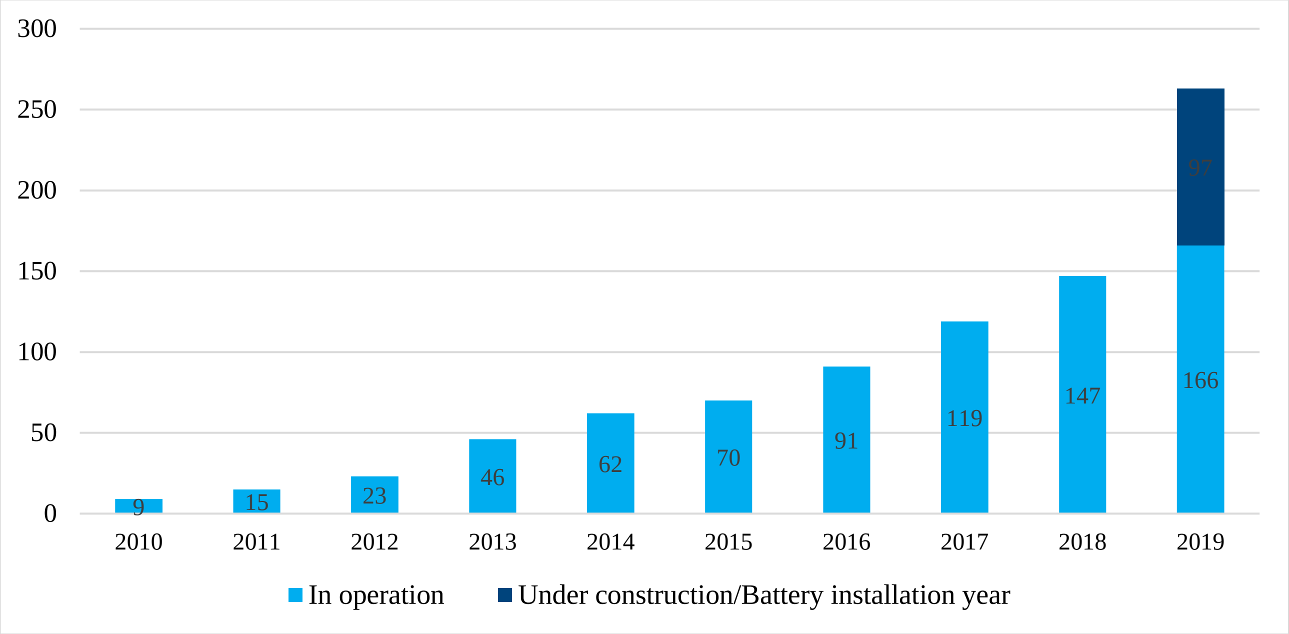

Figure 13 Development in number of vessels with installed battery, 2010–2019. Adapted data from DNV-GL's Alternative Fuels Insight (AFI) platform (DNV GL, n.d.)

Figure 11[11] shows that car and passenger ferries constitute the dominating segment in terms of the number of battery installations, followed by offshore supply vessels (OSVs). However, the road ferry segment is even more dominating with regard to total installed battery capacity, as ferries typically have larger batteries than OSVs. It is also interesting to observe the recent growth in battery installations on fishing and Ro-Pax vessels. For OSVs, changes in contract details regarding fuel costs are opening up the market for battery solutions for peak-shaving and lowering fuel consumption, as fuel costs are increasingly paid by shipowners rather than the company chartering their vessel: '*Previously, Statoil [now Equinor] paid for the fuel, and then there were no incentives for the shipowners to introduce innovations, because the cost were already covered – but that has changed now*' (TS5, 2017). Apart from emissions regulations, other incentives for shipowners to invest in BE technology seems quite individual, but a few examples are quick pay-back of the investment, decreased fuel costs, the desire to be a technological front-runner, and pressure from social norms (see also Section 3.2, 'Direction of search'): '*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*' (SD1, 2017).

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[11] The data shown in Figure 13 and Figure 14 were sourced from Maritime Battery Forum's database and DNV-GL's Alternative Fuels Insight platform. The data are global data, but relatively representative for the Norwegian MSS, since minimum of 42% of all maritime battery installations recorded in the database are from vessels operating within the Norwegian MSS.

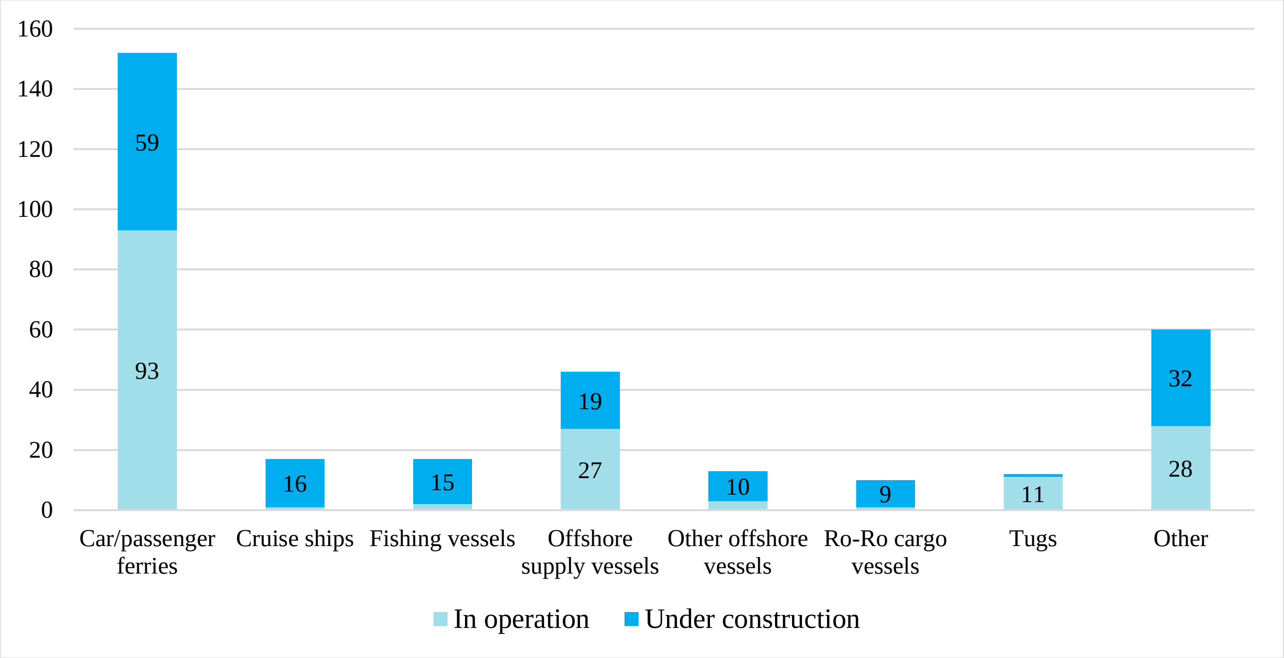

Figure 14 Number of vessels with batteries by vessel type. Data adapted from DNV-GL's Alternative Fuels Insight (AFI) platform (DNV GL, n.d.)

As for biofuels, two other important drivers of market formation in Norway are state-initiated development contracts and specifications in public procurement contracts. However, the shipyards experience a lot of pressure to deliver long-term services, even though their suppliers cannot guarantee the same long-term commitment. The perceived risk means some shipyards are hesitant to submit offers and they are pushing for a changed public procurement procedure, wherein the risk is split between different actors and more financial support is received from the state: '*The financial incentives the state provides is often directed to the shipowner or cargo holder, but the shipyard does not benefit from that. The shipowner does not have to pay a* CO_2 *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*' (SY2, 2017).

Since the market for maritime batteries and electrical installations has increased rapidly over the last ten years, and the political climate and emission policies will continue to create incentives for battery installation, the base for market formation is good. However, shipowners and shipyards take high risks when signing long-term contracts. The market formation for BE technology is therefore assessed as strong.

3.4.4 Hydrogen

Currently, the overall hydrogen market is limited, especially for fossil-free hydrogen, and actors are hesitant to invest in maritime hydrogen technology as it is believed to be a great risk as long as fuel prices are high (see also Section 3.2.4). So far, hydrogen pilot projects have been dispersed along the Norwegian coast, forcing the projects to produce their own hydrogen at very high costs: '*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&D4, 2017). Upscaling the means of production and control is seen as necessary for lowering hydrogen prices, which is considered a prerequisite to compete with the subsidized diesel costs. The hydrogen available on today's market is mainly produced from fossil fuels, and there is an overproduction of grey hydrogen that ends up being flared (PA2, 2016). According to specifications in public procurement contracts, all hydrogen used by contracted ships must be produced from renewable sources, meaning that the overflow grey hydrogen cannot be used within the maritime sector.

Parallel to increasing interest in hydrogen within the maritime sector, technology for cars, buses and trucks is making fast progress. The two sectors (maritime and transport) will probably push each other's markets forward, and together rapidly increase the demand for hydrogen. Two other important drivers of market formation are the state-initiated development contracts and demands in public procurement regulations: '*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&D4, 2017). These drivers are seen as likely to spark an upscaling of production of green hydrogen, resulting in lower hydrogen prices. However, the current situation leaves the hydrogen market for the MSS very limited and investors hesitant, and therefore the function is judged as weak.

3.5 Legitimation

The formation of legitimacy within a TIS includes social acceptance of the new technology, and achieving legitimacy is key to the successful implementation of new technologies as it attracts new actors, investors and other resources (Bergek et al., 2008). Alignment with the existing institutions is important for the legitimation of the TIS, whereas for the functional analysis of the legitimation process it is relevant to investigate the regulatory framework for the new technologies in the Norwegian MSS. For the investigation, a review of relevant regulations and standards up until Q1 2019 was performed and interviews held.

As mentioned earlier in Section 2.3, some regulations relating to conventional energy sources can be applicable to the emerging low- and zero-emissions technologies. At the same time, there are ongoing processes for developing regulations for some of the technologies, and the rules for the respective technologies are at different stages of development, which are presented in the following four sections (3.5.1-3.5.4).

