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# Complementarity formation mechanisms in technology value chains

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ABSTRACT

Recent literature has begun to discuss complementarities between sectors and technologies in the context of sustainability transitions. This paper contributes to this literature by theorizing *complementarity formation mechanisms* underlying such positive interactions within and across technology value chains. It pursues empirically founded theory building based on a case study of innovation in battery-electric, hydrogen and liquefied biogas technologies in Norwegian coastal shipping. Three complementarity formation mechanisms in technology value chains are identified: synchronization, amplification, and integration. *Synchronization* points to the need for co-development between the input and user sectors of a technology value chain. *Amplification* refers to the necessary expansion of input sectors to match the growing demand in user sectors. Finally, *integration* highlights the potential of convergence between different technology value chains in one or more user sectors. The paper concludes with a discussion of how policy may leverage such complementarity formation mechanisms to foster innovation in zero-carbon technologies.

## 1. Introduction

Pressing environmental problems, such as climate change, require transitions towards more sustainable modes of production and consumption in, for example, transport and food sectors. The academic field dedicated to the analysis of such transitions – sustainability transition studies – has made progress in developing theories and analytical tools such as the multilevel perspective (MLP) (Geels, 2002) and the technological innovation system (TIS) framework (Bergek et al., 2008) for better understanding of such complex processes (Markard et al., 2012). However, studies of sustainability transitions to date have often been limited to particular niche innovations in single sectors in a formative phase (Geels, 2018; Schot and Geels, 2008). Sustainability transitions in sectors such as electricity supply and personal mobility are, in several parts of the world, now in a phase of accelerated diffusion (Gielen et al., 2019; Victor et al., 2019). In this new phase of transitions, complex interactions across technologies and sectors have become particularly accentuated (Markard, 2018; Markard et al., 2020). However, the field of sustainability transitions has only recently begun to address such topics (Bergek et al., 2015; Geels, 2018). Hence, there is a need to delve more deeply into the multi-sectoral and multi-technological features of transitions (Andersen et al., 2020; Rosenbloom, 2020).

McMeekin et al. (2019) point to the challenges of changing the 'system architecture' of sectors and adopt a 'whole system' perspective on transitions. Others have elaborated on the value chains of TISs, notably those of clean energy technologies (Hanson, 2018; Malhotra et al., 2019; Stephan et al., 2017) and sanitation (van Welie et al., 2019), and how TISs may interact with various sectors (Bento et al., 2021; Haley, 2018; Mäkitie et al., 2018; Wirth and Markard, 2011). These contributions illustrate that interactions within and across sectors constitute a web of interdependencies that are at the heart of understanding innovation (Andersen and Markard, 2020; Markard and Hoffmann, 2016).

Despite these important contributions, the existing sustainability transitions literature provides limited conceptual tools for understanding the intricate interactions between sectors involved in the production, distribution, and consumption sides of sustainable technologies (Andersen et al., 2020). Moreover, the extant literature specifically studying multisectoral and multi-technological interactions remains mainly focused on sectors that produce components and provide services for technologies (Andersen et al., 2020). Meanwhile, less attention has been paid to the role of input sectors that provide the energy or other 'material throughput' necessary for sustainable technologies, such as the sourcing, production, and distribution of renewable energy or natural

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resources.

Innovation studies has long recognized the role of various types of complementarities and feedback mechanisms that hinder (e.g. path dependence) or drive innovation (Arthur, 1988; Dosi et al., 1990; Onufrey and Bergek, 2015; Rotmans et al., 2001; Suurs and Hekkert, 2009). Complementarities are crucial for the development and diffusion of technological innovations and they arise 'if the value of a combination of specific elements or assets is greater than the sum of the value of each individual element' (Markard and Hoffmann, 2016, p. 63). Such complementarities may also be identified within the value chains of technologies. Complementarities "span industry boundaries, which means that different actors, knowledge bases, business models and 'production logics' are involved" in the development, diffusion and functioning of a technology (Markard and Hoffmann, 2016, p. 66). Although Markard and Hoffmann (2016) provide a useful description of the structural features of complementarities (e.g. directionality, intensity, temporality, purpose), they elaborate less on the factors underlying the formation of complementarities in technology value chains. Therefore, there is a need for more attention to how complementarities come into being, and how they may be triggered or hindered by technological and sectoral characteristics, as well as actors and policymakers.

Against the background presented above, the aim of this paper is to examine and conceptualize mechanisms that may lead to the realization of complementarities (i.e. positive interactions) between sectors in technology value chains (TVCs). We thus engage in theory building with respect to *complementarity formation mechanisms*. We approach this task through a literature review and an exemplary case study (Eisenhardt, 1989). We conceptualize TVCs as the range of sectors providing the sourcing (e.g. extracting, harnessing) and processing of natural resources, production (e.g. of mechanical or electronic equipment), distribution, and the use of technologies.

Our case study is located in Norway and comprises three zero-carbon technologies considered highly relevant in the transition from conventional marine fossil fuels to the use of other sources of energy in coastal shipping (DNV GL, 2015c): battery-electric, hydrogen, and liquefied biogas (LBG). Functioning TVCs are needed for these technologies to be viable alternatives to fossil fuels. However, to varying extents, these TVCs are not yet fully in place, which implies that while some complementarities might already be realized, some are not. Through our empirical analysis we conceptualize three categories of complementarity formation mechanisms in TVCs: *synchronization*, *amplification*, and *integration*. Although our focus is on complementarity formation mechanisms in TVCs from the perspective of a specific focal user sector (coastal shipping), we also consider how TVCs in the adjacent user sector of land-based transport might have influenced innovation in coastal shipping.

The paper proceeds as follows. Section 2 reviews the key extant innovation and sustainability transitions literature on TVCs, sectoral interdependencies, and complementarities. Section 3 describes our research design, methods, and data. Thereafter, Section 4 presents the case study context and the TVCs of battery-electric, hydrogen, and LBG technologies in Norwegian coastal shipping. Section 5 explores complementarity formation mechanisms in the three TVCs, and Section 6 discusses these mechanisms further in light of existing theory. The concluding section, Section 7, presents the implications of our findings for policy, discusses the limitations of the study, and suggests promising avenues for future research.

## 2. Sectoral interdependencies and complementarities

### 2.1. Sectoral interdependencies in technology value chains

We understand technologies as physical artefacts and knowledge (Das and Van de Ven, 2000). Sectors are a network of collaborating and/or competing actors that provide products by using a certain set of technologies (Malerba, 2002). The products may be other technologies, components, or services, which are either consumed by consumers or incorporated into the products of other sectors (capital goods). Most modern technologies can be seen as complex systems comprised of subsystems and components (Arthur, 2009). Each of these subsystems and components typically rests on different knowledge bases and is produced by different sectors. Many technologies are also used in several sectors, such as multipurpose or general-purpose technologies. Sectors typically require energy or material inputs to operate technologies (e.g. electricity for electric vehicles). We denote the sectors involved in the development and use of a particular technology as a TVC (cf. Stephan et al., 2017). This approach implies a fundamental interdependence between technological and sectoral change.[1]

Sectoral interdependencies feature prominently in historical analyses of technological change. One well-documented example is the development of the Bessemer method for mass production of steel in the late 19th century, which introduced higher quality and cheaper steel to the market, and in turn allowed for the booming development and diffusion of products made of steel, especially vessels and railways (Fitzgerald, 1998). Higher quality steel also enabled better and more efficient machinery and other capital goods, such as steam engines, which in turn drove innovation in other industries (Rosenberg, 1976; Schumpeter, 1939). This example illustrates how the development of technologies and the systemic complementary developments in interlinked sectors and technologies are interdependent (Dahmén, 1988; Rosenberg, 1979). To understand the processes of technological innovation in the context of sectoral transitions (e.g. towards sustainability), it is particularly interesting to study the interdependencies of capital goods value chains (Dosi et al., 1990; Pavitt, 1984), such as energy TVCs in electricity supply, and heavy vehicle value chains in transport. On the one hand, technological development in the value chains of capital goods enables user sectors to expand, thus creating more demand for the capital goods and the materials and services necessary to manufacture and operate them, thereby inducing yet more innovation (Dosi et al., 1990; Schmookler, 1966). On the other hand, users of capital goods usually encounter various problems regarding new technologies that may create bottlenecks for further diffusion. These problems then often become objects of focus for suppliers' innovation and development activities that are seeking to overcome them (Rosenberg, 1976).

Thus, different types of sectors are involved in the evolution of a TVC. These include *user sectors* that adopt technologies (Pavitt, 1984), and *input sectors* that provide the necessary inputs for a technology to serve its purpose in a user sector. Three types of input sectors have been identified: sectors that (1) source *natural resources* or other raw materials, (2) *produce* natural resources into consumable products and commodities, and (3) *distribute* the products to user sectors' locations according to need (Freeman and Louçã, 2001; Perez, 2002).[2] For example, in the case of fossil-fuel based electricity supply, extractive sectors provide the natural resources (coal, natural gas, oil), which are then subject to transport and possibly to processing before being 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 between technologies.

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[1] It should be noted that the relationships between technologies and sectors can be characterized both as dependencies (e.g. a sector influencing a technology) and interdependencies (mutual influence) (Bergek et al., 2015; Markard and Hoffmann, 2016).

[2] As already mentioned, each of these sectors also has its own value chain that provides, for example, the materials, components, and services necessary for their operations, such as mining equipment required to produce raw materials, components, and machinery to allow production, and the storage and logistics facilities to enable distribution. However, such value chains are beyond the scope of analysis in this paper.

### 2.2. Dynamics of sectoral interdependencies in technology value chains

The fact that TVCs evolve over time is crucial for understanding how technologies emerge, diffuse, stabilize, and decline. Konrad et al. (2008) note that complementary relationships between public consumption patterns and production of utility services (e.g. sanitation, electricity) may lead to transformations in those systems through co-evolutionary dynamics. In an early phase of innovation, sectoral interaction of novel technologies is usually one-directional, where an emerging technology is dependent on sectors but not vice versa (Markard, 2020). For example, electric vehicles, in their formative phase, are dependent on electricity supply and charging infrastructure but have limited influence on the broader land-based transport sector or the electricity supply and distribution sectors. As the deployment of novel technologies increases, dependencies may turn into interdependencies (Markard, 2018; Markard et al., 2020), and technologies may increasingly begin to affect sectors (Markard, 2020); for example, the diffusion of electric vehicles may result in a need for upscaling and adaptation of electricity supply and transmission infrastructure. The expansion of TVCs is contingent upon the potential for upscaling and adaptation of the dependent and interdependent sectors (i.e. the sectors' characteristics).

