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The sectoral interdependencies of low-carbon innovations in sustainability transitions

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Abstract

Sectoral interdependencies of low-carbon technologies arguably become increasingly important as sustainability transitions accelerate. Nevertheless, few conceptual and empirical studies examine how the formation of interdependencies with various sectors, providing key inputs or applications within and across value chains of low-carbon technologies, affect acceleration. We provide novel insights on these topics by developing a multi-sectoral and multi-technological perspective on low-carbon innovation. Empirically, we apply the framework to Norwegian coastal shipping, and study how sectoral interdependencies across the value chains (raw materials, production, distribution and use) of battery-electric, hydrogen and liquefied biogas technologies affect innovation in these technologies in the formation and acceleration phases. We find the implications of interdependencies for acceleration to depend on sector characteristics. Low user sector adaptability (e.g. due to sunk costs), and interdependencies with input sectors with low scalability, constituted negative feedbacks for hydrogen and liquified biogas technologies. Meanwhile, battery-electric vessels' interdependencies with scalable input sectors created positive feedback loops, supporting acceleration. We conclude by noting that to foster acceleration, transition research and policy may need to address the sectoral interdependencies of low-carbon technologies already in the early phase of innovations.

Keywords

sectoral interdependencies, sustainability transitions, acceleration, low-carbon innovation, coastal shipping sector

1. Introduction

Pressing environmental problems, such as climate change, require further acceleration of transitions towards more sustainable modes of production and consumption in e.g. energy, transport and food. The academic field dedicated to the analysis of such sectoral transitions, sustainability transition studies, has made progress in developing theories and analytical tools for a better understanding of such processes. A key insight in the field is that transitions are systemic in nature, characterized by co-evolution between different actors, institutions, supply and distribution chains, etc. (Markard et al., 2012).

Empirical studies of sustainability transitions have thus far often been limited to singular niche-innovations in single sectors (Markard, 2018, Rosenbloom, 2020). Moreover, the inherent focus of frameworks such as the multi-level perspective (Geels, 2002) and the technological innovation system (Bergek et al., 2008) has been on a single focal sector or a technology, downplaying the multi-sectoral and multi-technological nature of transitions (Bergek et al., 2015, Geels, 2018). Such interactions within and across the value chains of technologies nevertheless constitute a web of interdependencies which are at the heart of understanding change in the *systems* of production and consumption (Rosenbloom, 2020). For instance, the value chain of solar PV technology consists of inputs from a number of different sectors (Hanson, 2018), while the safe disposal of waste water depend on e.g. adequate sewage systems and waste water treatment (van Welie et al., 2019). However, few studies have yet taken such a "whole system" perspective (Geels, 2018, Andersen et al., 2020, Markard et al., 2020).

Some authors have already taken on the scholarly challenge of addressing such interactions (Markard et al., 2020). For instance Markard and Hoffman (2016) have elaborated on the complementarities between technologies and sectors, while McMeekin and colleagues (2019) have pointed to the challenges of changing the "system architecture" of sectors. Andersen and Markard (2020) have addressed the importance of multi-technology interaction within and across sectors.

These interactions have been argued to be particularly important when sustainability transitions accelerate and sustainable innovations start diffusing rapidly (Markard, 2018, Markard et al., 2020). Challenges related to acceleration are therefore less about fostering the emergence of sustainable technologies or early-phase R&D, and more about rapidly increasing diffusion and necessary complementary developments in interdependent technologies and sectors. A case in point is the electricity sector, where an increased share of renewable energy sources in the electricity supply requires changes in e.g. electricity distribution (smart grids, transmission lines etc.), energy storage, and use (e.g. electric vehicles, smart homes) (cf. Andersen, 2014). It is therefore expected that the complex interactions between sectors and technologies become ever more pronounced as transitions advance, requiring more analytical efforts from sustainability transitions scholars to address such topics of acceleration (Markard, 2018, Gielen et al., 2019, Markard et al., 2020).

However, there is yet a need for more conceptual and empirical studies employing a multi-sectoral and multi-technological perspective in the context of acceleration. This need is further accentuated when considering the variety of different sectors that play important roles in transitions, including those that provide key inputs for sustainable innovations, such as low-carbon fuels, and those sectors in which these innovations are applied.

First, few studies on sustainability transitions have provided perspectives that allow a comprehensive analysis of interaction between several input sectors and low-carbon technologies. An exception is Malhotra and colleagues (2019) who showed how the value chains of different technologies may affect learning. It is nevertheless necessary to create further knowledge regarding the effect of sectoral interdependencies (including, but not limited to, learning) for low-carbon innovation, and how they may affect the complementarities and competition between low-carbon technologies. Such perspectives are also highly relevant for transition policy which may face the need of not only supporting technology development via e.g. R&D support, but also addressing barriers related to the emergence of whole value chains (Huttunen et al., 2014), potentially in *multiple* technologies (Magnusson and Berggren, 2018).

Second, while recent research has strengthened the understanding of sectoral couplings particularly in the production of technologies (Stephan et al., 2017, Malhotra et al., 2019, Andersen and Markard, 2020), little conceptual development has been directed towards the characteristics and dynamics of sectors providing the energy and material inputs for low-carbon technologies, especially as such innovations accelerate. This constitutes an important gap, as several empirical studies have recognized the importance of such input sectors for sustainability transitions, particularly in the case of biofuels where limited supply of raw materials (biomass) results in legitimacy issues for the technology (e.g. Bennett, 2012, Sutherland et al., 2015, Markard et al., 2016). It is necessary to build on this work to pay further attention to the capabilities of material and energy sectors to provide the necessary inputs in the context of accelerating sustainability transitions.

Third, there is a dearth of research into how the development of low-carbon innovations in one user sector may influence the development of technologies in other user sectors. It is nevertheless well known that radical innovations may develop in multiple niche applications prior to a breakthrough (Raven, 2007). For instance, solar PV technology has benefited from niche uses such as space satellites and consumer electronics on its way of becoming a cheap source of electricity (Nemet, 2019), and lithium-ion battery innovation has benefitted from development in multiple user sectors (e.g. electronics, transport, power) (Stephan et al., 2017). However, such interactions, and their implications, are yet little studied in the context of accelerating transitions.

In sum, the conceptual connections between sectoral interdependencies and acceleration need to be strengthened. We contribute by developing a framework for the analysis of sectoral interdependencies of technologies, providing a holistic perspective on the value chains of low-carbon technologies, and their implications for transitions. This multi-sectoral and multi-technological perspective elaborates on 1) the role the interdependencies of low-carbon technologies with sectors along their value chain segments of production, distribution and use, 2) how the characteristics of sectors providing key inputs or applications may affect the acceleration of low-carbon innovations, and 3) how the different sectoral interdependencies of low-carbon technologies may affect the complementarities and competition between technologies.

Empirically we analyse the ongoing sustainability transition in coastal shipping – a sector that has received limited attention in the sustainability transitions literature – in Norway. We study three novel low-carbon energy technologies considered highly relevant as alternatives to fossil fuels in coastal shipping (DNV GL, 2015c): battery-electric, hydrogen and liquefied biogas (LBG). Our multi-technological and multi-sectoral analysis unpacks the dependencies of these technologies throughout and across their value chains (raw materials, production, distribution, and use), all of which may have implications for a sustainability transition in Norwegian coastal shipping. Moreover, we assess how these relationships may evolve in both the early formative phase and the possible acceleration phase. We emphasize how the scalability of input sectors (e.g. production of biogas) and the adaptability of user sectors (coastal shipping) may influence the transition. Our qualitative analysis is based on 36 semi-structured interviews with various industry actors in Norwegian coastal shipping, industry reports, and participation in industry events.