3.5.1 Biodiesel

Biodiesel is currently used within the Norwegian MSS, especially in coastal areas, but is still a quite controversial fuel and has not achieved high legitimacy, and therefore the function is assessed as weak. The benefits of being able to use biodiesel in conventional engines are overshadowed by the drastically higher price, uncertainties regarding the origin of the fuel and its sustainability, and what quantities will be available long term. Sharper sustainability policies intended to force biodiesel production away from unsustainable sources would create a shortage of fuel and continue to increase the cost, which so far has resulted in the production of biodiesel from various sources with uncertain environmental implications. Compared with the cost, the emissions benefit raises questions: '*It costs the society eight million [NOK] a year to operate two express boats on biodiesel versus conventional diesel. I believe it is abuse of public money because the biodiesel releases just as much CO_2 as conventional diesel. For a 200-year perspective, everyone thinks that it is recyclable, but the CO_2 problem is acute*' (SO7, 2017).

3.5.2 LBG

Within the Norwegian MSS, knowledge of maritime use of LBG and its production is very limited (see also Section 3.1.2). A company producing LBG from fish farm waste has experienced resistance towards LBG within public procurement: '*There is one and another non-technological bureaucrat at the regional governments writing into public procurement documents that it [LBG] is not possible. We managed to get rid of it [the idea], but it still characterizes the entire procurement process if you have that idea*' (FP1, 2017). Legitimation of LBG could be helped by the possibility to mix LBG with LNG, and the fact that existing LNG-powered ships can use LBG without conversion of their engines. Existing rules and regulations for maritime use of methane as a fuel also apply to LBG and there is no need for them to be updated. Increased use of LBG for heavy road transport as well as Hurtigruten's intention to implement LBG from 2020 will increase LBG's legitimacy for the maritime sector. However, there are concerns about the availability of fuel: '*Biogas and biodiesel is good, but if everyone is to drive around using it there will be very little food to eat, so it is not sustainable. It could help with special things and it is very good to use waste for the production, but when you need to cultivate and take from the food production capacity it is not sustainable*' (SO12, 2018).

As knowledge about LBG for maritime use is limited and there are uncertainties regarding fuel availability and sustainability benefits, LBG's legitimacy is assessed as weak. However, the success rate of LNG ships and increased use of LBG for heavy road transport is likely to speed up the legitimation process in the near future.

3.5.3 Battery electric

BE has the most mature legitimation process of all four LoZeC technologies. The success rate of diesel electric engine solutions, which have been widely used since the introduction of diesel engines for ships in the early 1900s, has paved the way for a range of electric solutions, such as shore power and peak-shaving. The continued success of these technologies has increased the trust in BE technology. Furthermore, well-performing pilot tests and implementation of BE ferries have proved that the technology works: '*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). BE's legitimacy will be further strengthened by the rapid implementation of a number of BE ferries in the next few years. Additionally, lobbying by the Norwegian networks Maritime CleanTech (MCT), Maritime Battery Forum, and BE technology suppliers and system integrators is important for the legitimation process. The rapidly expanding market for electric cars in Norway has further increased general legitimacy for BE solutions among the public. 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 certain R&D projects on BE technology, some funding has been used for initiating the development of regulations and standards for the maritime sector, which is facilitated by DNV GL and Sjøfartsdirektoratet. Consequently, the battery framework is relatively complete. The most recent updates were adopted by DNV-GL in January 2018, and guidelines and regulations are frequently updated. However, actors within the Norwegian MSS find the lengthy process both frustrating and reassuring, as security is of importance: '*Sjøfartsdirektoratet 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*' (TS2, 2017). Despite the uncertainties regarding battery life length and power grid capacity, the function overall is assessed as strong, since regulations are more or less in place and under continuous improvement. Moreover, the success rate of early entrants and the rapidly increasing number of battery installations (see also Section 3.4.3) prove the perceived legitimacy within the Norwegian MSS, especially within the road ferry segment. However, some actors have expressed concern that there is strong hype around BE and that this may be at the expense of developing other LoZeCs that are needed for reduction of GHG emissions in all segments of the MSS.

3.5.4 Hydrogen

Increasing legitimacy was witnessed during the course of the data collection, and the concerns expressed in previous years by shipowners and shipyards about the safety of hydrogen technology have been declining. Several important actors across the value chain have expressed interest in hydrogen technology and are investing in it. However, rules and regulations regarding safety for maritime use of hydrogen are currently incomplete, making the construction of hydrogen-powered ships very expensive and complicated. The rules applicable for hydrogen propulsion were issued by DNV-GL in 2015 with updates in 2018. In 2017, the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) entered into force. Nevertheless, there are still regulatory gaps and barriers, such as those relating to design and storage (DNV GL, 2019). At the same time, the Norwegian Maritime Authority is participating in several pilot hydrogen projects, which is allowing it to observe the cases not covered by the current framework. Currently, hydrogen ships are treated as 'alternative designs' and are automatically rated at the strictest security level, resulting in monitoring over several years before the certification of the vessel is finalized. The further implementation of rules and regulations is likely to decrease further the hesitance regarding the safety aspects of hydrogen as a maritime fuel.

The Norwegian Government has expressed positivity regarding hydrogen as a sustainable fuel: '*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*' (SY4, 2018). Solberg also mentioned hydrogen (albeit produced from natural gas) as an important future fuel in her speech at Equinor's Autumn Conference in 2018 (Government.no, 2018). Three years earlier, she had participated in the opening of a hydrogen filling station for cars in 2015 (Kjeller Innovasjon, 2015), thus indicating the Government's interest in the fuel, which is likely to help the legitimation of hydrogen as a maritime fuel in the future. Lobbying from Norsk Hydrogenforum, both for maritime and land use of hydrogen, is also important for the legitimation process. The parallel process of developing hydrogen road transport is likely to speed up the legitimation process for hydrogen in the MSS. Since important actors have expressed interest and invested in maritime hydrogen technology, and because rules and regulations are likely to be developed in the next few years, the legitimation function is assessed as intermediate, even though there is a knowledge gap in maritime applications of the technology.

3.6 Resource mobilization

Allocation of resources is crucial to drive innovation processes forward. The resource mobilization function is intended to map the extent of resources invested in a new technology, both financial and human capital resources (Bergek et al., 2008). Different sources of resource mobilization have been identified through mapping and analysis of the volume of seed and venture capital, as well as LoZeC support from policy instruments. For additional information, interviews were conducted.

Current support policies that are relevant for the MSS (see Section 2.3.1) do not differentiate between the technologies or provide technology-specific support. Nevertheless, there is a division between LoZeC technologies, in which some biofuels have lower legitimacy due to their relatively limited potential for emissions reduction. Some support mechanisms allow for optimization measures for fossil-driven vessels or combinations of fossil and low- and zero-emissions technologies. As mentioned earlier (Section 2.3), the interviewees pointed out several support mechanisms as the most relevant and/or important for LoZeC technologies within the MSS. Overviews of support from NOx-fondet and Enova are provided in Figure 15 and Figure 16 (in Section 3.6.3). In addition, Innovasjon Norge provides support aiming at the use of LoZeC technologies or other measures that potentially will lead to emissions reduction (Innovasjon Norge, n.d.). However, no detailed overview is available for Innovasjon Norge' support for LoZeCs in the MSS.

3.6.1 Biodiesel

Since biodiesel can be used in conventional engines, Enova, Forskningsrådet, Innovation Norway, and NOx-fondet do not provide funding for investment in biodiesel: '*NOx-fondet does not give financial support to biodiesel as a* NO_x*-reducing measure. It does not require very high investment costs for the ship as you can use pretty much the same gear as you do for conventional diesel*' (NOx-fondet representative). Grønt Kystfartsprogram supported the building of the road ferry M/F *Hornstind*, which was supposed to run entirely on biodiesel. However, given various uncertainties regarding fuel supply and high biodiesel prices, the ferry is currently running on conventional diesel. Considering the lack of public funding support and little interest in the fuel, the function is assessed as weak.

3.6.2 LBG

NOx-fondet support is technology-neutral and is intended for both LBG and LNG. Figure 15 shows that there has been considerable financial support for LNG ships from NOx-fondet, as NOK 1.15 billion has been awarded to different projects over the last decade, peaking in 2014. The number of LNG projects awarded with funds from NOx-fondet has decreased in recent years, as financial resources have been increasingly allocated to BE technology. There are no data on support for vessels using LBG, thus indicating the current immaturity of the technology.

Both Innovasjon Norge and Enova support LBG production as well as the construction of infrastructure for LBG and LNG. The most notable example of support so far is Biokraft's LBG production facility (opened 2018), which has received NOK 82 million from Enova and an 'innovation loan' of NOK 55 million from Innovasjon Norge. The public funding and the signed ten-year contract with AGA were crucial for enabling a NOK 215 million loan to Biokraft from a Norwegian-Swedish consortium of banks and other finance institutions (Biokraft, 2016). Additionally, Enova has recently supported the second biggest LBG production facility in Norway (owned by VEAS) with NOK 37.5 million (VAnytt.no, 2018). The facility will start production intended for heavy road transport in 2020. Part of the production will be delivered to Hurtigruten, which has received more than NOK 625 million from NOx-fondet to support the conversion of six of its cruise ships operating along the coast between Bergen and Kirkenes (NOx-fondet, 2019a). In addition, one LNG project is part of Grønt Kystfartsprogram, while LBG projects are being considered for the last phase of Grønt Kystfartsprogram.

Although no private investments directly dedicated to LBG production were identified in the MSS as of June 2019, Biokraft (with the initial production intended for road transport) has received investments from its owners, which are two large private energy companies, as shown in Table 5 (in Section 3.6.3). Table 5 also shows all other identified venture and seed capital in the MSS.