Sectors have different knowledge bases, technologies, and input and demand, and their actors often have certain types of learning processes, competences, beliefs, objectives, and behaviour (Malerba, 2002). On the one hand, capabilities and sectoral institutions affect the adaptability of sectors vis-à-vis new technologies. Conversely, technology characteristics and fit with existing capabilities, structures, and sectoral institutions influence the adoption of technologies (Dolata, 2009). Therefore, novel technologies may match current sectoral configurations or they may require substantial changes in institutions, infrastructure, industry structures, and knowledge (Abernathy and Clark, 1985; McMeekin et al., 2019). An example of a technology with a high degree of fit with current sectoral characteristics is the use of biodiesel or e-fuels as drop-in fuels in shipping, while hydrogen solutions would imply the opposite (Bach et al., 2021). Furthermore, differences in the characteristics of different sectors involved in a TVC, such as in terms of interests and expectations of key actors, may lead to tensions and conflicts (Bakker, 2014).

#### 2.2.1. Complementarities

Complementarities between technologies and sectors have been recognized as important for innovation processes. For example, feedback between the use of innovations and their design, production, and distribution is salient in the chain-linked model presented by Kline and Rosenberg (1986). Sandén and Hillman (2011) differentiate between one-directional and two-directional positive, neutral, and negative interactions.[3] Positive implications emerge from interactions that propel the further development and adoption of a novel technology in a user sector (Dahmén, 1988; Markard and Hoffmann, 2016; Rosenberg, 1979). As an example, increased adoption of a new technology in a user sector will increase demand for components and material from input sectors, which in turn might drive technological change in those sectors. For instance, expansion of the automobile industry triggered innovation in petroleum refining, which facilitated that petroleum changed from being mainly a source of energy used for lighting to becoming a key energy source for transport (Kline and Rosenberg, 1986). Negative effects may emerge from the lack of such interactions, potentially causing delays or bottlenecks in technological innovation (Markard and Hoffmann, 2016). An example of a negative effect is the necessity of using scarce arable land to produce energy crops for biofuels, which creates competition between energy and food production (Sutherland et al., 2015) and limits the upscaling of biofuel input sectors. Often, the presence of such problems, which Hughes (1983) refers to as ‘reverse salients’ (ill-developed elements of a system that hamper its development), become foci of interest for innovation that can resolve bottlenecks (Hughes, 1983; Rosenberg, 1969).

Markard and Hoffman (2016) discuss key interactions for innovation through the concept of complementarities at the level of both technologies and sectors. They differentiate between technological, organisational, institutional, and infrastructural components or elements. Complementarities then refers to positive interactions between such elements. Moreover, complementarities are either one-directional or two-directional and have different intensities (strong or weak). Different types of complementary elements also tend to have different speeds of change. For example, physical infrastructures often change slowly, while development of the production capacity of components may change faster. Thus, the development of different parts of a TVC may be ‘out of sync’, which suggests that the features of complementarities may be dependent on the characteristics of the involved sectors. Slow or lacking development of complementary elements may create bottlenecks for further diffusion, such as the lack of energy storage for intermittent renewables or the lack of charging infrastructure for electrical vehicles (Markard and Hoffmann, 2016; Sinsel et al., 2020).

Several empirical analyses have hinted at the importance of TVC complementarities in technological innovation. For example, in the case of aviation biofuels, high demand is expected to be needed to initiate more biofuel production, which would then lead to reduced costs and in turn make biofuels more attractive to airlines (Kim et al., 2019). Also, more generally in transport systems, the existence of infrastructure (e.g. fuels and charging) has been found to precede the adoption of vehicles, which has then preceded increases in travel, thus forming complementarities between input and user sectors (Leibowicz, 2018). In the context of energy systems, diffusion of intermittent renewable energy technologies has required complementing innovations in electricity distribution such as high-voltage direct current (HVDC) power cables (Andersen, 2014; Haley, 2018).

Complementarities have also been identified between different user sectors. For example, in the case of zero-carbon hydrogen technologies, where TVCs are as yet largely non-existent, the adoption of hydrogen in one user sector (e.g. transport) may spur adoption in other user sectors (e.g. processing industry) and consequently support TVC development through joint production and infrastructure (Damman and Steen, 2021). However, such complementarities may not materialize if an input sector cannot scale up and cater to growing demand. A typical example is the limited availability of biomass and arable land for production of biofuels, which may lead to competition between user sectors (such as transport and food) (Sutherland et al., 2015; Wirth and Markard, 2011).

Thus, the literature recognizes the importance of TVC complementarities for innovation and sustainability transitions. While the above-reviewed literature has made some headway in terms of elucidating how relationships between input and user sectors may influence innovation, there is a lack of conceptual understanding of the mechanisms leading to the formation of complementarities in TVCs. In this paper, we understand complementarities as interactions between sectors in TVCs which affect the diffusion of a novel technology in a user sector. In the remaining part of this paper, we use our empirical case study to further analyse and conceptually unpack the different ways such complementarities come into being through what we hereafter refer to as *complementarity formation mechanisms*.

## 3. Methodology

### 3.1. Research strategy

We seek to contribute to theory building on the topic of complementarities' formation in TVCs and its relevance for zero-carbon innovation and transitions in a focal user sector. To facilitate this, we employ a case study of the TVCs of zero-carbon technologies in the Norwegian

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[3] Sandén and Hillman discuss interactions between technologies. However, their generic differentiation of types of interactions is useful also in informing our analysis of interactions between sectors and technologies.

coastal shipping sector – a frontrunner country within 'green' shipping (Mäkitie et al., 2022) (see more information about the case of Norwegian coastal shipping in Section 4.1).

As discussed in Section 2, the existing literature on complementarities and sectoral interdependencies provides useful starting points for how these factors may affect technological innovation. However, we found that the literature dealing with complementarities *within and across* TVCs is limited, especially in terms of mechanisms that lead to their formation. To contribute to an exploration of such mechanisms, we pursue theory building through a case study, inspired by Eisenhardt (1989) and later elaborated upon by Gehman et al. (2018). This approach is suitable when existing theory does not suffice in terms of explanatory power. In practical terms, the approach implies iterations between relevant pre-existing theory and inductive reasoning based on the properties of the case. Our aim is to arrive at analytical generalization (Yin, 2009), meaning knowledge that is of relevance to a broader class of phenomena, and thus to contribute to the development of both theoretical and empirical understandings. The novel understanding that we arrive at concerns the mechanisms through which complementarities form in TVCs.

We deem the case of coastal shipping most comparable with other 'hard-to-abate' transport user sectors (i.e. aviation and heavy land-based transport), in which there are multiple emerging (yet highly immature) zero-carbon energy technologies, and in which the functionality of the sectors is dependent on a geographically wide (national and international) network of fuel infrastructure, and in which most key users are private profit-seeking enterprises. The coastal shipping sector in Norway has an exceptionally high presence of domestic companies throughout the TVCs, which provide various types of services and products for shipping transport. However, we consider our findings are in general relevant for understanding complementarities in TVCs also in other geographical contexts and user sectors.

### 3.2. Data collection and analysis

This paper emanates from a multimethod research project that included 74 semi-structured interviews with various private and non-private actors in the Norwegian maritime sector (for an overview, see Steen et al., 2019). The interviews took place in the period 2015–2020 (mainly 2017–2019) and covered the development and diffusion of three focal technologies: battery-electric, hydrogen, and biofuels. The interviews lasted on average 70 min and were tailored for different types of actors (e.g. representatives of shipping companies, technology suppliers, fuel producers, public authorities). The participants comprised senior managers, business development and technology personnel, and maritime regulation experts. Of the 74 interviews, 59 were conducted in person and 15 via videoconference or telephone. All but eight interviews were recorded and transcribed in verbatim, and extensive notes were gathered in the unrecorded ones.

While the entire body of 74 interviews was focused on the necessary understanding of the innovation processes relating to these technologies, 36 interviews also discussed topics related to TVCs. The latter were held with representatives of different organizations (see Appendix A for an overview) and formed the main data source for our qualitative analysis as they provided insights into the formation of complementarities in TVCs. The primary data was supported by secondary material from industry reports, media, and industry events.

Interview transcripts (and notes) were coded in NVivo in three rounds. First, a *generic coding round* for the purposes of the overall research project (innovation in zero-carbon technologies) was performed using a top-down coding strategy to identify the relevant zero-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 with two or 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 by the authors and research group members. During that first round of coding, sectoral interdependencies in TVCs emerged as a notable feature related to innovation processes, and motivated further exploration.

The coded TVCs formed the main sample for the *second round of coding* (some additional coding was later added manually) that was performed for the research presented in this paper. Additionally, identified industry reports on energy TVC topics and notes from industry events on sustainable shipping were coded to supplement our primary data. In the second round we used a bottom-up approach by inductively identifying (1) the relationships between the input and user sectors for battery-electric, hydrogen, and LBG technologies respectively, and (2) the main characteristics and issues related to those relationships, which are relevant for innovation in the three focal technologies. The second-round coding was performed by the lead author and resulted in 27 initial codes. These coded data were evaluated for indications regarding the role of the TVCs and the potentially relevant characteristics of sectors for innovation in the specific zero-carbon technologies. The preliminary analysis was refined by discussing each code (with data excerpts) together with the other authors of this paper. In that step we recognized overlaps between the initial codes and therefore combined some codes, while rejecting others due to limited empirical evidence (less than three independent sources pointing to a finding), thereby reducing the number of codes from 27 to 12. The 12 codes were relevant for describing the case context and the sectoral interdependencies presented in Fig. 1 (see Appendix B for more information about these codes).

The *third round of coding* took place after the first draft of this paper had been written. The results of our second round of coding had hinted at interesting mechanisms leading to formation of complementarities within TVCs.[4] However, our existing coding did not provide details about such mechanisms. As we did not find such mechanisms sufficiently conceptualized in the existing literature, we ventured to identify higher order patterns in our data and to conceptualize them. This third round of coding was performed by the lead author and consisted of an inductive identification of patterns in *how* sectoral interdependencies have impacted the zero-carbon innovations in the focal user sector (coastal shipping in Norway). Thus, the exercise sought to identify the mechanisms that lead to the realization of complementarities in TVCs (i.e. that we label complementarity formation mechanisms). To qualify as a finding, there had to be at least three independent empirical examples of a complementarity formation mechanism, including at least one example in which the existence of the mechanism was seen to support the formation of complementarities, and one in which the lack of the mechanism seemed to hinder the formation of complementarities. Based on this screening process, three different types of complementarity formation mechanisms were identified. These findings with data excerpts were once again discussed and further refined by all authors, leading to minor clarifications. The three complementarity formation mechanisms are described in detail in Section 5.