2. Sectoral transitions and interdependencies

2.1. Interdependencies and acceleration

Although the sectoral interdependencies of low-carbon innovation is yet an understudied phenomenon in sustainability transitions, it is not a new topic in the wider field of innovation studies. For instance Rosenberg (1979) suggested that the development of technologies is dependent on complementary developments in interlinked technologies. Dahmén (1988) further argued that such complementarities take place in sequences and evolve over time, while the lack of complementary developments in interdependent systems may hinder the further development of technologies.

Such interdependencies become more evident as transitions accelerate, i.e. as innovations become rapidly more diffused (Markard et al., 2020). Acceleration is a result of positive feedback loops reinforcing each other (Rotmans et al., 2001). Such mechanisms exist in several forms. For instance, positive feedback loops may appear if the innovative activities of actors lead to further innovation processes and activities, thus providing momentum for technological innovation (Negro and Hekkert, 2008, Suurs and Hekkert, 2009). Feedback loops may also emerge between technologies, or between technologies and sectors, in the form of complementary developments driving innovation (Onufrey and Bergek, 2015, Markard and Hoffmann, 2016), or between policy and sectoral change (Edmondson et al., 2019). In contrast, the lack of complementary developments and feedback mechanisms may hinder acceleration (Wirth and Markard, 2011, Markard and Hoffmann, 2016).

2.2. Sectors and technologies

We understand technologies as physical artefacts and knowledge which serve a specific functional need in sectors (Das and Van de Ven, 2000). Conversely, technologies are dependent on various sectors for inputs and outputs. In this paper we focus on such interdependencies by discussing two archetypal sectors relevant for technological innovation: user sectors and input sectors (including raw material, production and distribution sectors).

Technologies are means to an end, and to e.g. mitigate climate change, unsustainable technologies in *user sectors* (e.g. the combustion engine in transport) may have to be substituted. The focus in sustainability transition studies is thus typically on transitions taking place in user sectors (Markard et al., 2012). Dolata (2009) argues that such sectoral change is affected by the transformative capacity of technologies, and the adaptability of socioeconomic structures, institutions and actors of the sector. The former refers to how technology characteristics may fit and supplement the existing structures and institutions of one user sector, and alternatively disrupt others. The adaptability of sectors refers to the capabilities and institutional mechanisms of user sectors and whether they enable to transform and adapt to new technologies, or alternatively ignore or resist technologies. Adaptability also refers to how fast sectors typically change. User sectors with long investment cycles, such as process industries (e.g. factories) and shipping (e.g. vessels and ports), are slow to change, and can thus pose barriers for sustainability transitions (Markard, 2011, Kushnir et al., 2020).

However, while Dolata's framework is useful in describing the interplays between technologies and user sectors, it says little on the role of *input sectors*, and how they may affect transitions. Input sectors refer to the value chain sectors providing inputs (e.g. renewable power supply) needed for the technology (e.g. electric vehicle) to fulfill its purpose in a user sector (e.g. land-based transport).

We outline three generic input sectors which 1) source *raw materials*, 2) *produce* these materials into consumable products and commodities, and 3) *distribute* them to user sectors' locations of need. In the case of electricity supply, sectors such as fossil fuel extraction or mining provide raw materials for electricity production. These materials (e.g. natural gas, coal) are converted into electricity in power plants. Finally, power transmission lines and grids are needed to distribute electricity to consumers. The relevance and types of input sectors differ across technologies. Technologies are also interdependent with various sectors producing components and services for technologies (Andersen et al., 2020), however, the evaluation of such relations remains out of scope of this paper (for this topic see e.g. Stephan et al., 2017, Malhotra et al., 2019, Andersen and Markard, 2020). Instead, we focus on input sectors that provide the energy or other material through-put necessary for applying sustainable technologies, i.e. the sourcing and production of renewable energy and zero-carbon fuels, and their distribution.

Input sectors' ability to meet the growing demand for raw materials, production and distribution is essential for acceleration. The *scalability* of input sectors is thus highly important. This refers to input sectors` ability to meet the growing demand caused by broader technology diffusion. Low scalability may severely hamper innovation, an example being the difficulties to acquire land for onshore wind power production in some European countries. In comparison, input sectors without scalability issues may help the innovation to accelerate.

2.3. Dependencies and interdependencies

The relationships between technologies and sectors can be characterized as *dependencies* (e.g. a sector influencing a technology) or *interdependencies* (a sector influencing a technology, and vice versa) (Bergek et al., 2015, Markard and Hoffmann, 2016). Interdependence is a two-way relationship where the state of one element influences or correlates with the state of the other element (Rinaldi et al., 2001). Dependence means a one-way relationship of influence. A single technology can have dependencies and interdependencies with multiple input and user sectors (Stephan et al., 2017).

Technologies and sectors evolve over time, which means that also their interaction changes. In the formative phase of technologies (i.e. early development, experimentation, niche market application), sectoral interaction is usually one-directional, where an emerging technology can be dependent on a sector, but not vice versa (Markard, 2020). For instance, electric vehicles in their formative phase have yet rather little influence on the land-based transport sector as a whole. However, dependencies may turn into interdependencies if the technological innovation enters an acceleration phase (Markard, 2018, Markard et al., 2020). In this phase the technology increasingly begins to affect multiple sectors (Markard, 2020). For instance, as electric vehicles move into an acceleration phase, changes in the value chain are likely to take place in terms of e.g. user behavior, charging infrastructure and power distribution.

Sectoral (inter)dependencies of technologies may have different implications for innovation (Raven and Verbong, 2007) which may affect the competitive status of technologies vis-à-vis other technologies (Andersen and Markard, 2020). For the purposes of this paper, we identify two main modes: positive (complementing) and negative (non-complementing) implications for innovation (Mäkitie et al., 2018). Positive (inter)dependencies are important for innovation because the development, effectiveness and significance of a technology may depend on the development of different sectors (Rosenberg, 1979, Sandén and Hillman, 2011). The interdependence may lead to positive feedback loops where the developments in a technology and a sector reinforce each other over time (Markard and Hoffmann, 2016), driving further acceleration, and strengthening the competitive position of the technology against others (cf. Sandén and Hillman, 2011).

Negative (inter)dependencies refer to an interaction that impedes technological innovation, potentially causing delays or bottlenecks in transitions (Markard and Hoffmann, 2016), and influence actors to focus on other, more promising, technologies. An example of negative interdependence is the necessity of using scarce arable land for producing energy crops for biofuels, creating competition between energy and food production (Sutherland et al., 2015).

Another characteristic of (inter)dependencies is their *intensity*, i.e. how critical the (inter)dependence is for innovation. Markard and Hoffman (2016) differentiate between strong and weak interdependence. Strong interdependence means that the acceleration of technological innovation is highly dependent on further development in a sector, and vice versa. Such interdependence may be absolute, e.g. electric vehicles and charging infrastructure. Weak (inter)dependence refers to a situation where developments in a sector has implications for acceleration but does not amount to high importance. An example is the adoption of technologies in niche markets: for instance powering oil and gas platforms may serve as a niche for floating offshore wind power (Hansen and Steen, 2015), but this technology has also many other potential (niche) markets (Mäkitie, 2020).