Given the lack of funding awarded for pure LBG projects and the limited number of actors involved in the LBG TIS, the resource mobilization is assessed as weak. However, there is potential for rapid development of the function as the technology matures.

3.6.3 Battery electric

Public financial support for BE solutions has been available through Enova, Forskningsrådet, Innovasjon Norge, and NOx-fondet in the last decade, which has enabled knowledge development, entrepreneurial experimentation and implementation of infrastructure (see Sections 3.1.3, 3.3.3 and 3.5.3). According to NOx-fondet, both BE and hydrogen technology are prioritized in its allocation of funding: '*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.*' As shown in Figure 15, NOx-fondet's financial support for BE has increased since 2006 and by the end of 2017 approximately NOK 71.7 million had been awarded to different projects. In 2018 approximately NOK 47 million was committed to BE projects by NOx-fondet (NOx-fondet, 2019b).

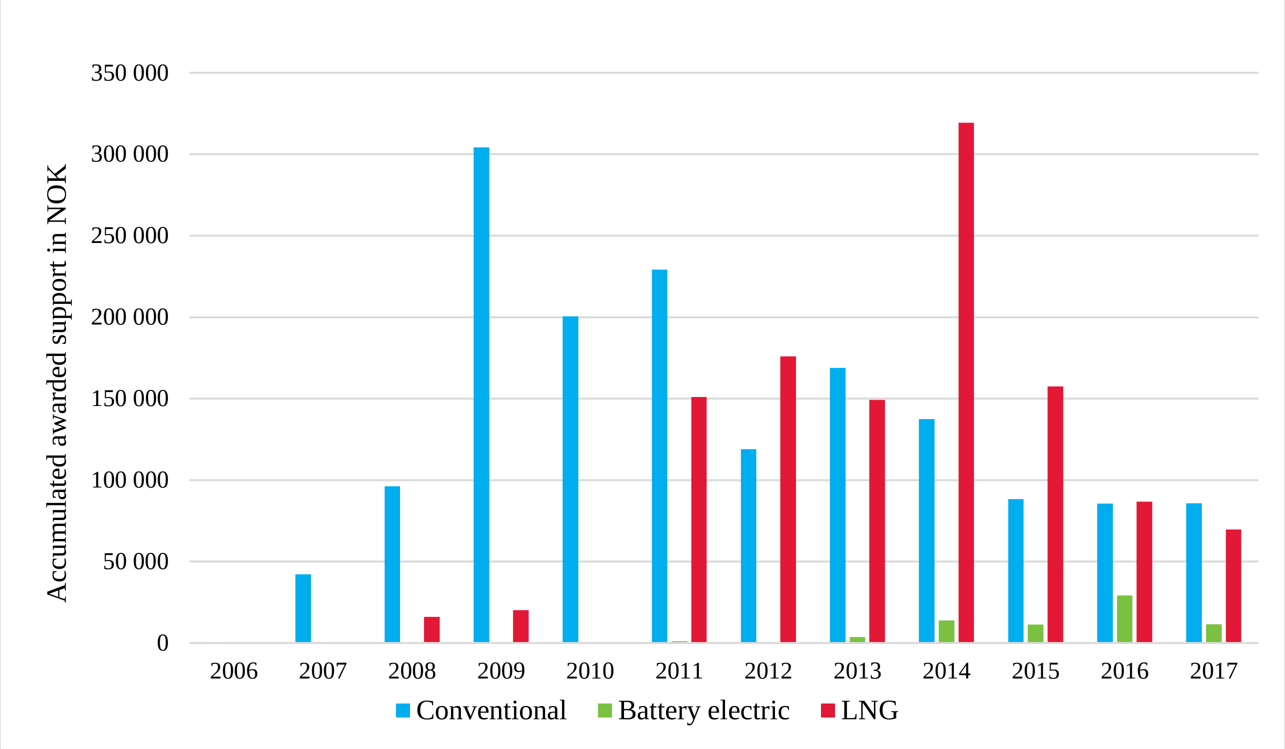

Figure 15 Verified sum of support awarded by NOx-fondet. Data adapted from NOx-fondet (2019b)

Between 2012 and 2018, Enova awarded in total approximately NOK 1.5 billion in financial support for BE solutions, divided between the aquaculture, fishing, freight, offshore, and passenger segments. As shown in Figure 16, the offshore segment received support for the highest number of projects. However, they were all smaller projects focusing on peak-shaving solutions. The passenger segment has been awarded the most money, NOK 823 million, for 18 projects concerning the development of BE ferries.

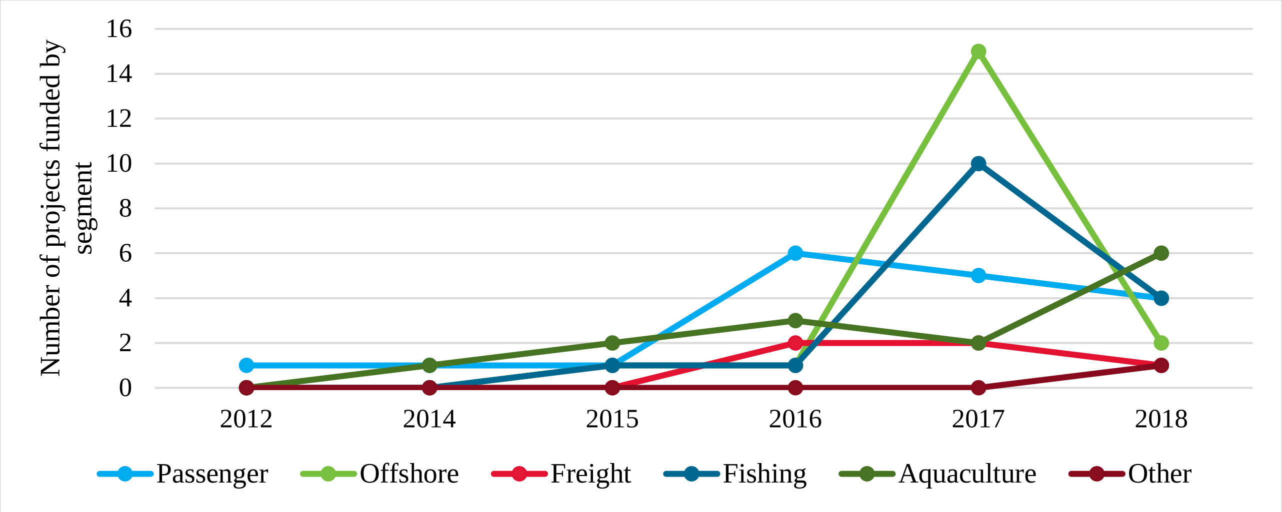

Figure 16 Enova support for battery technology within different segments. Source: Enova (n.d.)

In addition, Enova has financed five projects within the passenger segment (ferries) through its programme for county and municipal infrastructure support (two in 2017, three in 2018). The overall amount awarded to these projects was NOK 212.2 million. The PILOT-E programme awarded support to three battery projects in 2016 and two high-speed ferry projects that focused on BE solutions in combination with fuel cells. Grønt Kystfartsprogram's first phase embraced five battery projects from the passenger, offshore, aquaculture, and freight segments, as well as infrastructure development (see Appendix A.2). Three of the segments (offshore, aquaculture and infrastructure) were transferred to the second phase. The second phase also includes a new battery project (freight).

Charging infrastructure for BE ferries is in place and an increasing number of ports are investing in onshore power supply (OPS). Enova offers funding for both charging infrastructure and OPS, and has awarded a total of NOK 665 million for charging infrastructure for BE car and passenger ferries. According to the data available on Enova's support for onshore power supply in Norwegian ports, a total of NOK 518,076 was divided among 79 projects between 2016 and 2018 (Figure 17).

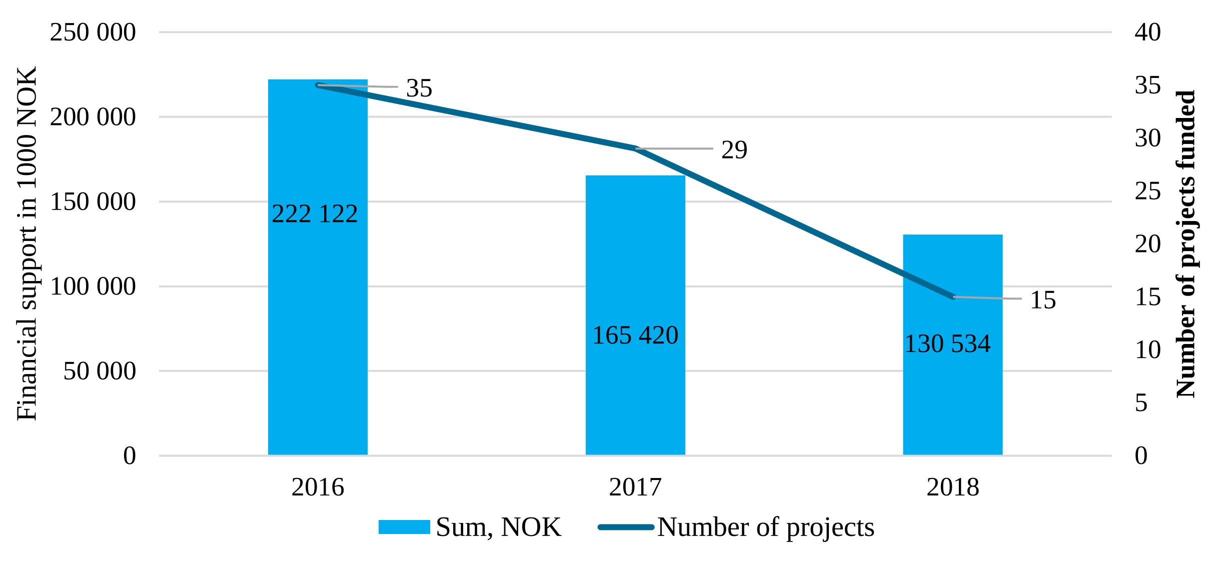

Figure 17 Enova's support for onshore power supply (OPS) in Norwegian ports in NOK 1000 in the period 2016–2018. Source: Enova (n.d.)