## 4. Zero-carbon innovation in Norwegian coastal shipping

### 4.1. Norwegian coastal shipping

The Norwegian fleet ranks among the world's largest and has a high share of advanced vessels, such as those used in offshore energy production. The domestic maritime sector forms a complete and highly competitive industrial cluster, with a broad range of actors, including shipowners, yards, designers, equipment suppliers and knowledge-intensive business services (Mellbye et al., 2016). The sector is supported by research institutes and universities.

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[4] We acknowledge the role of the anonymous reviewers and the editor in encouraging us to pursue more in-depth analysis of such mechanisms.

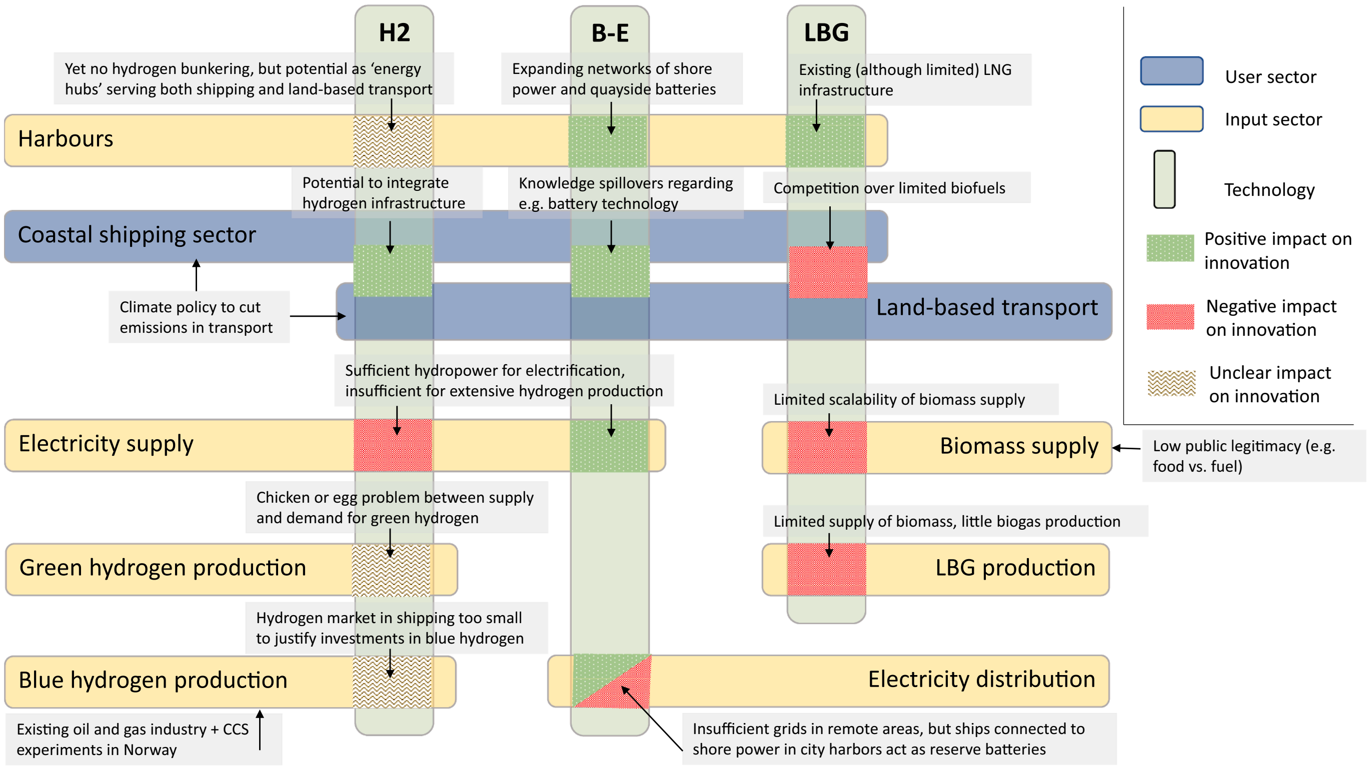

**Fig. 1.** Sectoral interdependencies of battery-electric, hydrogen, and biofuel technologies in Norwegian coastal shipping.

With a long and jagged coastline, transport by sea has always been important in Norway. Many of the key economic sectors are tightly linked to shipping, such as offshore petroleum, fishing, and aquaculture. To meet the harsh sea conditions, these sectors have articulated demand for robust and advanced ships. Due to the importance of logistics and transport by sea, greenhouse gas (GHG) emissions from maritime transport are relatively high in Norway compared with many other countries. Reducing GHG emissions, particularly for coastal shipping (wherein most vessels operate within domestic waters) has emerged as a key policy objective for climate mitigation. An important motivation for firms in the maritime sector has been to develop new energy solutions for the domestic market and that can also be exported globally (Steen et al., 2019). However, the empirical focus of our study is limited to domestic coastal shipping.

A key characteristic of shipping is that in general vessels have high upfront capital costs and a lifetime of several decades. This means that zero-carbon technologies are relevant for both new builds and for retrofitting of existing vessels. Moreover, the 'fit' and feasibility of energy solutions (new or otherwise) vary between market segments (e.g. ferries, offshore vessels) due to the large variety in vessel shapes and sizes (e.g. allowing for large fuel storage tanks or not), safety requirements (e.g. transporting goods or people), power needs (e.g. due to range or to onboard equipment), and operational profiles (e.g. long versus short routes or fixed versus variable routes) (Bergek et al., 2021; DNV GL, 2015c). Also, the choices regarding the type of power and/or propulsion system choices are affected by the longevity of ships. Shipowners ordering new vessels often consider the resale value of ships already during the initial investment decision. Therefore, high expenses and uncertain availability of zero-carbon energy solutions may hinder investment decisions in such technologies, while long-term competitiveness and possibilities of tightening emission regulations may encourage adoption (Mäkitie et al., 2022). Uncertainties related to the availability (current or future) of zero-carbon energy solutions may be particularly prominent among shipowners with coastal shipping vessels that frequently visit international waters and ports (Bergek et al., 2021).

LBG, battery-electric, and hydrogen vessels have until now been the most prominent zero-carbon technologies in Norwegian coastal shipping, driven by public innovation policy and development programmes, private investment, and national ambitions to reduce emissions (Steen et al., 2019). While these technologies share the same societal ambition of reducing GHG emissions, their value chain configurations look very different. For this reason, the Norwegian coastal shipping case offers a suitable empirical context for the analysis of complementarities and their formation within and across the TVCs of zero-carbon technologies.

### 4.2. *Zero-carbon technologies in Norwegian coastal shipping*

*Battery-electric* vessels have diffused rapidly in Norway since the mid-2010s, especially in the passenger and offshore segments (Bach et al., 2020; Bergek et al., 2021; Bugge et al., 2021). Batteries are used both in fully electric systems (mainly in new builds) and in hybrid systems in combination with conventional combustion engines (both new builds and retrofitted vessels). However, our analysis focuses on fully electric vessels with batteries that are charged from shore (in ports), as these vessels have the highest potential for emission cuts. With current technology, fully electric systems are only feasible on vessels that operate on short and fixed routes. While the existing electrical power and distribution system is well-developed in Norway, electrification in coastal shipping requires adaptation in grid infrastructure, as well as development and provision of charging solutions.

*Hydrogen* technology relies on the use of fuel cells, such as proton exchange membrane or solid oxide fuel cells, which convert hydrogen fuel into electricity (Tronstad et al., 2017).[5] Hydrogen vessels are as yet immature (Bach et al., 2020) and lack a full hydrogen value chain.

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

Hydrogen is considered a promising zero-emission solution for shipping segments needing to cross mid-range distances. The first hydrogen vessel (a ferry) in Norway is expected to be launched in 2022. Hydrogen can be produced by electrolysis, which uses electricity to split water into hydrogen and oxygen ('green hydrogen', if electricity from renewable sources is used), and by steam reformation of natural gas into hydrogen and carbon, either with or without carbon capture and storage (CCS), respectively 'blue hydrogen' and 'grey hydrogen'. As a large natural gas producer with a tradition of experimenting with CCS, blue hydrogen production has gained attention in Norway. Captured carbon is to be stored in depleted offshore petroleum reservoirs (cf. the Longship project of the Norwegian government aiming for realization of full-scale CCS with carbon storage in the Norwegian continental shelf) and to use existing petroleum infrastructure, such as pipelines and bunkering (DNV GL, 2018b). Thus, electricity and natural gas are the key natural resources for hydrogen production. Due to our interest in zero-carbon innovation, we exclude grey hydrogen from our analysis.

*LBG (liquefied biogas)* can be produced from organic waste and many other forms of biomass. Following liquefaction, LBG is fully interchangeable with liquefied natural gas (LNG) and can be used in same types of engines. Due to the gases' energy density, vessels using LNG/ LBG are suitable for long-distance shipping. However, although LNG has been used as an energy source in shipping for two decades, diffusion has stalled domestically despite strong growth internationally, which has had negative effects also on LBG innovation in Norwegian coastal shipping (Bach et al., 2021). It should be noted that many hybrid versions of these technologies with other zero-carbon technologies or with conventional fossil fuels exist. This applies especially to battery-electric technology.

A summarized version of the TVCs of the three zero-carbon technologies is presented in Fig. 1, together with the key factors (small grey boxes) related to the interactions between sectors and technologies. The green vertical boxes represent TVCs. There are overlaps between the technologies; for example, there is interdependence between the technologies onshore fuel and/or energy distribution (i.e. in harbours), and there is interdependence between both battery-electric and hydrogen technologies and electricity supply. Although our analysis focuses on innovation in battery-electric, hydrogen, and LBG technologies in the user sector of coastal shipping, it also incorporates attention to how the interaction with land-based transport affect these innovations. The main empirical findings are further elaborated upon in the next section (Section 5), as well as in Appendix B.

## 5. Complementarity formation mechanisms in the value chains of zero-carbon technologies in Norwegian coastal shipping

In our analysis, we understand complementarities as interactions between sectors in a TVC leading to a positive effect on the diffusion of a novel technology. Complementarity formation mechanisms are then the different ways through which such complementarities between sectors within TVCs come to being. Through our analysis we identified three distinct types of complementarity formation mechanisms that were seen to affect the formation of complementarities. We label these complementarity formation mechanisms *synchronization*, *amplification*, and *integration*. While we distinguish the mechanisms analytically, we understand them as being mutually connected. We elaborate on the mechanisms in the following subsections (Sections 5.1–5.3) and provide examples.