2.4. Analytical framework

Figures 1 and 2 summarize the dimensions of interdependencies in the formative and the acceleration phase. Figure 1 illustrates two different technologies (Tech 1 and 2) that are used in two sectors (User sectors 1 and 2). Besides user sectors, these technologies are linked with input sectors, portrayed here as the generic sectors of raw materials, production, and distribution. Technologies have different input sectors. For instance, while both hydrogen and biofuel technologies may be used in mobility sectors (e.g. aviation and land-based transport), their respective input sectors differ (e.g. supply of electricity, biomass). The input sectors, user sectors and technologies are embedded in political, economic and geographical contexts, and may also interact with other parallel sectors and technologies (cf. Bergek et al., 2015).

In the formative phase (Figure 1), when diffusion remains limited, technologies depend on input sectors and user sectors (black arrows) but as technologies are yet few in numbers, they are unlikely to have much impact on sectors (Markard, 2020). The influence is thus likely one-directional (from sector to technology). The effect of these dependencies on innovation differ in their mode (positive or negative for innovation) and intensity (strong or weak).

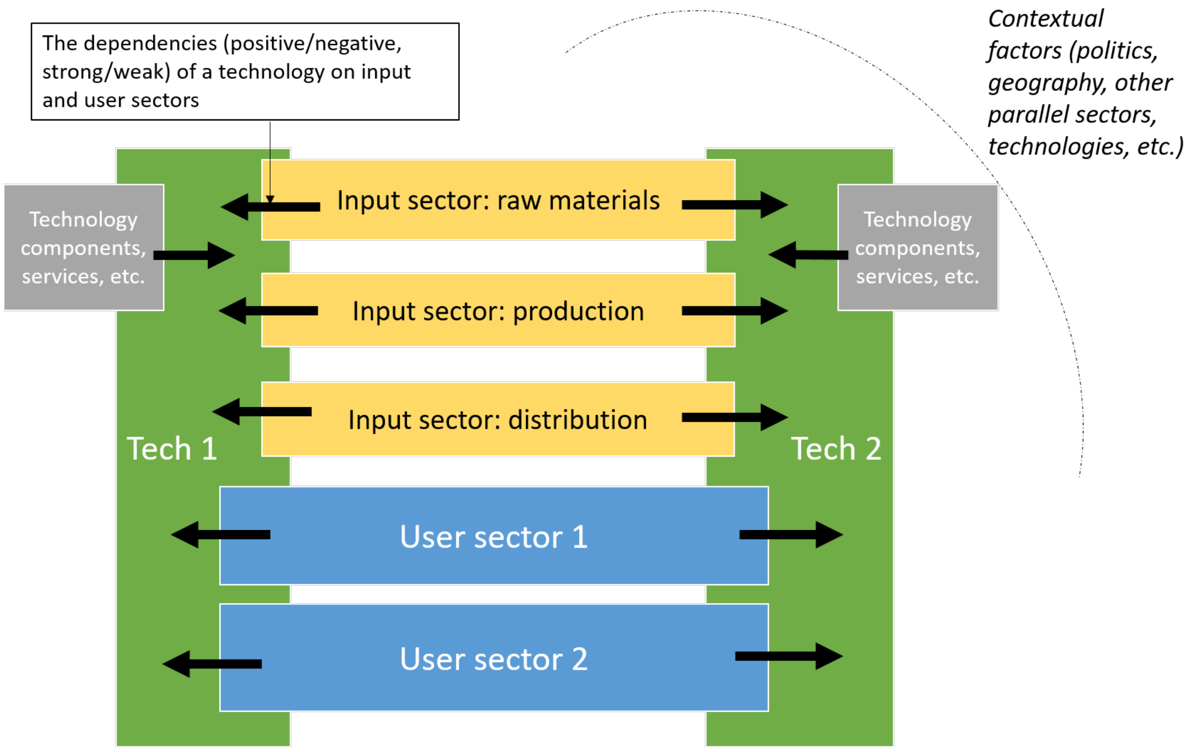

FIGURE 1 DEPENDENCIES OF TECHNOLOGIES ON INPUT AND USER SECTORS IN THE FORMATIVE PHASE OF INNOVATION.

These technology-sector relationships may increasingly turn into two-directional interdependencies in the acceleration phase (Markard, 2020) as feedback loops emerge (Figure 2). Importantly, because of this increased impact of a technology on input and user sectors, the characteristics of these sectors begin to play a larger role for innovation. We explore two types of sectoral characteristics relevant for acceleration. First, input sectors differ in terms of their *scalability*, i.e. their potential to cater for the growing demand caused by increased diffusion in user sector(s). The scalability of input sectors therefore acts as a precondition for positive feedback loops necessary for acceleration. Second, user sectors differ in terms of their *adaptability*, i.e. to what extent they are suited to adopt specific new technologies (Dolata, 2009). Adaptability of sectors, coupled with the characteristics of novel technologies, therefore affects the emergence of feedback loops in specific innovations, driving or stalling acceleration.

The same technology may be used in different user sectors, and different technologies may be interdependent with same input sectors. Such overlaps in interdependencies may have further system effects for innovation, as the increased diffusion of a technology in one user sector may have ripple effects for innovation in other user sectors. As an example, a technology's input sectors may scale up due to an increased demand caused by the technology diffusion, clearing the path for technology diffusion also in other sectors. For instance the possible future use of hydrogen in process industries may lead to increased adoption of hydrogen also in e.g. transport sectors, provided that the hydrogen production can be further upscaled. Contrariwise, if the input sector is unscalable, different user sectors may have to compete for the input. A typical example of such relationship is biofuels, where limited availability of biomass (given current technology) may not allow large-scale diffusion of biofuels in multiple user sectors.