Within the four public financial support funds, there are different levels of investment support, ranging from 40% to 100% of the project budget. Several shipyard representatives expressed that public funding was especially important during financial recession, as it enables them to continue with development and innovation. However, applying for financial support was seen as a lengthy and demanding process, and some companies have chosen not to apply to certain funds. According to representative of SO7, which operates within the road ferry segment, '*It is simply too demanding for us to apply to other funds than NOx-fondet. […] It is demanding to write the applications, to document our costs and to claim them back. NOx-fondet is much more standardized on what we are doing*' (SO7, 2017). Interviewees also complained that public funding was focused on new innovations, which made it difficult to continue to develop initiated projects when the initial funding period ended.

With regard to private investments in BE solutions, considerable investments have been made both as external (venture) capital investments and as firm-internal investments. The external investments identified in the Norwegian MSS are listed in Table 5. They are either corporate capital investments in new or young firms by large established firms or informal investors, as in the case of Evoy and Clean Marine Switchboards. The exact amount of invested capital is unknown because most investment deals are not disclosed. Corvus (Table 5), was originally a Canadian company, but in this respect it is considered a central part of the Norwegian MSS because most of its sales activities are in Norway, the majority of its owners are large Norwegian companies, and in 2018 it decided to invest NOK 80 million in a battery module factory in Norway (Stensvold, 2018b). Furthermore, in February 2019, Corvus acquired one of its competitors, Grenland Energy.

In addition to externally invested capital, several established companies in the Norwegian MSS have made considerable internal investments in BE solutions. For instance, Siemens has invested c. NOK 100 million in a battery module factory in Trondheim (Larsen, 2019), Rolls Royce has developed its own battery system (SAVe Energy), while both ABB (in collaboration with SINTEF) and Kongsberg Maritime have invested in Hybrid Laboratories to test and optimize diesel and BE systems, which are also integrated with fuel cells and hydrogen (Stensvold, 2019a). Overall, there are many large companies with their own budget for the development and innovation of BE technology, which means they are less dependent on external funding.

Table 5 Seed and venture capital for all technologies

Firm (year established)	Location	Product	Investor(s) and estimated sums
Biokraft (2009)	Skogn	LBG producer	- Local power company TrønderEnergi owns 44% - Swedish company Scandinavian Biogas Fuels owns 50.03%
Corvus (2009)	Bergen & Canada	Battery solutions	- Hydro invested c. NOK 100 million for 25.9% ownership (2017) - Statoil Technology Invest invested at least NOK 10 million for 17.7% ownership (2015) - The Norwegian controlled BW Group invested in 2014, and owns c.30%
ZEM (2009)	Asker	Battery solutions	- Technology supplier and system integrator Westcon invested an unknown amount for 6% ownership in 2017
Grenland Energy (2012)	Skien	Battery solutions	- Kongsberg Maritime invested in the company in 2014 - Acquired by Corvus, February 2019
Greenstat (2015)	Bergen	Hydrogen solutions	- Greenstat has received investments in the range of NOK 8–12 million from c.400 investors in several crowdfunding rounds
Clean Marine Switchboards (2017)	Brekstad	Supplier of maritime switchboards	- Erik Ianssen, shipyard owner and green maritime fuel enthusiast, has invested an undisclosed amount and owns 50%
Evoy (2018)	Florø	Electric propulsion for small vessels	- 10 informal investors invested NOK 3.75 million in 2018 - Crowdfunding campaign (Q3 2019)

With regard to human resources, the previous years' development within diesel-electric systems has built up competence within Norway that is applicable to BE propulsion, but with the increasing interest in maritime BE solutions, there has also been a need to recruit staff from other sectors, such as electrical engineers: '*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*' (TS5. 2017).

Considering the large amounts of public funding in both infrastructure and the development of BE solutions, in private investments, and in the well-developed competencies applicable to the new technology, the resource mobilization function is assessed as strong.

3.6.4 Hydrogen

With regard to the BE technology, public financial support for hydrogen technology is both available through and prioritized by Enova, Forskningsrådet, Innovasjon Norge, and NOx-fondet. However, as NOx-fondet only disburses funding after successful implementation of a project, the interviewed actors pointed out that in the case of hydrogen projects, the financial risk was still too high for a shipowner or shipyard to rely on funding from NOx-fondet. Currently, there is a lack of widespread bunker infrastructure for hydrogen, which forces pilot projects to provide local infrastructure. One of the interviewed actors had applied for funding from Enova to build bunkering stations, but the application was unsuccessful.

The PILOT-E programme has awarded financial support to three hydrogen projects: one in 2016 (in the passenger segment) and two in 2018, all of which plan to use hydrogen, either in combination with batteries or on its own (in passenger and freight segments respectively). In addition, in its second phase, Grønt Kystfartsprogram has accepted one hydrogen project (passenger segment). Another public organization, Statens vegvesen, can be seen as an important contributor to resource mobilization into hydrogen through its development contract for a hydrogen road ferry. Although Statens vegvesen is not investing directly in the technology development, as it will be the operator or shipyard that wins the contract that will make the investment, it will pay the higher operating cost.

Smaller businesses are struggling with resources to cover project costs and are often dependent on external investors, which may be difficult to find: '*Innovasjon Norge 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&D4, 2017). Public funding is also focused on covering investment costs and it is difficult to obtain financial support to cover the increased operation or fuel costs, which makes shipowners hesitant to invest in hydrogen-powered ships.

One company developing sustainable hydrogen production in Norway is hoping for c.50% of its costs to be covered by investors, such as larger energy companies: '*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 Statens vegvesen*' (FP2, 2017). However, although private investments in hydrogen solutions have been limited to date, they are increasing. Greenstat (see Table 5 in Section 3.6.3) is a young company focusing on hydrogen solutions and has initially succeeded in its crowdfunding approach. However, there are signs that internal investments in maritime hydrogen solutions are increasing, such as the case of the joint venture Hyon (see Section 2.2.2), which is internally funded by its corporate owners Nel ASA, Hexagon Composites ASA and PowerCell Sweden AB. Another example is ABB (in collaboration with SINTEF) and Kongsberg Maritime's investments in Hybrid Laboratories, for which the goal is to test and develop fuel cells and hydrogen integrated with other fuel solutions.

The human capital for maritime hydrogen technology is currently not very developed, but ship designers have confidence that they will manage to increase their knowledge: '*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*' (SD1, 2017).

Given the early formative phase of the hydrogen TIS and the immaturity of the technology, there is relatively good access to funding. It is likely that Statens vegvesen's development contract will pave the way for other projects to achieve legitimacy and increase their possibilities for receiving funding. Therefore, resource mobilization for the hydrogen TIS is assessed as intermediate.

3.7 Development of positive externalities

Positive externalities are benefits that become available to all actors within a TIS as a result of an investment or action made by another actor, such as the building of infrastructure or development of competence within the sector. One of the most important positive externalities is the reduction of uncertainty, as it lowers the threshold for new actors to join the TIS (Bergek et al., 2008). The purpose of this function is to identify actions that are indicative of the development of positive externalities, as this was done through interviews with key actors.

3.7.1 Biodiesel

Lack of specialized actors and networks for maritime use of biodiesel makes the development of positive externalities and synergies very limited. Therefore, the function is judged as weak.

3.7.2 LBG

Development of technology and infrastructure for LNG creates a freeriding opportunity for LBG, since the fuels are interchangeable. However, within the LBG sector, the development of positive externalities is very limited and therefore the function is assessed as weak. Improvements in maritime gas engines and systems are done in close collaboration between research institutions and technology suppliers, thus making the technology available for a range of actors: '*The environment up here [in Trondheim] (…) have been central in the development of the gas solutions that Rolls Royce and Wärtsilä are providing*' (R&D2, 2017).

3.7.3 Battery electric

Through having strong national and regional networks (see also Section2.2.1), the BE segment in Norway has developed several positive externalities. Pilot testing by early entrants speeds up processes for latecomers and is a main contributor to the diffusion of the technology. Especially Statens vegvesen's development contract for a BE road ferry, M/F *Ampere*, which started operating in 2014, contributed to development of knowledge and technology, which has been an important driver for the rapid expansion of BE in the passenger segment (see also Section 3.1.3). Construction of charging infrastructure or onshore power supply (OPS) by harbour companies could benefit different ships operating the harbours, but there is still a need for standardization of charging solutions and plugs to make the infrastructure widely available: '*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*' (IA3, 2017).

The Norwegian knowledge base for maritime BE technology is strong but is scattered between different applications and solutions. Standardization is still lacking in certain segments of the maritime sector. More widespread implementation of standards and classifications for maritime BE solutions would help to reduce uncertainties and contribute to development of general competencies among both installers and on-board personnel, which can be shared within the broader MSS. An increasing number of specialized suppliers, including system integrators who cover more or less the complete technical solution (on vessels and charging infrastructure), are entering the market, as previous suppliers of individual components have discovered the need for solutions that cover the entire installation process (see also Section 3.3.3).

Additionally, there are synergies between BE and hydrogen technologies: '*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&D4, 2017). It is noticeable that an increasing interest in one technology usually increases interest in other LoZeC solutions too.

There is potential for the development of several positive externalities, given the strong knowledge networks, the possibilities for infrastructure to be used by a number of actors, and the synergies between the BE and hydrogen technologies. However, neither regulations and standardizations nor infrastructure are fully in place and therefore the function is assessed as intermediate.

3.7.4 Hydrogen

The hydrogen network within Norway is developing and there appears to be substantial cooperation between different actors regarding this technology. This may stimulate future development of positive externalities within the sector. The new development contract for a hydrogen road ferry will probably contribute to the development of positive externalities in the same way as M/F *Ampere* has done for the BE segment: '*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&D4, 2017). The development contract and PILOT-E projects focused on hydrogen application in maritime transport will contribute to the preparation of standards and regulations, which will further strengthen the legitimation process in maritime applications of hydrogen technology (see also Section 3.3.4).