### 5.1. Synchronization

The first identified complementarity formation mechanism, synchronization, is linked to the notion that the diffusion of a novel technology requires a full and functioning value chain. Thus, the key aspect is that there is sufficient co-development between the sectors within a TVC. As already discussed, for novel technologies such a TVC may yet be non-existent or internally incoherent or dysfunctional. This situation was prevalent when we performed our analysis. Not only was the development of complete TVCs critical for diffusion of zero-carbon technologies, but the involved sectors also needed to be mutually *synchronized* for diffusion to occur. This relates to the inherent uncertainty in innovation that may hinder commercial actors from taking action to seize potential market opportunities in novel TVCs. Actors in the user sector may wait for the appropriate input sector functions (e.g. fuel supply, infrastructure) to emerge before investing in zero-carbon technologies, while input-sector actors may wait until there is large enough demand emanating from the user sector to justify their investments in providing these functions, leading to delays in the diffusion of a technology. Adjustments in practices and institutions are also needed, both at the sectoral interfaces and the TVC as a whole. Furthermore, alignment of expectations across different actor groups (in a TVC) can be an important feature of synchronization.

Thus, synchronization refers to the simultaneous and mutually supporting development between the input and user sectors in a TVC, enabling the emergence of a *full* TVC, and thus allowing the formation of complementarities between the sectors within a TVC. By contrast, the lack of synchronization may lead to 'waiting games' (Robinson et al., 2012) between actors within a TVC, and a 'chicken and egg problem' between the input and user sectors of a technology.

Synchronization, or the lack of it, was visible in the sectoral interdependencies of hydrogen, LBG and battery-electric technologies in Norwegian coastal shipping. For instance, because both existing production capacity and demand for green hydrogen are yet very limited, uncertainty was high for local hydrogen producers (and their investors) regarding future markets. The liquefied hydrogen for the first hydrogen vessel (MF Hydra) will be transported by truck from Germany, at least in the initial phase (Førde, 2021). One supplier company representative laconically summarized the situation, as follows: 'It is meaningless to produce hydrogen before you have a market for it' (Interview 5). Meanwhile, shipowners' willingness to invest in hydrogen vessels was impeded by the current lack and future uncertainty of hydrogen supply and availability. This is the classical chicken and egg problem regarding the supply and demand of novel fuels (DNV GL, 2018a). To some extent, this problem also applied to LBG, for which there is still limited production and liquefaction capacity. Although there were concrete plans for more LBG production plants domestically, they primarily targeted land-based transport (Interviews 10–12 and 34, DNV GL, 2018a). In 2021, due to the COVID-19 pandemic, the only LBG vessel project in Norwegian passenger shipping was cancelled, leaving no market pull that would incentivize increased production of LBG targeting coastal shipping. Although existing LNG bunkering facilities could be used, the actual bunkering of LBG remains very limited (Interviews 12, 28) (Sund Energy, 2018). Overall, such alignment opportunities of LBG with LNG have not resulted in good performance of LBG innovation in Norwegian shipping (Bach et al., 2021).

Inadequate electricity grid access constituted a similar challenge for battery-electric vessels in remote and sparsely populated areas. Due to often limited prior power demand in such places, substantial investments in grid infrastructure were needed to cater to the power demands of large ferries (Interviews 8, 18, 21, 25, 29) (DNV GL, 2015a). One interviewee described (in a caricature manner) the development of a fully electric ferry project in a peripheral location in Norway as follows: "They went to the grid operator: 'We want to build a ferry here, we need one megawatt.' The grid operator just laughed, threw them out. They didn't have one megawatt there" (Interview 6). Upgrading and building grid infrastructure is expensive, thus hindering willingness to make such investments (Interview 8). However, over time electricity producers and grid operators have reportedly become more engaged in the electrification of coastal shipping, for instance by developing new power transmission capacity and shore-power connectors, leading to co-development across the TVC (Interview 21). Shipowners and harbours have also circumvented inadequate power distribution by installing large batteries onshore, which may charge slowly within the limits of available power in the grid, and which battery-electric vessels may use to charge their own batteries when needed (Interview 21).

While synchronization challenges hindered battery-electric diffusion in remote areas, the situation was different in city harbours. Power distribution in populated places is usually not a problem, due to the existence of stronger grids. The presence of battery-electric vessels may even be beneficial for the local power grid; this is because large grid-connected vessels with megawatt-scale batteries may potentially act as a reserve power storage for local grid operators, providing additional flexibility to grid management (Interview 23). The above-mentioned points also imply that harbours play an important role in mediating power needs between electric vessels and power grids (Interviews 4, 6, 23).

To summarize, the above-presented examples suggest that synchronization is a key mechanism through which complementarities may arise in TVCs. This is particularly important for radically novel technologies (such as hydrogen in coastal shipping) where considerable co-development is needed in multiple sectors to ensure a fully functioning TVC. To solve synchronization challenges (e.g. chicken and egg), one interviewed fuel producer argued as follows:

> You must get going with parallel innovation in all steps. Upstream, production, distribution, use areas, integration in existing processes. You must start in regulation, business models. You must start the innovation parallelly in all links […] with industrial solutions in the whole value chain. (Interview 13)

### 5.2. *Amplification*

While synchronization highlighted co-occurring developments, amplification points to mechanisms that enable user sectors' *growing* adoption of a technology. Diffusion of a novel technology in a user sector creates demand for products and services in the input sectors of the TVC, making it imperative that input sectors are scalable enough to ensure a balance between supply and demand. Thus, economies of scale may emerge, driving further development and deployment in the user sector due to reduced costs, network effects, and increased availability of necessary services and products. Therefore, the amplification mechanism points to the expansion of input sectors to meet the growing diffusion of a technology in user sectors. It follows that amplification is contingent upon sectoral characteristics such as the ability to upscale. Amplification may lead to complementarities between input and user sectors that, in turn, may drive further diffusion of technologies. Amplification may emerge also between different TVCs, for example due to shared input sectors (e.g. the same energy sources or carriers used in transport and processing sectors), see more regarding this issue in Section 5.3. Meanwhile, the lack of amplification may hinder the formation of complementarities due to the inability of input sectors to respond to a growing demand, slowing down diffusion.

We found indications of both the existence and the lack of amplification in our empirical study. The former is exemplified by battery-electric vessels. Despite the above-described local electricity distribution issues, the Norwegian electricity system as a whole, with its plentiful and usually affordable hydropower, is expected to be able to carry the increased power demand from electrification of coastal vessels (DNV GL, 2015a). Thus, electricity supply is seen as sufficiently abundant to allow for diffusion of battery-electric vessels in segments where they are an applicable zero-carbon solution (Interviews 1, 17, 28). While in 2010 there were 13 battery-electric vessels worldwide, in 2021 there were 208 battery-electric vessels in Norway alone, either in operation or on order (Maritime Battery Forum, 2021).[6] Thus, a rapid diffusion of battery-electric vessels has been possible in the Norwegian energy system.

We also found indications of the importance of economies of scale in the amplification mechanism, particularly in the case of green hydrogen production. While large-scale green hydrogen production is currently non-existent in Norway, it is expected that growing numbers of hydrogen vessels will trigger investments in production capacity based on larger electrolysers that would further reduce costs. This example also illustrates the connection between the synchronization and amplification mechanisms. One supplier estimated that the price of hydrogen produced in large electrolysers (~50 MW) would be 50% cheaper than in small electrolysers (~1 MW) (Interview 14). Thus, economies of scale make hydrogen solutions cheaper for users, which in turn stimulates increased adoption in user sectors.

However, hydrogen production has scalability challenges in Norway. If both the production and use in fuel cells of green hydrogen are taken into consideration, green hydrogen has only c.25% energy-efficiency (Ingeberg et al., 2020; NCE Maritime CleanTech, undated), which makes it much less energy-efficient than, for example, electric vessels. Therefore, it is probable that broad application of hydrogen vessels in Norway would require more electricity production capacity (Interviews 5, 8, 14, 18, 23, 28) (DNV GL, 2018b). In other words, while the current Norwegian electricity supply is sufficient for battery-electric vessels, it is probably insufficient for an extensive diffusion of green hydrogen solutions in coastal shipping. Growth in electricity supply may be difficult to achieve due to the limited expansion potential of hydropower in Norway (Hanson et al., 2011), while onshore wind power has recently faced increasing public opposition. Thus, scalability issues might arise if electricity were to function as a shared input sector in battery-electric and hydrogen TVCs. By contrast, while blue hydrogen production also has low energy-efficiency, it has higher scale-up potential due to the still abundant natural gas and depleted oil and gas reservoirs on the Norwegian continental shelf, as a storage space for captured carbon. However, both natural gas and depleted reservoirs naturally have limits (Interviews 13, 28).

We also found lack of amplification particularly in the case of LBG. Biogas, like other biofuels, is dependent on the availability of biomass. First-generation biofuels are produced from crops, but competition with food production has a negative effect on their legitimacy and availability. Therefore, second-generation biogas produced from biowaste (e.g. from agriculture, aquaculture, communal waste) is more relevant in the context of Norwegian coastal shipping (Interviews, 10, 11, 12, 28) (Sund Energy, 2018). While biowaste is in principle bountiful, it is unclear how much of it can feasibly be commercially utilized.[7] Availability of biomass is believed to be too limited to cater for the growing diffusion in LBG vessels, which hampers its legitimacy among maritime actors (Interviews 5, 11, 32, 34) (DNV GL, 2014). Moreover, coastal shipping competes with other user sectors, such as land-based transport, over scarce biofuels (Interviews 10, 11, 34). As admitted by a biogas producer: 'There will never be enough biogas to cover the whole transport need. […] We believe that the future will have many, different fuels, electric, hydrogen and biogas' (Interview 11).

To summarize, the amplification mechanism refers to the ability of input sectors to cater for growing demand from user sectors, leading to complementarities.

### 5.3. *Integration*

The third identified complementarity formation mechanism in TVCs points mechanisms that lead to couplings or convergence between TVCs

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[6] They include both fully electric and hybrid vessels.

[7] Third-generation biofuels, based on raw materials such as micro and macroalgae, which do not require arable land, have been explored too (DNV GL, 2014). However, it has been questioned whether they will ever become a commercial alternative (Interview 32).

in one or more user sectors. Such mechanisms may be particularly important in the early phases of zero-carbon innovation (Markard and Hoffmann, 2016). For example, spillovers of knowledge and regulations (or standardization) from one user sector may affect the development and deployment of novel technologies in other user sectors. Moreover, the different TVCs of a user sector may intertwine, thus creating economies of scale and potentially strengthening amplification. This can occur if, for example, the infrastructure for production and distribution of new zero-carbon fuels serves two or more TVCs.