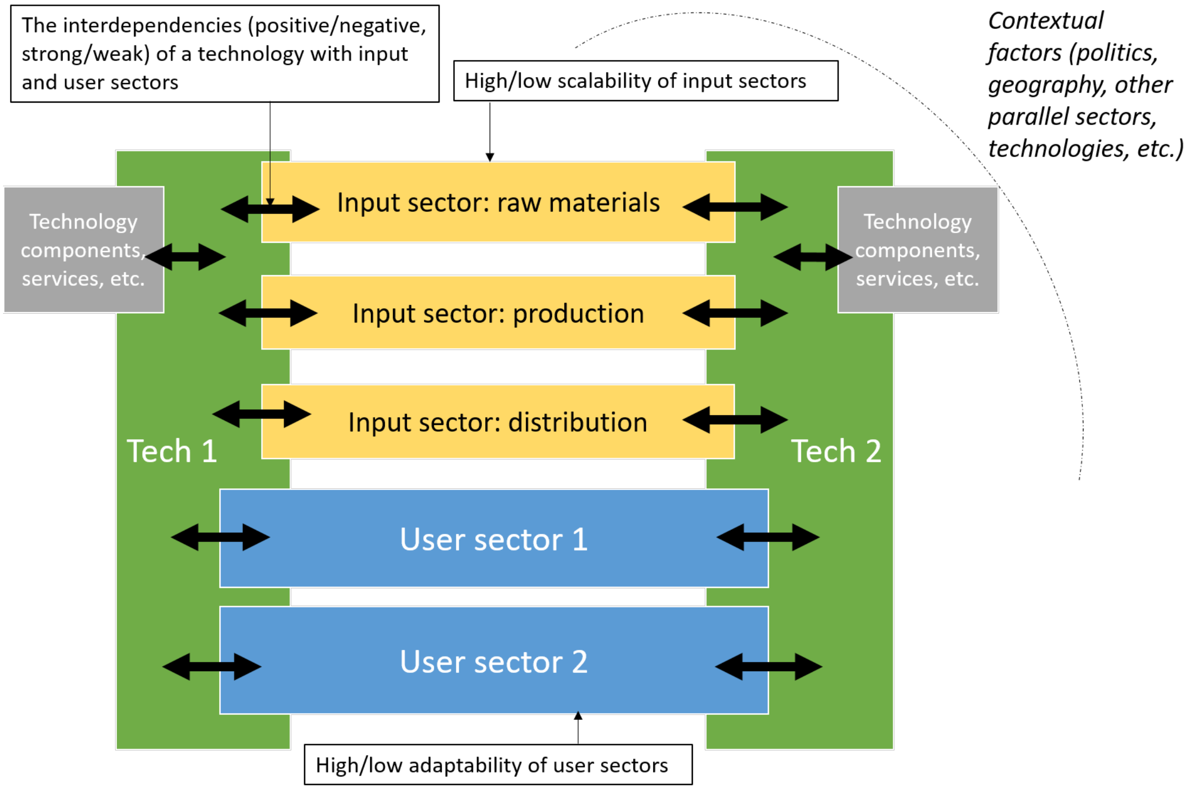

Figure 2 Interdependencies of technologies with input sectors and user sectors in the acceleration phase of innovation.

3. Methodology

We employ the framework presented in section 2.4 on a case study of low-carbon technologies in the Norwegian coastal shipping sector. This paper emanates from a research project wherein 74 semi-structured interviews were performed with various private and non-private actors in the Norwegian maritime sector over the time-period 2015-2020, with the bulk of interviews conducted in 2017-2019. Interviews covered the development and diffusion of battery-electric, biofuel and hydrogen powered vessels in the Norwegian coastal shipping sector. The interviews lasted on average 70 minutes and were tailored for different informant types (e.g. shipping companies, technology suppliers, fuel producers, public authorities). The informants were typically senior managers, business development and technology personnel, or maritime regulation experts. 59 of the interviews were conducted in person while 15 were made over videoconference/telephone. All but eight interviews were recorded and transcribed in verbatim, and extensive notes were gathered in the unrecorded ones.

While the whole body of 74 interviews formed the necessary understanding of the innovation processes around the technologies, 36 interviews discussed topics related to sectoral interdependencies. These 36 interviews (see Appendix for an overview) formed the main data source for our qualitative analysis. This primary data was complemented with secondary material from industry reports, media, and industry events.

Interview transcripts (and notes) were coded in NVivo in two rounds. Initially, a generic coding round for the purposes of the research project (innovation in low-carbon technologies) was performed by the research project team, using a top-down coding strategy identifying the relevant low-carbon technologies, innovation processes and contextual elements (including sectoral interdependencies). A codebook was developed and discussed between the authors and other research group members in a workshop. Thereafter a pilot round of two-three persons coding the same three interviews was performed to ensure coherence in interpretation. In the final step of the first round, coding was completed individually. During this first round of coding, technology-sector (inter)dependencies emerged as a salient feature related to innovation processes, and motivated further exploration.

The code of sector-technology relations thus formed the main sample for the second round of coding (some additional coding was later added manually) performed for the specific scope of this paper. Identified industry reports on sector-technology topics and notes from industry events were also coded to supplement our primary data. This second round used a bottom-up approach by inductively identifying 1) the (inter)dependent relationships between the battery-electric, hydrogen and biogas technologies and the identified input and user sectors, and 2) the main characteristics and issues related to these sectoral (inter)dependencies and sectors, relevant for innovation in the three focal technologies. This second round coding was performed by the lead author and resulted in a total of 27 codes having relevance for the studied low-carbon innovations. The data under these codes was evaluated for indications regarding the characteristics of (inter)dependencies (which technologies and sectors, 1- or 2-way interaction) and sectors (adaptability of user sectors, and scalability of input sectors) in both the formative and acceleration phase (where applicable), and finally, for the identified implications for further innovation of specific low-carbon technologies. This preliminary analysis was refined and discussed in a full day analysis workshop with all paper authors evaluating each code with the help of data excerpts. This process refined the preliminary 27 codes into final 17 codes, which formed the results presented in section 5.

4. Low-carbon transition in Norwegian coastal shipping

Maritime shipping constitutes one of Norway's largest and economically most important sectors. The Norwegian fleet ranks among world's largest, and has a high share of advanced vessels such as those used in offshore energy production (both petroleum and renewable). The maritime sector forms a complete and highly competitive industrial cluster, with a broad range of actors including ship owners, yards, designers, equipment suppliers and knowledge-intensive business services (Mellbye et al., 2016). The industry is supported by large research institutes and universities.

With a long and jagged coastline, transport by sea has always been important in Norway. Many of Norway's key economic sectors are tightly linked to shipping, such as offshore petroleum, fishing and aquaculture. To meet the harsh sea conditions in Norway, these sectors have articulated demand for robust and advanced ships. Due to the importance of logistics and transport by sea, the emissions from maritime transport are relatively high in Norway compared to many other countries. Reducing greenhouse gas (GHG) emissions to comply with Norwegian emission reduction targets is therefore a key policy objective, particularly for coastal shipping. These vessels operate mostly within Norwegian waters, subject to national emission reduction targets. A secondary motivation for firms in the maritime sector is to develop new energy solutions that can be exported globally (Steen, 2018). Nevertheless, the empirical focus of our study is limited to coastal shipping in Norway, e.g. passenger vessels (ferries and cruise vessels), offshore supply vessels, and fishing vessels, and thus excludes international deep-sea shipping.

Biogas, battery-electric and hydrogen vessels have until now attracted most attention in Norwegian coastal shipping, driven by public innovation policy and development programs, private investment and national ambitions to reduce emissions (Steen et al., 2019). The application of batteries on ferry and passenger vessels is well underway (Bergek et al., 2018, Sjøtun, 2019), and hydrogen demonstration projects are under development (Bach et al., 2020). While these technologies share the same societal ambition of reducing GHG emissions, their individual characteristics (e.g. different energy sources) imply different supply and distribution chains. This case therefore offers a suitable empirical context to analyze interdependencies within and across the value chains of multiple low-carbon technologies, and the resulting implications for a sustainability transition.

Biogas can be produced from multiple forms of biomass, such as organic waste. Following liquefaction, liquefied biogas (LBG) is fully interchangeable with liquefied natural gas (LNG) and can be used in same engines (Bach et al., under review). Due to its energy-density, vessels using LNG/LBG are suitable for long-distance shipping. Fully *electric* ships operate with chargeable battery-packs. With current battery technology, battery-electric vessels are only possible for relatively short operating distances (e.g. ferries). The use of *hydrogen* relies on the use of fuel cells, e.g. proton exchange membrane or solid oxide fuel cells, which convert hydrogen fuel into electricity (Tronstad et al., 2017).[1] Finally, it should be noted that all technologies also exist in hybrid versions where they are combined with each other or with conventional fossil fuel-based propulsion technologies.