Infrastructure for bunkering and suppliers is currently non-existent and needs to be developed. From the perspective of shipowners that are early movers, there are two possible main directions for implementation of infrastructure: '*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*' (SO7, 2017). Concentrated, large-scale production requires additional transport infrastructure, which is expensive but would make it easier for actors that are not able to invest in their own production to join the TIS.

The hydrogen TIS has potential for development of positive externalities due to development of knowledge networks and the development contract for a hydrogen road ferry. However, compared with the BE TIS, these lie farther in the future. Bunker infrastructure and regulations need to be developed, and currently the development of positive externalities for hydrogen is judged as weak.

4 Summary of structural and functional analysis

4.1 Biodiesel

The functional analysis shows that the biodiesel TIS, despite being a mature technology, has not achieved high legitimacy within the Norwegian MSS (see Table 6). All functions are assessed as weak, and although political policies and emission regulations could create interest in the fuel, the belief that biodiesel is only a temporary solution limits all functions, and the development of the TIS has stagnated. High fuel prices, uncertainties regarding availability, and the sustainability of biodiesel all overshadow the advantages of using biodiesel in conventional diesel engines and existing bunkering infrastructure. Both current entrepreneurial experimentation and knowledge development and diffusion are very limited, as there are few ongoing pilot projects or R&D projects. Lack of interest and legitimation hinders the formation of an extensive biodiesel market, and resource mobilization is practically non-existent. Given the rapid development of other LoZeC technologies, it is likely that maritime use of biodiesel (based at least on current technologies and biomass feedstock) in Norway will be phased out in the near future.

Table 6 Summary of the functional analysis of the biodiesel TIS

Knowledge development and diffusion	**Assessment: Weak**
Strengths: • Strong early knowledge development resulting in many patents • Increasing number of publications in the last 10 years • Research on environmental impacts of biodiesel	*Weaknesses:* • Current knowledge development and diffusion is very limited • Limited Norwegian participation in R&D projects • Few actors involved with creating knowledge
Direction of search	**Assessment: Weak**
Strengths: • Clear political goals directing attention towards LoZeC solutions • Emission regulations and specifications in public procurement contracts are early incentives for the use of biodiesel in conventional diesel engines	*Weaknesses:* • Biodiesel seen as temporary solution, making investors hesitant • The high fuel cost will exclude biodiesel from technology-neutral contracts
Entrepreneurial experimentation	**Assessment: Weak**
Strengths: • Previous participation in the EU R&D network	*Weaknesses:* • Limited participation in EU R&D projects • Low recent patenting activity • Limited experimentation regarding business models

Market formation	Assessment: Weak
Strengths: - Development contracts for LoZeC ships and demands for low emissions in public procurement contracts are a potential market driver - Sustainability demands from consumers may incentivize the fish farming industry to shift to biodiesel	*Weaknesses:* - Very low market share of the current Norwegian fuel market - Subventions of marine diesel makes the price difference even higher
Legitimation	**Assessment: Weak**
Strengths: - Successful operation with biodiesel on coastal vessels	*Weaknesses:* - Uncertainties regarding fuel availability, fuel sustainability and high fuel costs make investors hesitant - Sharper sustainability policies regarding raw material for biodiesel will create fuel shortage
Resource mobilization	**Assessment: Weak**
Strengths: - Coastal vessels buy biodiesel	*Weaknesses:* - Limited or no funding available from support organizations such as Enova, Forskningsrådet, Innovation Norge, and NO_x-fondet
Development of positive externalities	**Assessment: Weak**
Strengths: - None	*Weaknesses:* - Limited knowledge networks

4.2 LBG

The more advanced use of LNG in MSS and LBG for heavy road transport is currently influencing the LBG TIS within the Norwegian MSS (see Table 7). This in turn is steering the direction of search together with public policies and emission regulations. Furthermore, the influence from the other TISs creates spillover effects from both entrepreneurial experimentation and knowledge development and diffusion regarding technology development and production of LBG. With the exception of direction of search, which is assessed as intermediate, all functions are assessed as weak. Market formation is assessed as weak because the existing market for maritime use of LBG is limited. However, recent announcements by Hurtigruten suggest that market demand could increase within certain segments in the coming years. Nevertheless, resource mobilization is very limited, as Hurtigruten is the only shipowner to date to have received funding for the implementation of LBG technology. Development of positive externalities within the LBG sector appear to be limited, but also for this function the LBG TIS is influenced by the LNG sector, as general development of maritime gas technology benefits the LBG sector because the fuels are interchangeable.

Table 7 Summary of the functional analysis of the LBG TIS

Knowledge development and diffusion	Assessment: Weak
Strengths: • Spillover effect from knowledge development regarding LNG and gas engines in general, as well as LBG as a heavy transport fuel • Norwegian participation in the EU R&D network • Scandinavian knowledge network for LBG production under development	*Weaknesses:* • Few Norwegian actors involved with generating knowledge • Little attention given to maritime use of LBG
Direction of search	**Assessment: Intermediate**
Strengths: • Influenced by road transport and maritime LNG sectors • Clear political goals directing attention towards LoZeC solutions	*Weaknesses:* • Little attention given to maritime use of LBG
Entrepreneurial experimentation	**Assessment: Weak**
Strengths: • Spillover effects from experimentation within the LNG sector • Experimentation with business models regarding production of LBG • Development of new products from by-products and experimentation with raw materials	*Weaknesses:* • Limited experimentation with maritime applications for LBG
Market formation	**Assessment: Weak**
Strengths: • Growing market for LBG for heavy road transport could drive the market for maritime use of LBG • Liquefaction of biogas is a strategic market choice in general for the biogas market	*Weaknesses:* • Limited maritime market for LBG • Competition with the established LNG market with lower fuel prices
Legitimation	**Assessment: Weak**
Strengths: • Success rate of LNG ships and mixing LBG into LNG increases the legitimacy of LBG as a maritime fuel • Important actor investing in the technology • Increased use of LBG for heavy road transport could contribute to higher legitimacy within the maritime sector	*Weaknesses:* • Limited knowledge about maritime use of LBG • Uncertainties regarding fuel availability and fuel sustainability

Resource mobilization	**Assessment: Weak**
Strengths: • Public funding available from Enova, Innovasjon Norge and NO_x-fondet • Hurtigruten has signed a 7.5-year contract with Biokraft on LBG delivery	*Weaknesses:* • Limited number of actors applying for public funding of LBG projects
Development of positive externalities	**Assessment: Weak**
Strengths: • LNG infrastructure and technology development creates freeriding for LBG • Collaboration between research institutions and suppliers makes technology improvements available for a range of actors	*Weaknesses:* • Development of positive externalities within the LBG sector only is limited

4.3 Battery electric

The BE segment within the Norwegian MSS has developed rapidly in the last five years (see Table 8). The clear direction of search and diversity in entrepreneurial experimentation strengthens the current intermediate knowledge development and diffusion, which in turn contributes to the rapid development of the BE TIS. Due mainly to the success rate of pilot projects, BE propulsion technology has reached high legitimacy in a relatively short time, resulting in a rapid market expansion and the formation of nursing markets within the road ferry segment. Strong resource mobilization with available funding from several public institutions, as well as investments by shipowners, has enabled knowledge development and entrepreneurial experimentation, which in turn has reinforced legitimacy and belief in BE's growth potential. Development of positive externalities is currently limited to knowledge-sharing and synergies between the BE and hydrogen sectors, but has great potential once charging infrastructure, standards and regulations are fully in place.

Table 8 Summary of the functional analysis of the BE TIS

Knowledge development and diffusion	**Assessment: Intermediate**
Strengths: • Norwegian actors are central within the EU R&D network, as well as actively patenting BE technology • Strong national and regional networks increase knowledge development and diffusion through co-operation and competition	*Weaknesses:* • Still a need for development and upscaling of technology • Need for education of on-board personnel for operation and maintenance of new BE systems

Direction of search	Assessment: Strong
Strengths: • Clear political goals directing development, especially toward BE solutions • Influential, well-established actors have taken the lead on ordering BE ferries • Rapid technological development and drastically decreasing prices are incentives for new actors to invest • Synergies between different maritime electric solutions increases the legitimacy of BE propulsion	*Weaknesses:* • Reluctance among shipowners to try out different technologies at the same time, due to financial risk • Lack of standardizations and regulations to guide technology development
Entrepreneurial experimentation	**Assessment: Strong**
Strengths: • Experimentation initiated by several types of actors • Testing is done both in laboratories and on operating ships • Development contracts are positive for rapid technology development as well as operative testing and development of business models	*Weaknesses:* • Risk of technological lock-in due to specifications in public procurement contracts
Market formation	**Assessment: Strong**
Strengths: • Political climate goals and emission regulations create interest in BE technology • Rapidly increasing market size since 2010 • Size of battery packages growing fast • Ongoing changes in charter contracts for OSVs' new incentive for installation of battery packages	*Weaknesses:* • Shipowners and shipyards forced to take high risks when signing up for long-term public procurement contracts • Skewed financial support from the state in favouring larger actors
Legitimation	**Assessment: Strong**
Strengths: • Success rate of pilot testing and already operating BE ships shows that the technology works • Different types of electrical solutions increase the legitimacy of for BE propulsion • Current orders for BE ships will further improve the legitimacy	*Weaknesses:* • Uncertainties regarding battery life length and power grid capacity • Rules and regulations not entirely in place

Resource mobilization	Assessment: Strong
Strengths: - Funding available from both national and EU funds - Prioritized technology for national funding, with the highest support rate - Competence in BE solutions can be gathered from other electric power sectors	*Weaknesses:* - Competition relating to funding with other LoZeC technologies - Different levels of support within the respective funding schemes, and smaller actors struggle to obtain funding
Development of positive externalities	**Assessment: Intermediate**
Strengths: - Development contracts and strong knowledge networks broad extensive diffusion of knowledge and technology - Charging infrastructure can potentially be used by a number of actors - Synergies between BE and hydrogen technology	*Weaknesses:* - No standards for BE technology or charging infrastructure - Lack of cooperation between the BE and hydrogen TISs

4.4 Hydrogen

Maritime applications of hydrogen technology are currently only in operation in the form of pilot projects. However, second to electrification, hydrogen is believed to be the most promising future maritime clean fuel (see Table 9). Although most functions are currently assessed as intermediate, the clear direction of search steering innovation towards hydrogen technology will strengthen all functions within the hydrogen TIS once technological development speeds up. Especially Statens vegvesen’s development contract for a new hydrogen road ferry is likely to contribute to increased entrepreneurial experimentation, as well as knowledge development and diffusion, which in turn will increase legitimacy and spark the currently non-existent market formation. Furthermore, the development contract is likely to increase the possibilities for other projects to receive funding, as the technology will become more well-known, which will strengthen resource mobilization. Development of positive externalities, together with market formation, was identified as the weakest function, but as for the BE TIS, there is potential for future development of externalities once infrastructure and regulations have been implemented.