Thus, the integration mechanism points to convergence across TVCs in one or more user sectors through, for example, shared infrastructure and resources, leading to complementarities. Lack of such integration may lead to a slower pace of diffusion because a TVC then develops separately from other TVCs, only driven by specific action targeting it in a single user sector. Consequently, it does not benefit from complementarities with other TVCs.

We identified the integration mechanism notably between the user sectors of coastal shipping and land-based transport. While the use of battery-electric systems in shipping is a relatively recent phenomenon, electric vehicles in personal transport have been developed for decades. As such, coastal shipping has benefitted from knowledge spillovers from land-based transport with regard to lighter weight batteries with higher energy density and charging capacity. The input sectors that produce battery cells and battery packs are already well developed for land-based transport, making it easier to establish dedicated battery manufacturing and assembly also for maritime use. As a consequence, while technical adaptation of battery technology (e.g. cell and module design, software) is necessary, the application of battery-electric technologies in coastal shipping has been fast-tracked due to spillovers from earlier developments in other user sectors (Interviews 2, 7, 25, 30) (DNV GL, 2015b).

Hydrogen and LBG powered vehicles have diffused much less than electric vehicles. Nevertheless, integration between land-based transport and coastal shipping could emerge also in the context of hydrogen and LBG technologies. As full LBG and hydrogen TVCs do not yet exist, there have been initiatives to combine the distribution needs of both shipping and heavy land-based transport into a joint network, which has created sufficient aggregate demand and economies of scale to make production economically feasible (Interviews 27, 31). For instance, ports could serve as ‘energy hubs’ (i.e. production and distribution sites of, for example, hydrogen and/or LBG) (Interviews 3, 14, 31) (Damman and Steen, 2021), as also described by a supplier company:

> What industrial actors are concerned about in terms of economics and financing is how to combine hydrogen [supply] in several segments, both on land and sea, that is important. […] So that we do not just have many small hydrogen plants, [but] that we manage to do it bigger. (Interview 3)

Thus, energy hubs that concentrate demand from different user sectors can provide the critical mass necessary to encourage the formation of hydrogen and LBG supply.

Also, integration between the hydrogen TVC in coastal shipping and processing industry (here understood as an energy user sector) may support the diffusion of hydrogen technologies. For example, metal industries needing to decarbonize are potentially large future users of hydrogen. If the demand for clean hydrogen expands drastically (e.g. in steel production), as has been planned in both Norway and Sweden (Kushnir et al., 2020), the realized economies of scale could push green hydrogen prices down also for coastal shipping (Interview 14). Similar processes are key also for blue hydrogen production, which is considered unfeasible in low production volumes mainly because of high CCS costs. Even wide diffusion of hydrogen vessels in coastal shipping might not suffice to trigger investments in blue hydrogen production. This possibility highlights that the integration of demand from several sectors may be key for further diffusion, especially in early stages of value chain formation.

To summarize, the integration between different user sectors with similarities in energy demands is an important mechanism forming complementarities between sectors. Integration may occur through knowledge spillovers, shared institutional frameworks, or development of joint physical infrastructure.

## 6. Discussion: theorizing complementarity formation mechanisms in technology value chains

Our paper contributes to the existing literature in innovation and sustainability transitions by analysing mechanisms in multisectoral and multi-technological interactions that lead to formation of complementarities (Andersen et al., 2020; Bergek et al., 2015; McMeekin et al., 2019; Rosenbloom, 2020). Such mechanisms, we argue, are not only important in the phase of accelerated diffusion where multisectoral and multi-technological interactions become more prevalent (Markard, 2018; Markard et al., 2020), but also already in early stages of innovation. While earlier literature has recognized the existence of TVC complementarities (Markard and Hoffman, 2016), our analysis of the value chains of three zero-carbon technologies (battery-electric, hydrogen, and LBG) in Norwegian coastal shipping has allowed to identify three mechanisms (synchronization, amplification, and integration) whereby complementarities (i.e. positive interactions) may arise within TVCs. Better understanding of the formation of complementarities has implications for thinking how zero-carbon innovations and transitions can be fostered. Moreover, by including energy and material throughput sectors we have expanded the analysis of technology value chains (TVCs) in innovation and sustainability transitions literature beyond component-producing sectors (Andersen and Markard, 2020; Stephan et al., 2017).

The identified complementarity formation mechanisms point to different ways in which positive interactions between sectors in TVCs may form. We argue that such mechanisms are necessary for complementarities to emerge within TVCs. These mechanisms are driven by agency (e.g. firms, entrepreneurs, networks, policymakers, users) and are affected by sectoral characteristics (e.g. scalability, adaptability). In their simplest form, complementarity formation mechanisms are linked to the mere capability of input sectors to enable the fulfilment of a technology's function in a user sector. In more complex forms, the development and deployment of a technology in one use sector may be affected by developments in other TVCs and user sectors.

The focus on complementarity formation mechanisms allows for analysis of how different TVCs affect technological innovation in different ways. It also enables the identification of challenges related to a particular TVC from the perspective of a focal user sector. The differentiation between complementarity formation mechanisms offers a better understanding of the enabling and constraining factors within TVCs for innovation. In turn, this more detailed understanding of how complementarities emerge between technologies and sectors allows policymakers and industry actors to better identify and act upon some of the critical drivers and barriers to zero-carbon innovation.

The sectoral interdependencies in TVCs and the complementary mechanisms that can contribute to the diffusion of zero-carbon technologies, and consequently the sustainability transition, in a focal user sector are shown schematically in Fig. 2.[8]

We conceptualized the first complementarity formation mechanism as *synchronization*. Timing, understood as co-occurring developments across sectors, is central in synchronization. It is crucial for a novel technology that actors in all TVC's sectors have incentives to engage in

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[8] Actors within the sectors of a technology value chain are also embedded in political, economic, and geographical contexts, and may interact with other parallel sectors and technologies (Bergek et al., 2015), as well as sectors providing, for example, components and various services for a focal technology. However, such interactions are not elaborated upon in this paper.

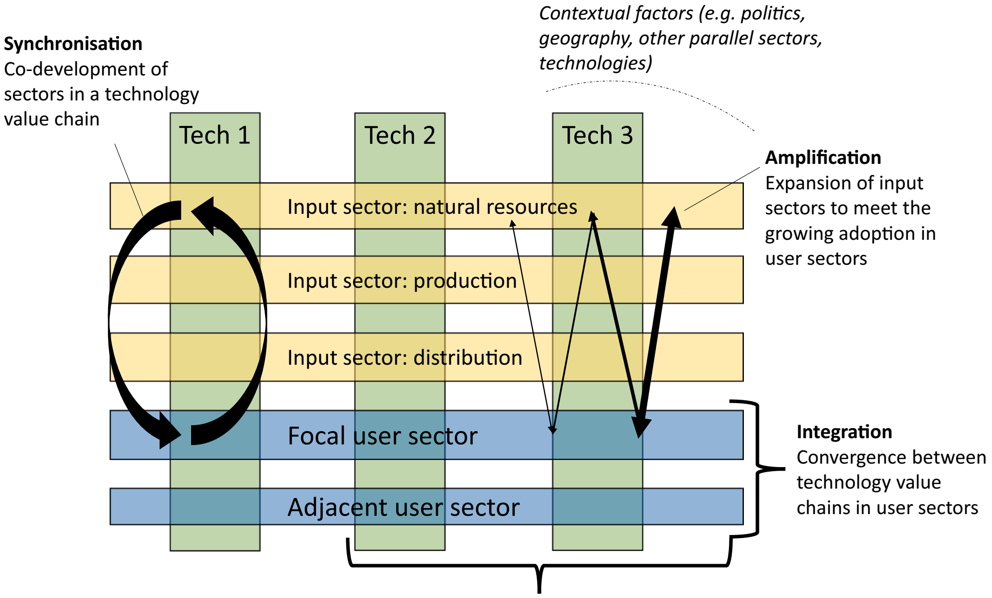

**Fig. 2.** Complementarity formation mechanisms in technology value chains.

the development of the TVC. For example, the functioning of input sectors may precondition the deployment of a novel technology in a user sector (Leibowicz, 2018). At the same time, such technology deployment in user sectors can be a precondition for input sectors to be incentivized to provide their products or services in the TVC, which underlines the necessity of a synchronous development across segments that are necessary to form a functioning TVC (Andersen, 2014; Hughes, 1987; van Welie et al., 2018).

In our case study we found that the institutional characteristics of the sectors may contribute to the formation (or absence) of synchronization. In the case of battery-electric, rural grid extensions were identified as a bottleneck, where input and user sectors were characterized by differing operational goals and ambitions. While the user sector wished to reduce emissions of shipping through electrification, actors in the grid input sector were more concerned with providing a functional power grid and did not see grid extension as cost-efficient. Such differing goals and ambitions across interdependent sectors may also influence the degree to which problems become a solvable reverse salient (Hughes, 1987). We found that the three TVCs in our study differed in terms of how synchronization was able to form. For example, with regard to battery-electric vessels, we found that the lack of grid extensions in rural areas became a reverse salient that was solved by means of onshore battery packs. By contrast, in the case of LBG and hydrogen, institutional misalignment originating from uncertainties has hampered synchronization so far. Additionally, LBG and hydrogen are hindered by chicken and egg problems, pointing to lack of synchronization. Thus, it is not surprising that the two technologies still lag behind battery-electric technology in terms of deployment. Hence, coordination and intermediation (Kivimaa et al., 2019) are needed to foster synchronization between the sectors in a TVC in order to overcome, for example, market uncertainty for firms in different sectors of a TVC. Thus, synchronization within the value chain may require conscious system-building by actors (Musiolik et al., 2020). However, this may be challenging, either because the interests and expectations of key actors may not be aligned (Bakker, 2014) or because actors may lack important competences (Hellsmark and Hansen, 2020).

Whereas synchronization points to co-development in TVCs, *amplification* is central in allowing for growing deployment of novel technologies. It is tightly linked to the scalability of input sectors. In the studied case, we see this unfolding positively for battery-electric vessels where the power and grid sectors are able to cater for the increasing deployment, leading to complementarities within the battery-electric TVC. Notably, such situations may trigger positive feedback loops, whereby positive developments (e.g. reduction in natural resource or production costs) in one sector will lead to other positive developments (e.g. increased legitimacy) in other parts of the TVC. For example, the availability of storage and distribution infrastructure for hydrogen may incentivize shipping companies to invest in hydrogen vessels, which in turn may incentivize more investments in fuelling infrastructure.