5. Sectoral interdependencies of low-carbon vessels

In Figure 3 we summarize our analysis of the sectoral (inter)dependencies of hydrogen (H2), battery-electric (B-E), and LBG technologies in their formative phase, while Figure 4 presents the possible acceleration phase of these innovations. Horizontal boxes refer to input (yellow) and user (blue) sectors, while the vertical green boxes represent the technologies. The arrows across boxes refer to the sectoral (inter)dependencies of technologies and their direction: one-way arrow indicates dependence of a technology on a sector, while two-way arrows refers to an interdependence, where low-carbon innovations also have implications for a sector. Thin and thick arrows refer to (inter)dependencies with weak and strong intensity, respectively. Green color indicates a positive implication for innovation in the low-carbon technology from a sectoral (inter)dependence, red a negative implication, while yellow points to yet unclear implications. Letters a-m refer to specific (inter)dependencies explained in detail in the following sections. Both figures also have brief notes pointing to important contextual factors affecting the sectors and interdependencies.

[1] Moreover, ammonia, produced from hydrogen and nitrogen, is being explored as an energy carrier in ships, allowing longer operating distances than fuel cells. As ammonia-driven vessels have thus far been little explored in coastal shipping, we however excluded them in the present analysis.

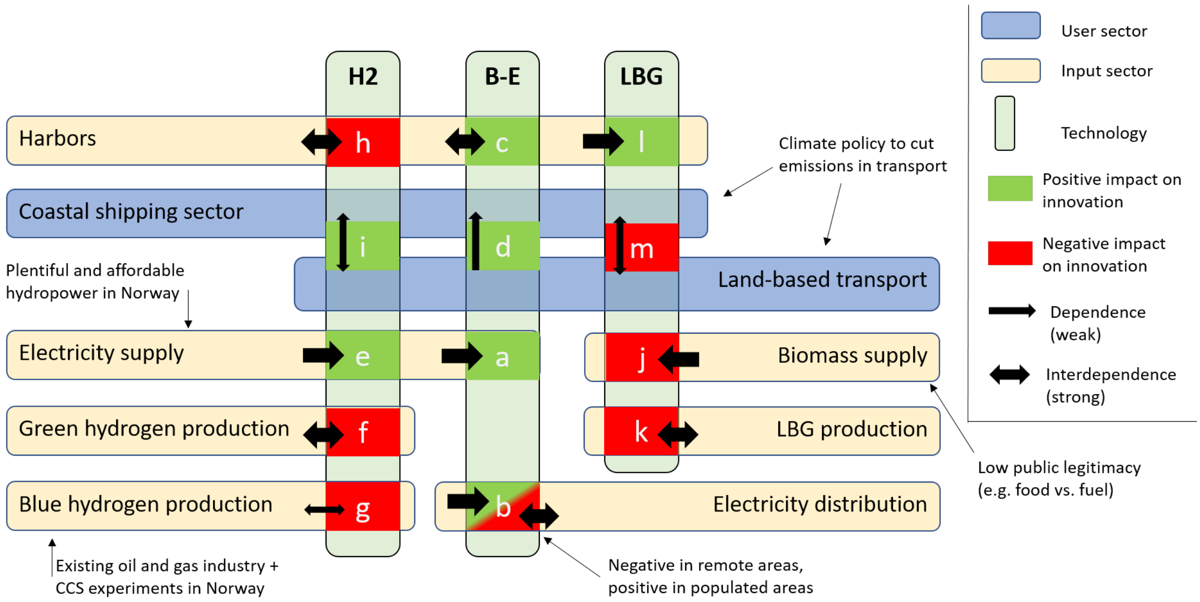

FIGURE 3 SECTORAL INTERDEPENDENCIES OF LOW-CARBON TECHNOLOGIES IN THE FORMATIVE PHASE.

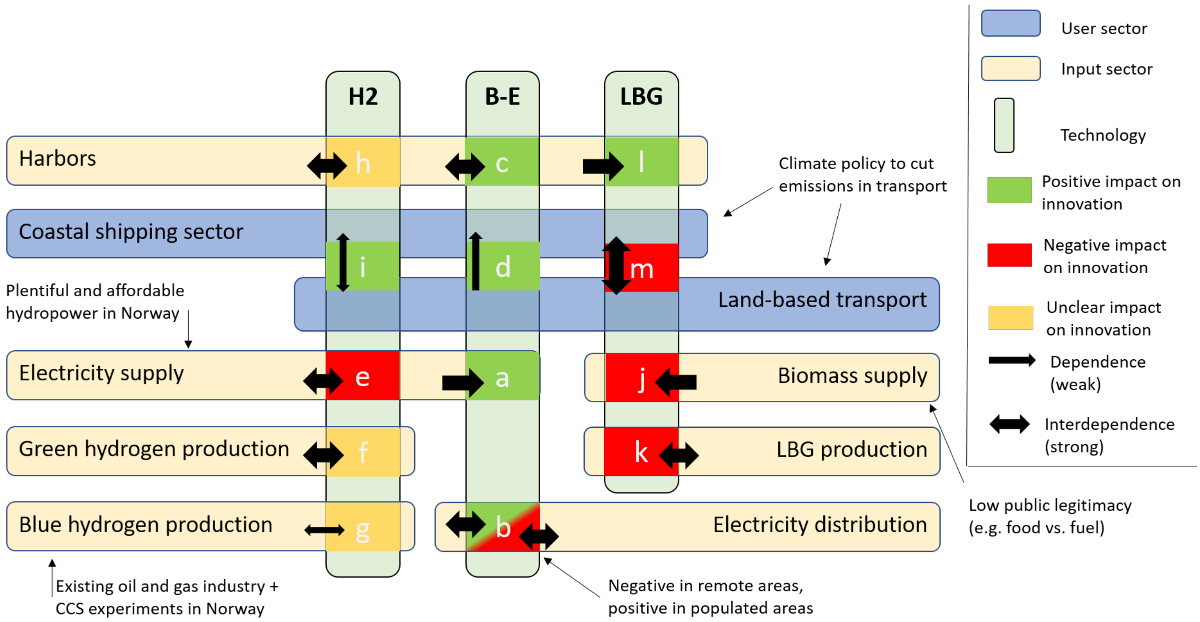

FIGURE 4 SECTORAL INTERDEPENDENCIES OF LOW-CARBON TECHNOLOGIES IN THE ACCELERATION PHASE.