Table 9 Summary of the functional analysis of the hydrogen TIS

Knowledge development and diffusion	Assessment: Intermediate
Strengths: - Norwegian actors are central within the EU R&D network, as well as actively patenting fuel cell technology - Good collaboration between several types of actors within national and regional networks	*Weaknesses:* - Further development and large-scale testing of hydrogen technology needed - Need for education of on-board personnel for operation and maintenance of new hydrogen systems

Direction of search	**Assessment: Intermediate**
Strengths: • Clear political goals directing development toward hydrogen solutions • Seen as a complementary technology to BE technology, not as a competitor	*Weaknesses:* • Reluctance among shipowners to try out different LoZeC technologies at the same time, in part due to financial risk • Lack of standardizations and regulations to guide technology development
Entrepreneurial experimentation	**Assessment: Intermediate**
Strengths: • Pilot testing in operation, development contract starting in 2019 • Experimenting with different types of fuel cells, and sustainable production of hydrogen	*Weaknesses:* • Few actors involved in experimentation
Market formation	**Assessment: Weak**
Strengths: • Increasing market for hydrogen as a road transport fuel	*Weaknesses:* • Very limited market with need for large investments also in production and distribution • Investors hesitant due to high fuel prices • Available grey hydrogen not allowed to be used, given specifications in public procurement contracts
Legitimation	**Assessment: Intermediate**
Strengths: • Important actors starting to invest in hydrogen technology • Increasing belief in safety of the technology • Development of regulations as part of PILOT-E projects and Statens vegvesen's development contract • The parallel process of introducing hydrogen cars may speed up the legitimation process within the MSS	*Weaknesses:* • Rules and regulations lacking • Hydrogen ships currently classified as 'alternative designs', indicating technical immaturity
Resource mobilization	**Assessment: Intermediate**
Strengths: • Funding available from both national and EU sources • Prioritized technology for national funding, with the highest rate of support	*Weaknesses:* • Competition with other LoZeC technologies for funding • Difficult to find external investors willing to invest in hydrogen technology • Shortage of human capital with hydrogen competence

Development of positive externalities	Assessment: Weak
Strengths: • The development contract for the coming hydrogen road ferry will contribute to positive externalities • Synergies between BE and hydrogen technology	*Weaknesses:* • Non-existent MSS fuel infrastructure • Knowledge networks under development • Lack of cooperation between the BE and hydrogen TISs

4.5 TIS comparison

Our TIS functions assessment of the four different LoZeCs is summarized in a very simple form in Table 10. It is apparent that the biomass-based TIS are 'performing' poorly compared with hydrogen and especially battery electric. It is important to note that our assessment focuses on these energy solutions in the context of the Norwegian MSS. Developments in other application domains (e.g. road transport) may have both positive and negative impacts on the status of these LoZeCs in maritime transport. Furthermore, the assessment concerns their current status, yet we know from previous research that, for example, legitimacy may be gained rapidly but also lost very rapidly (Ruef and Markard, 2010)

Table 10 Comparison of TIS functions for biodiesel, LBG, hydrogen, and battery electric in the context of the MSS (red = weak, yellow = intermediate, green = strong)

Function Technological innovation system	Knowledge development and diffusion	Direction of search	Entrepreneurial experimentation	Market formation	Legitimation	Resource mobilization	Positive externalities
Biodiesel	🟥	🟥	🟥	🟥	🟥	🟥	🟥
LBG	🟥	🟨	🟥	🟥	🟥	🟥	🟥
Battery electric	🟨	🟩	🟩	🟩	🟩	🟩	🟨
Hydrogen	🟨	🟨	🟨	🟥	🟨	🟨	🟥

The above assessment forms the basis for our policy recommendations in the next section.

5 Policy recommendations

Although shipping only accounts for 3% of global GHG emissions and is a more sustainable option for transportation of goods than, for instance, road transport, there is still an urgent need to decrease emissions, as future global economic growth is expected to result in increased global trade and hence an increased need for transportation. Reducing emissions from maritime transport is especially important for Norway, as coastal shipping is a crucial part of the transportation system and also a large contributor to domestic GHG emissions. As Norway is already a global frontrunner within sustainable shipping, it is in a strong position to accelerate the development and uptake of low- and zero-carbon (LoZeC) alternatives to conventional fossil fuels.

It is well-established that policy mixes encompassing both market-pull measures and technology-push measures are needed to drive transformation processes towards sustainability (Rogge and Reichardt, 2016). This is shown in Figure 18, where this logic is applied to the development and deployment of renewable energy production technology. Figure 18 also highlights the industrial development needed to generate momentum, which represents new value creation opportunities associated with ‘green technologies’.

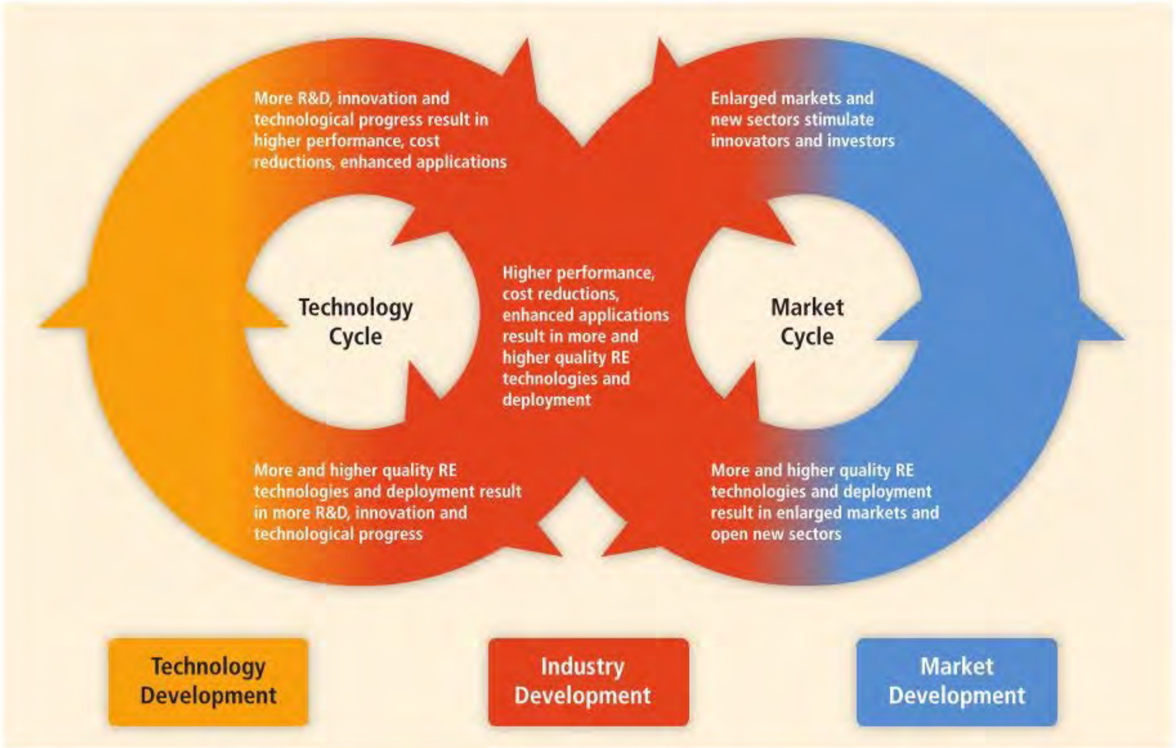

Figure 18 The mutually reinforcing cycles of technology development and market deployment. RE refers to renewable energy. Source: IPCC (2012)

Before providing TIS-specific recommendations, we provide some general policy recommendations:

- *Support variety:* The different TISs have advantages and disadvantages that make them suitable for different segments within the Norwegian MSS. The technologies presented in this report differ considerably in their maturation and implementation. Apart from biodiesel, they can all be regarded as being in early phases of development. Given the immense variety in ships and vessels (and hence energy needs), it is important that different LoZeCs are supported.

- *Beware of competition between emerging technologies:* Although not covered explicitly in this report, emerging TISs often compete for market shares and scarce resources. A policy challenge is to support various LoZeCs simultaneously, for example by ensuring that niche market opportunities exist for different technological solutions.

- *Make choices:* LoZeC technologies can be implemented in pure or hybrid forms. Given the abundance of cheap, renewable electricity in Norway, there is considerable potential for the expansion of BE and hydrogen. Although we refrain from making clear recommendations on which energy solutions to choose for which market segments, it appears that further development and uptake of hydrogen could be supported by focusing on this energy solution for high-speed ferries.

- *R&D support:* It is highly recommended that policies continue to support R&D, which is needed in both upstream and downstream dimensions of the different TIS. This includes supporting Norwegian participation in EU R&D networks.