However, limited scalability of input sectors may impede amplification and thus complementarities. In our case study we found that the diffusion of LBG vessels had been particularly hindered by inadequate biogas supply and related legitimacy issues. Therefore, our insights are similar to those of, for example Bennett (2012) and Sutherland et al. (2015), in that we find that low scalability or expansion capability of input sectors may constrain the biofuel innovation. This illustrates the difference between synchronization and amplification. While synchronization is about getting TVC segments in place in a timely fashion, amplification concerns the scalability of input sectors over time.

The third complementarity formation mechanism, *integration,* points to situations where knowledge and institutions regarding a novel technology that was developed primarily for the purposes of one user sector may contribute to innovation also in other technologies and/or user sectors (cf. Raven, 2007; Stephan et al., 2017). Integration is thus characterized by spillovers of system resources (knowledge, market access, technology legitimacy, financial investments) between TVCs (Binz and Truffer, 2017). In our empirical study, especially battery-electric technologies in coastal shipping benefited from knowledge spillovers from land-based transport. Integration may also manifest when multiple user sectors utilize the same infrastructure. Such complementarities may be particularly important in the case of production and distribution of novel fuels and energy carriers that require some level of scale to be commercially feasible. For example, coastal shipping and land-based transport could mutually benefit from sharing hydrogen and LBG infrastructure in harbours (Bjerkan et al., 2021). Moreover, different technologies may have the same input sectors in their value chains, which may support the innovation also in other technologies with the same input sector. However, such situations may also hinder complementarities in TVCs from forming if, for example, scarcity of a key resource or the product of an input sector becomes unavailable for other uses or if strong development in one TVC ‘crowds out’ developments in other TVCs by capturing the attention and efforts of actors. For instance, in the case of LBG, we observed that competition between coastal shipping and land-based transport over scarce supplies of LBG limited the formation of such complementarities.

Our empirical material has allowed us to analyse complementarity formation mechanisms in the early phases of innovation (LBG and hydrogen), as well as in instances characterized by accelerated diffusion (battery-electric). Thus, it seems likely that the mechanisms matter in both early and more mature phases of innovation. The complementarity formation mechanisms may however also vary in their relevance, depending on the maturity of innovation and transition processes. Synchronization and integration appear particularly relevant in the early phase of innovation, when TVCs are often still emerging. When a full TVC is in place, synchronization may encourage actors to make further investments. Later, it seems that amplification becomes more relevant. Therefore, we suggest that synchronization precedes amplification. The integration mechanism may also be important in early development phases, especially in cases such as hydrogen, where the TVC may yet not exist at all and where interest from multiple user sectors may induce actors in input sectors to invest in production and distribution.

The different types of complementarity formation mechanisms are interconnected and occasionally they feed into each other. Integration may further drive amplification through economies of scale and scope between other user sectors and/or technologies. Additionally, further deployment of novel technologies through amplification (i.e. in new user sectors) creates a need for value chain ‘resynchronization’ to deal with the reverse salients that typically emerge. This highlights how synchronization remains an important complementarity formation mechanism throughout the different phases of innovation.

## 7. Conclusions

This paper contributes to theory building around a multisectoral perspective on technological innovation by exploring the mechanisms through which complementarities form in technology value chains (TVCs). We venture to suggest that the synchronization, amplification, and integration mechanisms identified in this paper are relevant beyond our particular case (coastal shipping in Norway), although further research would be needed to validate this claim. We conclude this paper by discussing the implications of our findings for sustainability transitions policy, as well as limitations and future research opportunities.

### 7.1. Implications for sustainability transitions policy

The notion of complementarity formation mechanisms in TVCs has relevance for policy measures that are intended to meet the urgent need to foster rapid societal transformations towards, for example, decarbonized patterns of production and consumption. Synchronization highlights the need for intermediation (Kivimaa et al., 2019) across the sectors within a TVC. While intermediation is important for, for example, the formation of collective expectations and knowledge sharing (Glaa and Mignon, 2020), fostering synchronization may require additional objectives for intermediaries. For example, in order to avoid chicken and egg problems, cluster organizations could contribute by facilitating interactions across TVCs, R&D programmes may have to address innovation throughout TVCs, and public support instruments may need to consider production and distribution in addition to demand-side issues (Mäkitie et al., 2021). In other words, both public and private intermediaries could foster synchronization through various instruments that support simultaneous development (where needed) in different sectors of a TVC. Importantly, such value chain considerations in governance should be implemented early on to help circumvent waiting games between input and user sectors. Also, intermediation and coordination will likely face a need to handle vested interests among actors in the TVC (Kivimaa et al., 2019). This could require intermediaries to attend to institutional differences across the sectors in a TVC.

Amplification underlines that challenges related to the scalability of input sectors may become bottlenecks for innovation. Such considerations regarding the amplification mechanism can offer insights for policymaking, particularly in situations with multiple technological options, where policymakers face dilemmas regarding which technologies to support, given resource constraints (Magnusson and Berggren, 2018). This dilemma is strengthened by how technological innovation can be dependent on synchronization of the TVC, meaning that policy may need to support the emergence of an entire TVC. Therefore, adequate policy support to foster *all* novel technologies *and* their respective TVCs may not be feasible. Deeper analysis of TVCs and related complementarities can reveal bottlenecks that need to be addressed by policy and identify emerging technologies whose acceleration seems unrealistic due to, for example, scalability problems.

The integration mechanism points to the need for policymaking to not only consider the formation of complementarities within a TVC, but also between TVCs and user sectors. Integration may open attractive opportunities for policymaking. For example, through integration, R&D support for one technology may support knowledge development in multiple user sectors. Moreover, strategic infrastructure may potentially support value chain formation for several technologies (cf. the energy hub concept). This may make TVC building more commercially attractive for private companies and increase the environmental impact (e.g. GHG mitigation) of such policy instruments. In other words, integration between the value chains of novel technologies (e.g. in terms of fuel supply) may offer ‘two-for-one’ opportunities for policy to address issues in multiple user sectors or technologies with a single policy instrument.

### 7.2. Limitations and further research

Our research strategy of case-based theory building to arrive at analytical generalization naturally has limitations, which thus opens up opportunities for further research.

First, our analysis of sectoral interdependencies and complementarity formation mechanisms is limited to data that were available in the current early phase of some of the zero-carbon innovations (LBG and hydrogen). Historical case studies would nevertheless be highly useful to further expand our understanding of complementarity formation mechanisms.

Second, our assessment of sectoral dependencies and interdependencies is based on qualitative data and thus does not include quantitative assessment of, for example, the scalability potential of input sectors. Therefore, our analysis is focused primarily on the experiences, perceptions, and estimations of actors. Future research could seek to combine quantitative assessments (e.g. techno-economic modelling) and qualitative assessments that are relevant for evaluating complementarity formation mechanisms in TVCs, for example in scenario development or transition pathway analysis.

Third, our analysis is limited to a single case study in a single country. The battery-electric, hydrogen, and LBG technologies' sectoral interdependencies (e.g. the availability of biomass, grid infrastructure) certainly can be expected to vary between countries and regions, which limits the empirical generalizability of the findings from our case study. Future research is needed to study zero-carbon innovation in coastal shipping and complementarity formation mechanisms in TVCs in general, also in other countries and sectors.

Finally, while being outside of the scope of analysis in this paper, complementarity formation mechanisms can likely be identified also in the dependencies and interdependencies between technologies (Markard and Hoffman, 2016; Sandén and Hillman, 2011). Further exploration of the types and roles of such mechanisms between technologies is thus an interesting topic for further research on technological innovation.

## CRediT authorship contribution statement

**Tuukka Mäkitie:** Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. **Jens Hanson:** Conceptualization, Investigation, Writing – review & editing, Funding acquisition. **Markus Steen:** Conceptualization, Investigation, Writing – review & editing, Project administration, Funding acquisition. **Teis Hansen:** Conceptualization, Methodology, Investigation, Writing – review & editing, Funding acquisition. **Allan Dahl Andersen:** Conceptualization, Writing – review & editing.

## Declaration of competing interest

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

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## Appendix A. Interviews conducted with representatives of organizations

| Interview Number | Actor type |
|---|---|
| 1 | Components and services 1, B-E |
| 2 | Components and services 2, B-E |
| 3 | Components and services 3, H2 |
| 4 | Components and services 4, B-E |
| 5 | Components and services 5, H2 & B-E |
| 6 | Components and services 6, maritime |
| 7 | Components and services 7, maritime |
| 8 | Components and services 8, B-E |
| 9 | Components and services 9, maritime |
| 10 | Fuel production and distribution 1, LBG |
| 11 | Fuel production and distribution 2, LBG |
| 12 | Fuel production and distribution 3, LBG |
| 13 | Fuel production and distribution 4, H2 |
| 14 | Fuel production and distribution 5, H2 |
| 15 | Yards and ship design 1 |
| 16 | Yards and ship design 2 |
| 17 | Yards and ship design 3 |
| 18 | Yards and ship design 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, maritime |
| 27 | Industry association 2, H2 |
| 28 | Industry association 3, maritime |
| 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 |

## Appendix B. Second-round coding: identification of sectoral interdependencies

| Code | Description | Number of sources | Example of data excerpt |
|---|---|---|---|
| B-E: Car industry supports battery-electric innovation in maritime sector | EV innovation supports the battery development (e.g. lighter components, charging capacity and time) in shipping. However, adaptations to maritime use are necessary. | 6 | Interview 7: 'It is the car industry that drives this with the battery technology. It is certain that the weight of batteries will come down and the charging capacity and time will become better.' |
| B-E: Need for large enough grid capacity on quaysides | B-E vessels require high charging capacity on quaysides, for which reason it might be necessary to build grid access and capacity, especially in remote places. In populated areas, vessel batteries can also be used as reserve power for onshore grid. | 7 | Interview 21: 'We had a big challenge in relation to getting enough power at the quay in [ferry crossing] because they had bad grid there. […] When we began working with that ferry crossing, the grid owner said straight out that they do not like new things. Therefore, we needed to sell our idea of a battery at quay to take care of the grid of the grid owner, and we see that |

(*continued on next page*)