5.1. The adaptability of Norwegian coastal shipping sector

A key issue characterizing shipping is that vessels generally have high upfront capital costs and a lifetime of several decades. Low-carbon technologies are thus relevant for both new-builds and retrofitting of existing vessels. Moreover, different market segments (ferries, offshore vessels etc.) put different requirements for vessels and thus affect how appropriate and feasible (new) energy solutions are (DNV GL, 2015c, Bergek et al., 2018). First, ships and boats differ in shape and size, which strongly influences the feasibility of e.g. retrofitting vessels with a new large hydrogen storage tank. Vessels also differ in terms of security requirements (e.g. vessels transporting passengers vs. goods). Second, the choices regarding the type of power/propulsion system choices are affected by the long lifetime of ships. Shipowners ordering new vessels often consider the re-sale value of ships already during the initial investment decision. Uncertain availability of a low-carbon fuel may therefore hinder investment decisions in such technologies, while foreseen possibilities of tightening emission regulations pose a risk to commit to conventional fuels. Moreover, low-carbon fuels that can be used in existing vessels (e.g. as drop-in fuels) have a lower transformative capacity than fuels requiring a new-build, making them attractive for shipowners seeking to decarbonize their existing fleet. Third, ships vary greatly in terms of their power and fuel availability needs. Some ships operate on daily fixed routes (e.g. ferries), while others have more variable routes but primarily operate out of the same port (e.g. many fishing vessels). Some operate only domestically whereas others frequently visit international waters and ports. Such factors thus affect the adaptability of coastal shipping vis-à-vis the different low-carbon technologies

5.2. Battery-electric vessels

Battery-electric vessels have diffused rapidly in Norway in the late 2010s, especially in the passenger segment. In addition to new fully electric vessels, existing vessels (e.g. in offshore supply) can be converted into battery-hybrids, where battery-packs complement combustion engines in e.g. dynamic positioning and redundancy (i.e. emergency power to prevent full black-outs). Our analysis is however focused on fully-electric vessels (usually requiring new-builds, leading to higher transformative capacity) whose battery-packs are charged at harbor, as these vessels have the highest potential for emission cuts.

5.2.1. Electricity supply (dependence "a" in Figures 3 & 4)

Battery-electric vessels are strongly dependent on (renewable) electricity as a readily available power source. Norway is well-suited for this, with plentiful and affordable hydropower. The national power production as a whole is therefore able to carry an increased power demand even from an accelerated electrification of coastal vessels, some regional variation (with limited nearby power production) notwithstanding (DNV GL, 2015a). Electricity production is therefore considered scalable for the purposes of further electrification in coastal shipping, enabling acceleration in battery-electric innovation (Interviews 1, 17, 28).

5.2.2. Electricity distribution (b)

Equally important to the overall supply of electricity is its distribution to charge vessels at quay at specific moments. This can be a somewhat more challenging task in Norway. E.g. for electric ferries, which often operate e.g. highway fjord-crossings in sparsely populated areas, there may simply not be adequate grid connections readily available, requiring building or upgrading local grid networks (8, 18, 21, 25, 29, DNV GL, 2015a). Therefore, the first electric ferries reportedly initially revoked resistance among distribution system operators. As the battery-electric ferry experiments gained momentum, these actors were however ultimately "forced" to adapt and upgrade grid connections around the planned ferry crossings (21). Scalability issues around power distribution are related to the high sunk costs in existing grids and investment needs. This has thus led to an interdependent relationship, as vessels are dependent on power distribution, while a partial transformation in the distribution sector may also be necessary to cater for this new kind of demand. Further diffusion of battery-electric vessels only aggravates such needs. The impact of power distribution on battery-electric innovation has therefore been somewhat negative in remote areas with limited existing grid infrastructure.

In more populated areas, power distribution has been less challenging due to the existence of stronger grids. In a potential acceleration phase of battery-electric vessels, there may even be benefits for grids. Large grid-connected vessels at the city harbor with megawatt-level battery packs may potentially act as a reserve power storage, providing additional flexibility to grid management (23). The sectoral dependence (and potential partial interdependence in an acceleration phase) with power distribution is therefore somewhat positive for battery-electric vessels in areas with adequate existing grid infrastructure.

5.2.3. Harbors (c)

In addition to power production and distribution, harbors act as a crucial interface for vessels to charge their batteries. Adequate shore-power connectors, i.e. devices allowing the charging of vessels' batteries, are necessary to install at quay, pointing to an interdependence between electric vessels with harbors (23, 28). High performance, reliability and sufficient power in shore-connectors is necessary particularly in cases where vessels stay only a very limited time at quay, and thus have limited time for charging, e.g. at busy ferry crossings. To prepare for potential lack of power in the grid during e.g. hours of peak consumption, harbors may need to install onshore batteries as a back-up power source (4, 6, 23). Shore-power devices may need to cater to the needs of very different kinds of vessels with varying power needs (23, 28). Despite such challenges, while adequate shore-power infrastructure is yet limited, several Norwegian harbors, such as in Bergen, are investing in shore-power connectors. Hence, there are signs that the interdependence between electric vessels and harbors, functionally seen as part of electricity distribution, seems to create positive feedback loops with battery-electric vessels, enabling acceleration.

5.2.4. Land-based transport (d)

Development of electric vessels has also been somewhat dependent on the development of electric (personal and heavy) vehicles in the user sector of land-based transport. While electric vessels are relatively novel, electric vehicles have been developed for decades. The development of electric vessels has therefore benefitted especially from knowledge spillovers (e.g. regarding lighter weight and charging capacity of batteries) from land-based transport. While some adaptation of batteries to maritime use is necessary, land-based transport sector has had a positive impact for battery-electric innovation in coastal shipping, paving the way for electric vessels especially in their formative phase (2, 7, 25, 30, DNV GL, 2015b).

5.3. Hydrogen vessels

Hydrogen vessels are yet immature and have high transformative capacity (requiring e.g. a hydrogen supply chain, which does not yet exist), but are considered a promising technology solution for shipping segments needing to cross longer distances. The first hydrogen-powered passenger vessels in Norway are expected in 2021. Hydrogen is primarily produced through electrolysis ("green") and reformation of natural gas with ("blue") or without ("grey") carbon capture and storage (CCS). Hence, electricity and natural gas are the key "raw materials" for hydrogen production. Due to our focus on sustainability transitions, we only consider green and blue hydrogen as acceptable alternatives.

5.3.1. Green hydrogen production (f)

Because electrolysis has a relatively low efficiency rate, production of green hydrogen is highly dependent on abundant and cheap renewable electricity. As already discussed, this precondition for the initiation of green hydrogen production (relation e in Figure 3) is fulfilled in Norway. However, in a possible acceleration phase of hydrogen in several user sectors, more electricity production capacity would likely be needed (5, 8, 14, 18, 23, 28, DNV GL, 2018b). This may prove difficult, due to limited expansion potential of hydropower in Norway (Hanson et al., 2011), while onshore wind power has recently faced increasing public opposition. Hence, while in the initial formative phase the dependence on electricity production has some positive attributes, the poor energy-efficiency of green hydrogen production and the somewhat limited scalability of renewable energy supply converts this strong dependence into a negative interdependence, hindering acceleration in hydrogen innovation.

The existing production capacity of green hydrogen is very limited. This represents a typical "chicken or egg" problem: hydrogen production is hindered by limited demand, and limited supply creates uncertainty regarding availability, impeding shipowners' willingness to invest in hydrogen vessels (DNV GL, 2018a). In the formative phase, this thus is a sectoral interdependence of high intensity with negative implications for hydrogen vessel innovation.