- *Financial support:* As suggested in the report on the maritime sector to the expert committee on green competitiveness[12] (Grønt Kystfartsprogram, 2016), financial support (e.g. in the form of favourable loans or guarantee schemes) is needed in order to reduce risks associated with investing in ships with new energy solutions.

- *Cluster and networking support:* The existing maritime clusters (e.g. NCE Maritime CleanTech) appear to be an important locus of innovation activities related to LoZeC solutions. Support for cluster and networking initiatives should be continued and strengthened.

- *Increase the cost of fossil fuels:* In order to create economic incentives to make implementation of LoZeC technologies attractive to shipowners and public procurers, fossil fuel subsidies should be removed. The implementation of a CO_2 tax would incentivize fuel savings. Incomes from the CO_2 tax, as well as the public money currently spent on subventions of marine diesel, should assist the implementation of LoZeC technologies, for example through a LoZeC bonus or a CO_2 fund similar to NOx-fondet.

- *Harbour fees:* The implementation of differentiated harbour fees depending on individual ships' emissions (e.g. reduced harbour fees for ships with low emissions) can create further economic incentives for the introduction of alternative LoZeC solutions. However, there may be a need for national coordination and harmonization of harbour fees and other economic instruments between different ports, to avoid both complexity and inter-port competition (i.e. ports competing by charging low fees to attract customers)

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[12] Ekspertutvalget for grønn konkurransekraft, see https://www.gronnkonkurransekraft.no/files/2016/10/Strategi-for-gr%C3%B8nn-konkurransekraft.pdf

- *Licenses to operate:* In both the petroleum and aquaculture sectors, licenses to operate should include GHG emission-level requirements for maritime transport (e.g. supply ships, workboats, and feed carriers).

- *Provide support-seeking assistance:* A number of our interviewees reported that accessing the existing support measures (e.g. from Enova and Innovasjon Norge) was sometimes challenging. This applied especially to shipowners with limited administrative capacity, typically in segments such as fishing and freight. We recommend considering whether 'application assistance' could be provided to facilitate access to these funds for a broader group of actors.

- *Increase the number of development contracts:* The development contracts resulting in the first BE ferry and the first hydrogen ferry have been very important for the development of these LoZeC technologies. We recommend increasing the number of development contracts. However, in order to mitigate economic risks, increased financial support within the development contracts should be considered.

- *Public procurement as a tool:* In the passenger ferry segment, public procurement has been of central importance to facilitating the development and uptake of various LoZeC technologies and LNG. Through public procurement (i.e. by requiring low- or carbon-free transport of goods), public actors can stimulate a transition also in other segments, such as freight.

- *Maintain clear direction:* It is of central importance to keep and further sharpen climate policies and emissions regulations, both on the national level and the international level. As a global frontrunner within sustainable shipping, Norway should continue lobbying the IMO and other international actors for stricter emission regulations and targets for maritime transport.

5.1 TIS-specific recommendations

In addition to the general policy recommendations for all LoZeC technologies, we propose the following specific recommendations for the respective technologies, based on the strengths and weaknesses of their TIS.

5.1.1 Biodiesel

Since all functions for the biodiesel TIS are judged as weak, several types of policy actions would be needed to strengthen the TIS. Given that it is possible to use biodiesel in conventional diesel engines, the best incentive for increased use of this alternative fuel would be to subsidize the high price. Financing the subvention could be done by removing the subvention of marine diesel. However, given the considerable concerns about biodiesel availability and sustainability (with current production methods), as well as the fact that it may prolong the use of fossil fuels, our recommendation is to not focus policy support on biodiesel within the MSS per se. However, support for continued R&D on new ways of producing biodiesel would be beneficial.

5.1.2 LBG

The LBG TIS is currently overall not very strong, as all functions apart from *direction of search* are assessed as weak. The main measure recommended for implementation in order to strengthen the entire TIS is to support *resource mobilization* through increased public funding. Support is needed for the production of LBG, construction of bunker infrastructure, and for the building of gas-powered ships. Parallel to developing infrastructure for fuel production and distribution, it is important to stimulate *market formation*. This could also be done via LBG-dedicated (localized) pilot projects that include upstream LBG production. Apart from *resource mobilization*, this would strengthen *knowledge development and diffusion* and *entrepreneurial experimentation*. Furthermore, to support market uptake, LBG could be subsidized to the extent that it would match the market price for LNG.

Maintaining a clear *direction of search* is crucial in order to succeed in strengthening the remaining functions. Therefore, our recommendation is to reinforce the *direction of search* by implementing policies aimed at increased use of LBG within the MSS. Initially, the targets for LBG-LNG mixes should be established.

5.1.3 Battery electric

Although there has been a rapid expansion of BE in the passenger segment in recent years, the BE TIS is still in need of further support. The main system strengths of the BE TIS is its high *legitimacy*, clear *direction of search*, strong *market formation* and *resource mobilization*, as well as the diverse *entrepreneurial experimentation*. These functions provide the foundation for the success of large-scale implementation of BE storage systems in the Norwegian MSS. In order to preserve these functions' strengths, it is if central importance to maintain funding possibilities and innovation support. This in turn is important to ensure continued uptake of BE also in other market segments (e.g. fishing and freight). The measure would also strengthen *knowledge development and diffusion*, which is currently assessed as intermediate, as one of the identified system weaknesses is the continued need for development and upscaling of technology.

To strengthen *knowledge development and diffusion* further, we recommend the implementation of policies aimed at more cooperation between the BE and hydrogen TISs, in order to create further synergies between the two technologies, which would also strengthen the *development of positive externalities*. This could be done through, for example, dedicated R&D and pilot programmes that encompass both technologies. We have also identified a need for education of ship personnel regarding maintenance and operation of BE systems. Education could strengthen the *knowledge development and diffusion* and the *development of positive externalities*, as it would build up experience that could be shared within the TIS. Ensuring access to standardized charging infrastructure would further strengthen the *development of positive externalities* and increase the process of *legitimation* of the BE TIS. This would require that current issues related to electricity grid development and upgrading are addressed.

5.1.4 Hydrogen

Hydrogen appears to be a promising alternative for several segments in the future and is one of few feasible options for larger vessels. Considering the immaturity of the technology and its maritime applications, it is important to increase *resource mobilisation* to create possibilities for *knowledge development and diffusion* and for *entrepreneurial experimentation*, which in turn would strengthen *legitimation* and create *market formation*. We recommend that the *resource mobilisation* should be strengthened through increasing public funding of hydrogen ship technology by prioritizing hydrogen technology within the public funding programmes. To achieve a rapid introduction of hydrogen propulsion, it is important that funding is offered to hydrogen production, the building of infrastructure, and the development of maritime applications and construction of ships.

To strengthen further the currently intermediate functions *knowledge development and diffusion* and *entrepreneurial experimentation*, we strongly recommend that further development contracts should be awarded in the passenger segment, especially for high-speed ferries. In addition, to continue the improvement in the regulatory framework, especially regarding safety aspects, it is crucial to increase the process of *legitimation* within development contracts. It is especially important to achieve a classification of hydrogen ships, to avoid the costs of constructing a hydrogen vessel as an 'alternative design', which is Sjøfartsdirektoratet's current classification. This, in combination with the development contracts, would also strengthen *market formation*.

To initiate *market formation*, we recommend that initially the use of grey hydrogen should be permitted in order to increase available volumes rapidly. However, to avoid unnecessary use of natural gas-based hydrogen without carbon capture and storage (CCS), and to encourage further the sustainable production of hydrogen, a time limit on the use of grey hydrogen should be implemented. Given limited fuel availability, we also recommend starting the implementation of hydrogen in segments in which the impact on emission reductions will be substantial, notably passenger vessels.

Along with the implementation of hydrogen ship technology, there will be a need for education of on-board personnel regarding the maintenance and operation of the new systems. In addition, universities and maritime schools should update their curricula to include the operation of hydrogen ships. Apart from creating *knowledge development and diffusion*, education would also strengthen the *development of positive externalities*, as it would build up human capital. With regard to the BE TIS, we recommend the implementation of policies aimed at more cooperation between the BE and hydrogen TISs, in order to create further synergies between the two technologies, which would also strengthen the *development of positive externalities* (see also Section 5.3).

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A Appendixes

A.1 Overview of regulations

<table>
<tr><th colspan="4">Regulations potentially applicable to low- and zero-emissions energy solutions for the Norwegian maritime shipping sector</th></tr>
<tr><th>Battery</th><th>Hydrogen</th><th colspan="2">Biofuels</th></tr>
<tr><td></td><td></td><td><i>Liquefied Biogas (LBG)</i></td><td><i>Biodiesel</i></td></tr>
<tr><td colspan="4">International guidelines</td></tr>
<tr><td colspan="4">Guidelines for the approval of alternatives and equivalents provided in various IMO instruments, 2013</td></tr>
<tr><td></td><td colspan="3">ADR/RID – Regulations for transportation of dangerous cargo (on roads and railways) (1957 and 2008)</td></tr>
<tr><td></td><td colspan="2">International code for the construction and equipment of ships carrying liquefied gases in bulk (IGC Code) (1986)</td><td></td></tr>
<tr><td></td><td colspan="3">International code of safety for ships using gases or other low flashpoint fuels (IGF Code) 2015, entered in force in 2017 (fuel cells expected to be included in 2020)</td></tr>
<tr><td></td><td colspan="3">International maritime dangerous goods code (IMDG Code) (2016 Edition became mandatory in 2018)</td></tr>
<tr><td colspan="4">Norwegian national laws and other acts (both seaside and landside)</td></tr>
<tr><td colspan="4">Pollution Act (1981, last amended in 2017)</td></tr>
<tr><td colspan="4">Fire and explosion protection Act (2002, last amended in 2015)</td></tr>
<tr><td></td><td colspan="2">Regulation on pressure equipment (2017)</td><td></td></tr>
<tr><td colspan="4">Norwegian national laws and other acts (seaside)</td></tr>
<tr><td colspan="4">Shipping Act (1994, last amended in 2018): the vessel class defines the organization to approve the vessel at stake</td></tr>
<tr><td colspan="4">Ship Safety Act (2007, last amended in 2015)</td></tr>
<tr><td colspan="4">Regulation on maritime electrical installations (2002, last amended in 2013)</td></tr>
<tr><td colspan="4">Regulation on working environment, safety and health for those working aboard ships (2005, last amended in 2018)</td></tr>
<tr><td></td><td colspan="2">Regulation on vessels using fuel with a flashpoint below 60 °C (2017)</td><td></td></tr>
<tr><td>Guidelines for chemical energy storage - maritime battery systems, issued by the Norwegian Maritime Authority (2016)</td><td colspan="3"></td></tr>
</table>