(*continued*)

| Code | Description | Number of sources | Example of data excerpt |
|---|---|---|---|
| | | | they were forced into a setting where they have to change their attitude with these grid improvements.’ |
| B-E: Enough renewable energy in Norway to charge vessels | B-E vessels require a lot of renewable electricity. However, in general, Norway has sufficient electricity production to cover this need. | 4 | DNV GL, 2015a (translated from Norwegian): ‘The power sector seems to be able to deliver sufficient capacity to the electrification of the ferry sector. Combined consumption of electricity for this purpose – c.240 GWh – is completely marginal compared with the overall access to electricity in the Norwegian power system, but it presumes the building of power grids.’ |
| B-E: Need for batteries on quaysides | B-E vessels may need large charging batteries on quaysides, in case availability of power from the grid is an issue. Batteries on quaysides increase flexibility and decrease dependence on power availability. | 4 | Interview 23: ‘Grid operators do not need to guarantee us the delivery [of power] because we have a battery anyway, so they can cut us out with a warning.’ |
| H2: A lot of cheap renewable energy is needed in electrolysis | Production of H2 through electrolysis requires a lot of available cheap (renewable) electricity. Extra wind and solar power can be particularly good in this case. Produced oxygen can be used (e.g. in aquaculture). | 8 | Interview 5: ‘For electrolysis, it is decisive that you have cheap enough energy. […] Generally speaking, the power is cheap enough. If you manage to avoid grid rent, it is very positive. If you can utilize extra wind power, it is very positive.’ |
| H2: Blue hydrogen is a scalable production method | Blue hydrogen (natural gas + CCS) production is seen as a scalable way to produce H2. This requires a high demand for H2 to make it worthwhile (e.g. due to the cost of CCS). However, CCS is limited by the availability of storage spaces (which are limited and are highly localized). | 3 | Interview 13: ‘It is gigantic investments you have in gas fields. You have gas production, you have gas pipelines, you have gas terminals. All this you can use and need in order to produce hydrogen from gas. You have it. So you can convert that natural gas to hydrogen. […] Here we talk about hydrogen in very large volumes. […] Our challenge in maritime hydrogen is that we have a good [blue hydrogen] solution the day when the market is pretty big, but it is difficult to get there.’ |
| H2: H2 bunkering and production on quaysides can be used by several user sectors | H2 bunkering (storage) or production is needed on quaysides. This same infrastructure can also be used for other H2 use, such as land-based transport. However, there has been little H2 production to date. | 5 | Interview 3: ‘We will get facilities that combine wind and sun for hydrogen production, which in turn can be used by maritime applications, but also land-based transport. When you try to centralize production of the energy carrier, there you get the lowest cost on the whole system. If you have the production facility locally at quay, then you should use it, and then busses and trucks must come to the quay.’ |
| LBG: Waste from different sources can be used in biogas production | Various types of waste, such as dead fish from aquaculture or communal waste, can be used to produce biogas for biogas vessels. This in turn can create a life cycle perspective on biogas. | 5 | Interview 28: ‘There are plenty of examples within biogas production that someone else's waste [and] someone else's problem, becomes gas producers’ raw material. That someone actually needs to pay to pollute or pay to get rid of it, and then it can be valued as a raw material in biogas production. It is very exciting.’ |
| LBG: Biomass from algae | Algae production is a potential future source of biomass for biogas production. Currently, it is in a very early phase. However, it is unclear if it will be ever commercially viable. | 3 | Interview 32: ‘There is plenty of research ongoing, especially on algae, but if you wish to grow algae to produce biofuels, there is no economics in that.’ |
| LBG: Little biogas production at present | There is currently too little biogas production and liquefaction capacity. | 5 | Interview 34: ‘Today we more or less only have this one large production plant up in Trøndelag, and if they follow the plans and add another production line, which they have the possibility to do, and, of course, they could double their production and that might open up possibilities.’ |
| LBG: LNG infrastructure and equipment are well developed | There is existing natural gas infrastructure that can be used also for biogas distribution and storage. Also, gas vessels and engines already exist and are relatively mature. | 3 | Interview 28: ‘We have gas motors today, we have gas tank, we have system, we have certificates. This is an area where Norway has a lot of knowledge.’ |
| LBG: Not enough biomass for large-scale biogas production | Availability of biomass is limited and therefore biogas is not highly scalable and not in sufficient quantities to fuel all land-based transport. However, somewhat high theoretical potential in utilizing waste streams for LBG production. | 5 | Interview 11: ‘There will never be enough biogas to cover the whole transport needs. Then we would have to waste much or use virgin land to grow [crops for biofuels], and that is not something we particularly support. We believe that the future will have many different fuels, electric, hydrogen and biogas.’ |

## References

Abernathy, W.J., Clark, K.B., 1985. Innovation: mapping the winds of creative destruction. Res. Policy 14, 3–22.

Andersen, A.D., 2014. No transition without transmission: HVDC electricity infrastructure as an enabler for renewable energy? Environmental Innovation and Societal Transitions 13, 75–95.

Andersen, A.D., Markard, J., 2020. Multi-technology interaction in socio-technical transitions: how recent dynamics in HVDC technology can inform transition theories. Technol. Forecast. Soc. Chang. 151 (Article 119802).

Andersen, A.D., Steen, M., Mäkitie, T., Hanson, J., Thune, T.M., Soppe, B., 2020. The role of inter-sectoral dynamics in sustainability transitions: a comment on the transitions research agenda. In: Environmental Innovation and Societal Transitions, 34, pp. 348–351.

Arthur, W.B., 1988. Self-reinforcing mechanisms in economics. In: Anderson, P.W., Arrow, K.J., Pines, D. (Eds.), The Economy as an Evolving Complex System. CRC Press, Boca Raton, pp. 5–20.

Arthur, W.B., 2009. The Nature of Technology. What It Is and How It Evolves. Penguin Books, London.

Bach, H., Bergek, A., Bjørgum, Ø., Hansen, T., Kenzhegaliyeva, A., Steen, M., 2020. Implementing maritime battery-electric and hydrogen solutions: a technological innovation systems analysis. Transp. Res. Part D: Transp. Environ. 87 (Article 102492).

Bach, H., Mäkitie, T., Hansen, T., Steen, M., 2021. Blending new and old in sustainability transitions: technological alignment between fossil fuels and biofuels in Norwegian coastal shipping. Energy Res. Soc. Sci. 74 (Article 101957).

Bakker, S., 2014. Actor rationales in sustainability transitions – interests and expectations regarding electric vehicle recharging. Environmental Innovation and Societal Transitions 13, 60–74.

Bennett, S.J., 2012. Using past transitions to inform scenarios for the future of renewable raw materials in the UK. Energy Policy 50, 95–108.

Bento, N., Fontes, M., Barbosa, J., 2021. Inter-sectoral relations to accelerate the formation of technological innovation systems: determinants of actors’ entry into marine renewable energy technologies. Technol. Forecast. Soc. Chang. 173 (Article 121136).

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Res. Policy 37, 407–429.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. Environmental Innovation and Societal Transitions 16, 51–64.

Bergek, A., Bjørgum, Ø., Hansen, T., Hanson, J., Steen, M., 2021. Sustainability transitions in coastal shipping: the role of regime segmentation. In: Transportation Research Interdisciplinary Perspectives, 12 (Article 100497).

Binz, C., Truffer, B., 2017. Global innovation systems—a conceptual framework for innovation dynamics in transnational contexts. Res. Policy 46, 1284–1298.

Bjerkan, K.Y., Ryghaug, M., Skjølsvold, T.M., 2021. Actors in energy transitions: transformative potentials at the intersection between Norwegian port and transport systems. Energy Res. Soc. Sci. 72 (Article 101868).

Bugge, M.M., Andersen, A.D., Steen, M., 2021. The role of regional innovation systems in mission-oriented innovation policy: exploring the problem-solution space in electrification of maritime transport. Eur. Plan. Stud. https://doi.org/10.1080/09654313.2021.1988907.

Dahmén, E., 1988. 'Development blocks' in industrial economics. Scand. Econ. Hist. Rev. 36, 3–14.

Damman, S., Steen, M., 2021. A socio-technical perspective on the scope for ports to enable energy transition. Transp. Res. Part D: Transp. Environ. 91 (Article 102691).

Das, S.S., Van de Ven, A.H., 2000. Competing with new product technologies: a process model of strategy. Manag. Sci. 46, 1300–1316.

DNV GL, 2014. A Broader View: The Future of Shipping (downloaded on 4 January 2022 from. https://issuu.com/dnvgl/docs/dnv_gl_-_the_future_of_shipping/1.

DNV GL, 2015a. *Elektrifisering av bilferger i Norge – kartlegging av investeringsbehov i strømnettet*. Report No. 2015-0500 downloaded on 4 January 2022 from. https://www.energinorge.no/contentassets/0ae3a2b651ae4e83a0487ad493c3270c/elektrifisering-av-bilferger-i-norge.pdf.

DNV GL, 2015b. *In Focus – the Future is Hybrid – A Guide to Use of Batteries in Shipping* Downloaded on 4 January 2022 From. https://issuu.com/dnvgl/docs/in_focus-the_future_is_hybrid.

DNV GL, 2015c. *Vurdering av tiltak og virkemidler for mer miljøvennlige drivstoff i skipsfartsnæringen*. Report No.: 2015-0086 Downloaded on 4 January 2022 From. https://www.regjeringen.no/contentassets/cffd547b30564dd9a2ae616042c22f26/vurdering_av_tiltak_og_virkemidler_for_mer_miljovennlige_drivstoff_i_skipsfartnaringen.pdf.

DNV GL, 2018a. *Grønt kystfartsprogram barrierestudie: Barrierer for lav- og nullutslippsløsninger for transport av tørrlast med skip*. Rapportnr.: 2018-0126, Rev. 1 Downloaded on 4 January 2022 From. https://grontskipsfartsprogram.no/wp-content/uploads/2021/02/GKP_barrierestudie_torrlast_final_rev1.pdf.

DNV GL, 2018b. Hydrogen as an Energy Carrier: An Evaluation of Emerging Hydrogen Value Chains. downloaded on 4 January 2022 from. https://www.dnv.com/Publications/hydrogen-as-an-energy-carrier-134607.

Dolata, U., 2009. Technological innovations and sectoral change: transformative capacity, adaptability, patterns of change: an analytical framework. Res. Policy 38, 1066–1076.

Dosi, G., Pavitt, K., Soete, L., 1990. *The Economics of Technical Change and International Trade.* Laboratory of Economics and Management (LEM). Sant'Anna School of Advanced Studies, Pisa (Eds).

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manag. Rev. 14, 532–550.

Energy, Sund, 2018. Biogass kan blandes inn i LNG til skip i Norge: Potensiale for doble utslippskutt. Sund Energy, Oslo.

Fitzgerald, F., 1998. Bessemer: the technology and the times. Interdiscip. Sci. Rev. 23, 362–371.

Førde, T., 2021. Drivstoffet til verdens første hydrogenferge hentes med lastebil fra Tyskland. *Tu.no*, 8 March 2021.

Freeman, C., Louçã, F., 2001. As Time Goes by: From the Industrial Revolutions to the Information Revolution. Oxford University Press, New York.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31, 1257–1274.