However, green hydrogen production is expected to pick up. Technically speaking electrolysis is a well-known process, and it is possible to build production units close to hydrogen's end use, e.g. in harbors (8, DNV GL, 2018b). Larger (multi-megawatt) electrolysis units are nevertheless coming to the market which may also help to reduce the price of hydrogen in comparison to smaller (<1MW) production units (14). Hence, while green hydrogen production has a strong interdependence with hydrogen vessels, the impact of this (yet non-existing) production in the possible acceleration phase remains unclear.

5.3.2. Blue hydrogen production (g)

As a large natural gas producer with a tradition of experimenting with CCS, blue hydrogen production has also gained attention in Norway. Captured carbon is envisioned to be stored in e.g. depleted petroleum reservoirs under the North Sea. Moreover, blue hydrogen production may use existing physical petroleum infrastructure, such as pipelines and bunkering (13, DNV GL, 2018b). However, CCS is considered an economically viable option only in very large quantities, e.g. providing hydrogen for multiple user sectors. It has a seemingly high scale-up potential due to the still abundant natural gas and depleted reservoirs as a storage space, albeit both of these do have limits (13, 28). Even wide diffusion of hydrogen vessels in coastal shipping may not suffice to support investments in large-scale blue hydrogen production, suggesting that strong demand will also be needed from other user sectors and countries (13). Blue hydrogen production is currently not available, making it a non-existing option during the formative phase of hydrogen vessels. Hence, blue hydrogen remains a hypothetical opportunity for the acceleration phase.

5.3.3. Harbors (h)

While harbors may produce green hydrogen, their main role is arguably in bunkering and distribution, suggesting a strong interdependence between onshore infrastructure and hydrogen vessels. Yet very little bunkering exists, and also some safety concerns remain, thus having a negative impact on innovation in this formative phase (12, DNV GL, 2018a). However, some harbors are exploring hydrogen distribution, also shared with land-based transport (see below), while safety concerns are being investigated. However, whether these efforts lead to substantial investments in infrastructure, which could lead to positive implications for the hydrogen innovation, remains yet unclear.

5.3.4. Land-based transport (i)

Compared to electric vehicles, hydrogen vehicles are yet less diffused. Nevertheless, we found some indications of positive sectoral interdependencies between land-based hydrogen transport and hydrogen vessels in establishing distribution networks. There are initiatives to combine the hydrogen distribution needs of both shipping and heavy land-based transport by establishing harbors as "energy hubs", and combine the aggregate demand of land-based transport and shipping to motivate localized hydrogen production (3, 14). Such synergies between user sectors in creating critical mass for hydrogen production may therefore provide some support for the hydrogen innovation, and support acceleration.

5.4. Liquefied biogas vessels

Due to its interchangeability with LNG, there are already several vessels in the coastal shipping sector capable of using LBG, making this part of the sector highly adaptable for LBG. However, although LNG has been in use for two decades, diffusion has stalled domestically (despite strong growth internationally) because of e.g. high prices, having negative effects also on LBG in coastal shipping (Bach et al., under review).

5.4.1. Biomass supply (j)

Biogas, like other biofuels, is dependent on the availability of biomass as a raw material. First generation biofuels are produced from grown crops, but competition with food production strongly and negatively affects their legitimacy. They therefore do not commonly feature as an energy option for coastal shipping. Instead, various raw materials for second generation biogas have been identified, particularly biowaste (from agriculture, aquaculture, communal waste in larger cities etc.) (10-12, 28, Sund Energy, 2018). Third generation biofuels, based on raw materials such as micro and macro-algae, do not yet exist as commercial fuels, but are being researched (14, DNV GL, 2014). They are energy crops but require very little resource inputs and do not compete with food crops for e.g. arable land, and are thus more scalable. It has however been questioned whether they will ever become a commercial alternative (32).

A key problem in biomass supply for first and second generation is scalability. Availability of biomass is believed to be too limited to cater for the growing diffusion LBG vessels, hampering its legitimacy already in the formative phase (5, 11, 32, 34, DNV GL, 2014). For instance, while technically there is plenty of biowaste to utilize, it is unclear how much can be commercially utilized. Moreover, it may be more attractive to use e.g. the biowaste from aquaculture to other higher-value purposes (because of its high protein-content). Hence, the strong dependence of LBG technologies on poorly scalable biomass supply is negatively affecting LBG innovation, hindering acceleration.

5.4.2. Biogas production (k)

Availability of biomass also affects the opportunities for LBG production, and there is yet limited production and liquefaction capacity (10-12, 34, DNV GL, 2018a). In early 2020, there was only one known LBG project in coastal shipping, and thus little market pull incentivizing increased production. There are nevertheless some on-going initiatives to build more biogas capacity, targeting also e.g. land-based transport (see below). The strong dependence on biogas production nevertheless has negative implications for LBG vessels in the formative phase, and due to above discussed scalability issues regarding biomass, negative feedback loops emerge, hindering acceleration.

5.4.3. Harbors (l)

LBG vessels are highly dependent on the distribution of LBG in harbors. Here LBG benefits from its interchangeability with LNG, as the same infrastructure (e.g. bunkering) can be used (12, 28, Sund Energy, 2018), leading to a positive effect, supporting LBG innovation in the formative and acceleration phases. However, yet few harbors in Norway have LNG infrastructure, limiting this effect.

5.4.4. Land-based transport (m)

Biogas has this far been used mostly in land-based transport. Because of the above-discussed low scalability of biogas, land-based transport and other user sectors compete with shipping over the scarce LBG (10, 11, 34). The relationship with land-based transport is therefore that of interdependence with negative, yet in the formative phase rather weak, implications for innovation. Due to the scalability problem, the intensity of this competition is set to aggravate if biogas technologies diffuse further, hindering acceleration.

6. Discussion and conclusion

In this paper we have provided a perspective that enables the analysis of systemic multi-sectoral and multi-technological interactions inherent to sustainability transitions, with a particular emphasis on sectoral (inter)dependencies and their role for acceleration. In the following we discuss the contributions of our work to sustainability transitions research and policy.

6.1. Contributions to sustainability transitions research

Our analysis has contributed to the analysis of (inter)dependencies of low-carbon technologies within and across value chains, and how they may influence the acceleration of innovations, consequently impacting sustainability transitions (Stephan et al., 2017, Malhotra et al., 2019, Andersen and Markard, 2020). Our results show that (inter)dependencies may trigger positive or negative feedback loops, which may partly help to explain the successes and problems of sustainable innovations. Positive feedback loops with sectors may support acceleration, while negative feedback loops may hinder it (cf. Suurs and Hekkert, 2009, Onufrey and Bergek, 2015, Markard and Hoffmann, 2016). In our case study of Norwegian coastal shipping, the sectoral (inter)dependencies of battery-electric vessels (e.g. sufficient renewable electricity supply and distribution) have largely supported further development of this innovation. With the support of also other factors, such as the development of battery technologies in land-based transport and decisive policymaking, positive feedback loops have emerged between the battery-electric technology and interdependent sectors, supporting this innovation in certain shipping segments, such as ferries. Meanwhile, the diffusion of LBG vessels has been particularly hindered by the inadequate biogas supply and related legitimacy issues, leading to negative feedback loops. In the case of hydrogen vessels, uncertainties regarding hydrogen supply (both green and blue) has had a negative effect on hydrogen innovation, leading to a chicken or egg problem between supply and demand of hydrogen, hindering acceleration. In the light of these negative feedback loops in the value chains of hydrogen and LBG vessels, it is therefore unsurprising that the diffusion of battery-electric vessels has until now surpassed these two other technologies.