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<tr><td colspan="4">Norwegian national laws and other Acts (landside)</td></tr>
<tr><td colspan="4">Energy Act (1990, last amended in 2018)</td></tr>
<tr><td colspan="4">Regulation on hazardous accidents (2016)</td></tr>
<tr><td></td><td colspan="3">Regulation on treatment of hazardous substances (2009, last amended in 2015)</td></tr>
<tr><td></td><td colspan="2">Regulation on simple pressure vessels (2017)</td><td></td></tr>
<tr><td></td><td colspan="3">Regulations for the areas with explosion risk (ATEX)</td></tr>
<tr><td></td><td></td><td>Norwegian gas standard (2005, in continuous development)</td><td></td></tr>
<tr><td colspan="4">Examples of other potentially applicable rules and guidelines</td></tr>
<tr><td>DNV GL Handbook – Maritime offshore battery systems (2016)</td><td>DNV-GL Rules for classification (2015, updated 2018)</td><td>DSB Thematic guide on the manufacturing and treatment of hazardous substances – process plants and biogas plants (2012)</td><td>European Committee for Standardization EN14214 (2012)</td></tr>
<tr><td>DNV-GL Rules for classification (2015, updated in 2018)</td><td>IEC 62282 Fuel cell technologies (2012)</td><td></td><td>European Committee for Standardization EN590 (biodiesel) (2013)</td></tr>
<tr><td></td><td>ISO 16110 Hydrogen generators (2007, reviewed and confirmed in 2016)</td><td></td><td></td></tr>
<tr><td colspan="4">International Acts establishing the context for the sustainability transition in maritime and shipping</td></tr>
<tr><td colspan="4">MARPOL [Marine Pollution] Annex VI (2011, IMO) with amendments for CO_2 adopted in 2016</td></tr>
<tr><td colspan="4">IMO guidelines on noise from commercial shipping and its adverse impacts on marine life (2013)</td></tr>
<tr><td colspan="4">Directive 2014/94/EU of the European Parliament and of the Council on the deployment of alternative fuels infrastructure (2014)</td></tr>
<tr><td colspan="4">EU monitoring, reporting and verification regulation (MRV) (2015)</td></tr>
<tr><td colspan="4">EU directive on sulphur content in marine fuels 2012/33/EU (2012)</td></tr>
<tr><td colspan="4">European strategy for low-emission mobility (2016)</td></tr>
<tr><td colspan="4">NECA regulation on Baltic and North Sea NOx environmental control area (2017)</td></tr>
<tr><td colspan="4">Resolution MEPC 304 (72) on initial IMO strategy on reduction of GHG emissions from ships (2018)</td></tr>
</table>

Note: The overview is based on a number of reports addressing the legal frameworks for respective technologies, as well as information available at the public website lovdata.no

A preliminary version of the overview was sent to a representative of Sjøfartsdirektoratet for confirmation and adjusted in compliance with received comments. This summary does not aim to provide a full overview of the regulatory framework, but rather illustrate the multi-scalar nature of governance and formal institutions in the Norwegian maritime shipping sector.

A.2 Projects in phase 1 and 2 of the Grønt Kystfartsprogram. Sources: Stensvold (2016a), Stensvold (2016b), Kystrederiene (2017)

Project manager	Project	Technology	Segment	Phase
Norlines	Plug-in hybrid freight ferry	Battery	Passenger	1
Teekay	Battery hybrid shuttle tanker	Battery	Offshore	1, 2
ABB/Fraktefartøyenes rederiforening	Hybrid-propulsion for fish farm vessels	Battery	Aquaculture	1, 2
Øytank Bunkerservice/Energigass Norge	Transformation of freight ship to a hybrid LNG bunkering vessel	Battery	Freight	1
Risavika Port	Green port – electrification and promotion of lower energy consumption	Battery	Port/infrastructure	1, 2
Torghatten	Plug-in hybrid biodiesel ferry	Biodiesel	Passenger	2
Flora Municipality	Hydrogen-driven high-speed passenger boat	Hydrogen	Passenger	2
Kongsberg	Zero-emission autonomous container ship	Battery	Freight	2
Kystrederiene	Fish transport from road to sea	LNG	Aquaculture	2
Fiskebåt	Low-emission fishing vessel	Battery, LNG or biofuel (several concepts considered)	Fishery	2

A.3 Interview overview

Int. No.	Organization type	Year	No. of interviewees	Interview reference
1	NGO	2015	1	NGO1, 2015
2	Industry association	2015	1	IA1, 2015
3	Industry association	2015	1	IA2, 2015
4	Classification company	2015	1	C1, 2015
5	Public authority	2016	1	PA1, 2016
6	Public authority	2016	1	PA2, 2016
7	Shipyard	2017	1	SY1, 2017
8	Public support agency	2017	2	PSA1, 2017
9	R&D	2017	1	R&D1, 2017
10	Technology supplier	2017	1	TS1, 2017
11	Shipowner	2017	2	SO1, 2017
12	R&D	2017	1	R&D2, 2017
13	R&D	2017	1	R&D3, 2017
14	Fuel producer	2017	1	FP1, 2017
15	Public authority	2017	3	PA2, 2017
16	Classification company	2017	1	C1, 2017
17	Technology supplier	2017	1	TS2, 2017
18	Other	2017	1	O1, 2017
19	Public support agency	2017	1	PSA2, 2017
20	Technology supplier	2017	2	TS3, 2017
21	Public authority	2017	2	PA3, 2017
22	Cluster organization	2017	2	CO1, 2017
23	Shipowner	2017	1	SO2, 2017
24	Technology supplier	2017	1	TS4, 2017
25	Technology supplier	2017	2	TS5, 2017
26	Shipowner	2017	1	SO3, 2017
27	Public authority	2017	2	PA2, 2017
28	Shipowner	2017	1	SO4, 2017
29	Shipyard	2017	1	SY2, 2017
30	Ship design	2017	1	SD1, 2017
31	R&D	2017	1	R&D4, 2017
32	Technology supplier	2017	1	TS6, 2017
33	Shipowner	2017	2	SO5, 2017
34	Technology supplier	2017	1	TS7, 2017
35	Shipowner	2017	1	SO6, 2017
36	Public authority	2017	2	PA4, 2017
37	Fuel producer	2017	2	FP2, 2017
38	Industry association	2017	1	IA3, 2017
39	Shipowner	2017	1	SO7, 2017
40	Shipowner	2017	1	SO8, 2018
41	Shipowner	2018	1	SO9, 2018
42	R&D	2018	2	R&D5, 2018
43	Industry association	2018	1	IA4, 2018
44	Shipowner	2018	1	SO10, 2018
45	Ship design	2018	1	SD2, 2018

Int. No.	Organization type	Year	No. of interviewees	Interview reference
46	Technology supplier	2018	2	TS8
47	Shipowner	2018	1	SO11, 2018
48	Shipyard	2018	2	SY3, 2018
49	Tech.-specific interest group	2018	1	TIG1, 2018
50	Ship design/shipyard	2018	2	SD/Y3, 2018
51	Shipyard	2018	2	SY4, 2018
52	Technology supplier	2018	2	TS9, 2018
53	Public authority	2018	3	PA3, 2018
54	Shipowner	2018	1	SO12, 2018
55	Shipowner	2018	1	SO13, 2018
56	Public authority	2018	1	PA1, 2018a
57	Shipyard	2018	1	SY5, 2018
58	Shipowner	2019	1	SO14, 2019
59	Industry association	2019	1	IA1, 2019
60	Tech.-specific interest group	2019	1	TIG2, 2019
61	Industry association	2019	1	IA5, 2019
62	Other	2019	1	O1, 2019
63	Fuel producer/distributor	2019	2	FP3, 2019
64	Fuel producer	2019	1	FP4, 2019
65	R&D	2019	1	R&D6, 2019
66	Tech.-specific interest group	2018	1	TIG3, 2018
67	Industry association	2018	2	IA6, 2018
68	Technology supplier	2018	1	TS2, 2018
69	Shipowner	2018	1	SO7, 2018
70	Public authority	2018	1	PA1, 2018b
71	Technology supplier	2018	1	TS10, 2018
72	Technology supplier	2018	1	TS11, 2018

A.4 Overview types of members of networks, 2018. Compilation based on organizations' websites

Members Network	Total number of members	Shipowners	Shipyards	Technology suppliers (for vessels)	Tech. supplier (for infrastructure)	Technology supplier (other)	Classification/standardization	Ship/maritime designers	System integrators	R&D	Public support agencies	Public authorities	NGOs	Local/regional government	Logistic operators	Ports/harbours	Power source specific	Non-maritime	Other
GCE Blue Maritime	141	11	7	53	2	20	1	4	2	7	3	1	0	2	3	0	0	4	21
Grønt Kystfartsprogram	26	4	0	3	0	0	1	0	1	0	1	0	0	2	0	1	4	0	9
Norsk Hydrogenforum	44	0	0	1	0	3	1	0	0	8	2	2	2	0	0	0	12	9	4
Maritime Battery Forum	45	4	1	14	0	0	3	0	1	5	2	4	0	0	1	0	7	0	3
NCE Maritime CleanTech	74	9	3	17	0	8	1	3	1	8	0	1	0	4	1	1	5	3	9

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