Geels, F.W., 2018. Low-carbon transition via system reconfiguration? A socio-technical whole system analysis of passenger mobility in Great Britain (1990–2016). Energy Res. Soc. Sci. 46, 86–102.

Gehman, J., Glaser, V.L., Eisenhardt, K.M., Gioia, D., Langley, A., Corley, K.G., 2018. Finding theory–method fit: a comparison of three qualitative approaches to theory building. J. Manag. Inq. 27, 284–300.

Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R., 2019. The role of renewable energy in the global energy transformation. In: Energy Strategy Reviews, 24, pp. 38–50.

Glaa, B., Mignon, I., 2020. Identifying gaps and overlaps of intermediary support during the adoption of renewable energy technology in Sweden – a conceptual framework. J. Clean. Prod. 261 (Article 121178).

Haley, B., 2018. Integrating structural tensions into technological innovation systems analysis: application to the case of transmission interconnections and renewable electricity in Nova Scotia, Canada. Res. Policy 47, 1147–1160.

Hanson, J., 2018. Established industries as foundations for emerging technological innovation systems: the case of solar photovoltaics in Norway. Environmental Innovation and Societal Transitions 26, 64–77.

Hanson, J., Kasa, S., Wicken, O., 2011. Energirikdommens paradokser: innovasjon som klimapolitikk og næringsutvikling. Universitetsforlaget, Oslo.

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

Hughes, T.P., 1983. Networks of Power: Electrification in Western Society, 1880–1930. Johns Hopkins University Press, Baltimore.

Hughes, T.P., 1987. The evolution of large technological systems. In: Bijker, W.E., Hughes, T.P., Pinch, T. (Eds.), The Social Construction of Technological Systems. MIT Press, Cambridge, MA, pp. 51–82.

Ingeberg, K., Bronmo, G., Handberg, Ø.N., Helseth, A.M., Bruvoll, A., Vestlie, M., 2020. Scenarioanalyse av infrastrukturbehov for alternative drivstoff til fartøy i maritime sektor. Rapport R-2020-001. downloaded on 4 January 2022 from. https://www.menon.no/publication/scenarioanalyse-infrastrukturbehov-alternative-drivstoff-fartoy-maritim-sektor/.

Kim, Y., Lee, J., Ahn, J., 2019. Innovation towards sustainable technologies: a socio-technical perspective on accelerating transition to aviation biofuel. Technol. Forecast. Soc. Chang. 145, 317–329.

Kivimaa, P., Boon, W., Hyysalo, S., Klerkx, L., 2019. Towards a typology of intermediaries in sustainability transitions: a systematic review and a research agenda. Res. Policy 48, 1062–1075.

Kline, S.J., Rosenberg, N., 1986. An overview of innovation. In: Council, N.R. (Ed.), The Positive Sum Strategy: Harnessing Technology for Economic Growth. National Academies Press, Washington, D.C., pp. 275–306

Konrad, K., Truffer, B., Voß, J.-P., 2008. Multi-regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors. J. Clean. Prod. 16, 1190–1202.

Kushnir, D., Hansen, T., Vogl, V., Åhman, M., 2020. Adopting hydrogen direct reduction for the Swedish steel industry: a technological innovation system (TIS) study. J. Clean. Prod. 242 (Article 118185).

Leibowicz, B.D., 2018. Policy recommendations for a transition to sustainable mobility based on historical diffusion dynamics of transport systems. Energy Policy 119, 357–366.

Magnusson, T., Berggren, C., 2018. Competing innovation systems and the need for redeployment in sustainability transitions. Technol. Forecast. Soc. Chang. 126, 217–230.

Mäkitie, T., Andersen .D., A., Hanson, J., Normann, H.E., Thune, T.M., 2018. Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power. J. Clean. Prod. 177, 813–823.

Mäkitie, T., Danebergs, J., Hanson, J., Medbø, E.G., 2021. Solving the Chicken and Egg Problem in Maritime Hydrogen Value Chains in Western Norway. FME NTRANS Report 3/21. downloaded on 4 January 2022 from. https://www.ntnu.edu/documents/1276062818/1283878281/Solving+the+chicken+and+egg+problem+in+maritime+hydrogen+value+chains+in+Western+Norway.pdf/2fcae60c-d6a2-b19b-9740-354bfb97a21d?t=1631778244006.

Mäkitie, T., Steen, M., Sæther, E.A., Bjørgum, Ø., Poulsen, R.T., 2022. Norwegian ship-owners' adoption of alternative fuels. Energy Policy 163 (Article 112869).

Malerba, F., 2002. Sectoral systems of innovation and production. Res. Policy 31, 247–264.

Malhotra, A., Schmidt, T.S., Huenteler, J., 2019. The role of inter-sectoral learning in knowledge development and diffusion: case studies on three clean energy technologies. Technol. Forecast. Soc. Chang. 146, 464–487.

Maritime Battery Forum, 2021. *Alternative Fuels Insight*. Online Database. Entered on 2 December 2021. DNV GL.

Markard, J., 2018. The next phase of the energy transition and its implications for research and policy. Nat. Energy 3, 628–633.

Markard, J., 2020. The life cycle of technological innovation systems. Technol. Forecast. Soc. Chang. 153 (Article 119407).

Markard, J., Hoffmann, V.H., 2016. Analysis of complementarities: framework and examples from the energy transition. Technol. Forecast. Soc. Chang. 111, 63–75.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Policy 41, 955–967.

Markard, J., Geels, F.W., Raven, R., 2020. Challenges in the acceleration of sustainability transitions. Environ. Res. Lett. 15 (Article 081001).

McMeekin, A., Geels, F.W., Hodson, M., 2019. Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016). Res. Policy 48, 1216–1231.

Mellbye, C.S., Rialland, A., Holthe, E.A., Jakobsen, E.W., Minsaas, A., 2016. *Maritim næring i det 21. århundret - prognoser, trender og drivkrefter*. Analyserapport til arbeidet med Maritim21-strategien. Menon-publikasjon 11-2016. downloaded on 4 January 2022 from. https://www.maritim21.no/siteassets/analyserapport—menon.pdf.

Musiolik, J., Markard, J., Hekkert, M., Furrer, B., 2020. Creating innovation systems: how resource constellations affect the strategies of system builders. Technol. Forecast. Soc. Chang. 153 (Article 119209).

NCE Maritime CleanTech, n.d.. Norwegian Future Value Chains for Liquid Hydrogen. Downloaded on 4 January 2022 from https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf.

Onufrey, K., Bergek, A., 2015. Self-reinforcing mechanisms in a multi-technology industry: understanding sustained technological variety in a context of path dependency. Ind. Innov. 22, 523–551.

Pavitt, K., 1984. Sectoral patterns of technical change: towards a taxonomy and a theory. Res. Policy 13, 343–373.

Perez, C., 2002. Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages. Edward Elgar, Cheltenham.

Raven, R., 2007. Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: an assessment of differences and pitfalls. Energy Policy 35, 2390–2400.

Robinson, D.K.R., Le Masson, P., Weil, B., 2012. Waiting games: innovation impasses in situations of high uncertainty. Tech. Anal. Strat. Manag. 24, 543–547.

Rosenberg, N., 1969. The direction of technological change: inducement mechanisms and focusing devices. Econ. Dev. Cult. Chang. 18, 1–24.

Rosenberg, N., 1976. Perspectives on Technology. Cambridge University Press, New York.

Rosenberg, N., 1979. Technological interdependence in the American economy. Technol. Cult. 20, 25–50.

Rosenbloom, D., 2020. Engaging with multi-system interactions in sustainability transitions: a comment on the transitions research agenda. Environmental Innovation and Societal Transitions 34, 336–340.

Rotmans, J., Kemp, R., van Asselt, M., 2001. More evolution than revolution: transition management in public policy. Foresight 3, 15–31.

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

Schmookler, J., 1966. Invention and Economic Growth. Harvard University Press, Cambridge, MA.

Schot, J., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. Tech. Anal. Strat. Manag. 20, 537–554.

Schumpeter, J.A., 1939. Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process. McGraw-Hill, New York.

Sinsel, S.R., Markard, J., Hoffmann, V.H., 2020. How deployment policies affect innovation in complementary technologies—evidence from the German energy transition. Technol. Forecast. Soc. Chang. 161 (Article 120274).

Steen, M., Bach, H., Bjørgum, Ø., Hansen, T., Kenzhegaliyeva, A., 2019. Greening the Fleet: A Technological Innovation System (TIS) Analysis of Hydrogen, Battery Electric, Liquefied Biogas*, and Biodiesel in the Maritime Sector*. SINTEF Rapport 2019: 0093. SINTEF, Trondheim.

Stephan, A., Schmidt, T.S., Bening, C.R., Hoffmann, V.H., 2017. The sectoral configuration of technological innovation systems: patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. Res. Policy 46, 709–723.

Sutherland, L.-A., Peter, S., Zagata, L., 2015. Conceptualising multi-regime interactions: the role of the agriculture sector in renewable energy transitions. Res. Policy 44, 1543–1554.

Suurs, R.A.A., Hekkert, M.P., 2009. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. Technol. Forecast. Soc. Chang. 76, 1003–1020.

Tronstad, T., Høgmoen Åstrand, H., Haugom, G.P., Langfeldt, L., 2017. Study on the Use of Fuel Cells in Shipping. EMSA (European Maritime Safety Agency) downloaded on 4 January 2022 from. https://www.studocu.com/en-gb/document/brunel-university-london/energy-conversion-technologies/emsa-study-on-the-use-of-fuel-cells-in-shipping/5956606.

Victor, D.G., Geels, F.W., Sharpe, S., 2019. Accelerating the Low Carbon Transition: The Case for Stronger, More Targeted and Coordinated International Action (downloaded on 4 January 2022 from. https://www.brookings.edu/wp-content/uploads/2019/12/Coordinatedactionreport.pdf.

van Welie, M.J., Cherunya, P.C., Truffer, B., Murphy, J.T., 2018. Analysing transition pathways in developing cities: the case of Nairobi's splintered sanitation regime. Technol. Forecast. Soc. Chang. 137, 259–271.

van Welie, M.J., Truffer, B., Yap, X.-S., 2019. Towards sustainable urban basic services in low-income countries: a technological innovation system analysis of sanitation value chains in Nairobi. Environmental Innovation and Societal Transitions 33, 196–214.

Wirth, S., Markard, J., 2011. Context matters: how existing sectors and competing technologies affect the prospects of the Swiss Bio-SNG innovation system. Technol. Forecast. Soc. Chang. 78, 635–649.

Yin, R.K., 2009. Case Study Research: Design and Methods, 4th ed. SAGE, Thousand Oaks, CA.