Our analysis shows that the implications of sectoral (inter)dependencies are influenced by the characteristics of both user and input sectors. First, we pointed out how the long life-time and capital intensive nature of physical infrastructures affect user sector adaptability (cf. Dolata, 2009), particularly when low-carbon technologies require new-built vessels and new fuel supply chains. The uncertainty regarding the availability of bunkering of low-carbon fuels (especially in terms of hydrogen and LBG) was seen to hinder the commitment of shipowners to invest in especially hydrogen vessels. The transformative capacity of hydrogen and LBG fuels (LNG vessels notwithstanding) was therefore high vis-à-vis the existing supply chains in shipping, while the adaptive capacity of the shipping sector generally speaking is rather low (e.g. because of high sunk costs in vessels). These two factors, combined with the immaturity of LBG and hydrogen supply chains, therefore led to negative feedback loops, slowing down the adoption of hydrogen and LBG.

Second, we observed input sector scalability to be a key feature in the sustainability transition in coastal shipping in Norway. Scalability was particularly hindering the LBG innovation, but also hydrogen vessels, which suffered from poor outlooks to scale up the production of these fuels. We therefore reached similar insights as e.g. Bennett (2012) and Sutherland and colleagues (2015) in finding that the low scalability of biofuels may be a key hindrance of further diffusion. We further contribute by showing how such scalability problems in value chains may lead to negative feedback loops. Indeed, we show that the scalability of input sectors can be a crucial feature facilitating the acceleration of low-carbon innovations.

Moreover, we found indications of feedback loops between user sectors (cf. Raven, 2007, Stephan et al., 2017), namely coastal shipping and land-based transport. In the case of battery-electric and hydrogen technologies, we could observe complementarities (e.g. knowledge spillovers and potential sharing of hydrogen supply chains), while coastal shipping and land-based transport were found to compete over the available biogas. These examples show that feedback loops may emerge also between user sectors, driving or hinder acceleration of low-carbon innovations.

As shown in the above insights, the sectoral interdependencies of technologies affected the expectations of actors already in the formative phase of low-carbon innovations (e.g. low scalability of LBG, uncertainties regarding hydrogen supply). While the sustainability transitions literature has thus far emphasized the importance of sectoral interdependencies in the acceleration phase of innovations (Markard et al., 2020, Markard, 2018), our results suggest that actors in sectors with long investment cycles consider the value chains of technologies (e.g. future availability of fuels) already in the early phase of innovations, affecting their willingness to commit to new technologies. In other words, the perceived problems or uncertainties regarding technologies' value chains may sink an innovation before it even makes it out of the safety of a harbor.

6.2. Contributions to sustainability transitions policy

Taking sectoral interdependencies into consideration also leads to new policy perspectives, moving beyond the confines and interests linked to single technologies and sectors. Instead of focusing solely on e.g. R&D in low-carbon technologies, policies may have to be directed towards ensuring positive feedback loops across entire value chains (cf. Markard and Hoffmann, 2016). This is particularly relevant in sectors with long lifecycles, such as transport and process industry. In such sectors, transition policy instruments should incorporate value chain considerations already in the formative phase of innovations to help solving the chicken or egg problems (cf. Huttunen et al., 2014, Andersen and Markard, 2020).

Often several alternative technologies can contribute to e.g. the decarbonization of sectors, which may lead to dilemmas for policy-makers to decide which technologies to support, given limited resources (Magnusson and Berggren, 2018). This dilemma is amplified by the above discussed notion that technological innovation can be dependent on the simultaneous development of its value chain (e.g. supply of low-carbon fuels), meaning that policy may need to support the emergence of an entire value chain. Therefore, policy support in *all* low-carbon technologies *and* their value chains may not be feasible (Magnusson and Berggren, 2018, Edmondson et al., 2019). The deeper analysis of sectoral interdependencies can reveal bottlenecks that need to be addressed by policy and identify emerging technologies whose acceleration seems unrealistic due to e.g. scalability problems. Hence, we argue that an analysis of sectoral (inter)dependencies of low-carbon technologies may identify which parts of value chains need to be addressed with supportive policies, and offer insights regarding which innovations seem more likely to accelerate (e.g. due to positive feedback loops with various sectors).

While a multi-technological and sectoral analysis may identify such weaknesses in innovations, it may also reveal synergies. For instance, if the value chains of sustainable technologies (e.g. in terms of fuel supply) overlap, it may offer a "two-for-one" opportunity for policy to address specific challenges in multiple innovations with a single policy instrument. In our empirical analysis we illustrated that both green hydrogen and battery-electric technologies were dependent on the production of renewable electricity. Therefore, a given policy measure to support the growth of renewable electricity production would favor both electrification and hydrogen innovations. We thus argue that the analysis of the sectoral (inter)dependencies of innovations can reveal synergies across value chains, opening opportunities for policy to exploit them.

6.3. Limitations and further research

Our work has limitations, which open opportunities for further research.

First, our analysis of sectoral (inter)dependencies is limited to data that is available in the current early phase of low-carbon innovations. Hence, while useful to understand potential barriers and opportunities for acceleration phase (arguably a phase where the sectoral interdependencies and feedback loops are accentuated), our forward-looking analysis is based on *a priori* perspectives. Further analysis should take on e.g. historical studies to analyze how the role of sectoral interdependencies of technologies evolves throughout the innovation development.

Second, our assessment of sectoral (inter)dependencies is based on qualitative data, and thus does not include a quantitative assessment of e.g. the scalability potential of input sectors. Our analysis is therefore focused on how the actors in the coastal shipping sector perceive these interdependencies (which presumably affect their actions in relation to the discussed low-carbon innovations), rather than e.g. a techno-economic assessment of interdependencies. Future research should seek to combine such quantitative and qualitative assessments of sectoral interdependencies in low-carbon innovations.

Finally, our analysis has been limited to a single case study in a single country. For instance, the battery-electric, hydrogen and LBG technologies' sectoral interdependencies (the availability of biomass, the quality of power grids etc.) may however vary from one country to another, limiting the generalizability of our case study. Future research is needed to study sustainability transitions in coastal shipping, and the sectoral interdependencies in low-carbon innovations in general, also in other countries.

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Appendix: Interview organizations

Number	Actor type
1	Components and Services 1
2	Components and Services 2
3	Components and Services 3
4	Components and Services 4
5	Components and Services 5
6	Components and Services 6
7	Components and Services 7
8	Components and Services 8
9	Components and Services 9
10	Fuel production and distribution 1
11	Fuel production and distribution 2
12	Fuel production and distribution 3
13	Fuel production and distribution 4
14	Fuel production and distribution 5
15	Yards and Shipdesign 1
16	Yards and Shipdesign 2
17	Yards and Shipdesign 3
18	Yards and Shipdesign 4
19	Shipping 1
20	Shipping 2
21	Shipping 3
22	Shipping 4
23	Shipping 5
24	Shipping 6
25	Standardization and Classification
26	Industry Association 1
27	Industry Association 2
28	Industry Association 3
29	Research Organization 1
30	Research Organization 2
31	Research Organization 3
32	Research Organization 4
33	Public Funding Agency 1
34	Public Funding Agency 2
35	Public Authority 1
36	Public Authority 2

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