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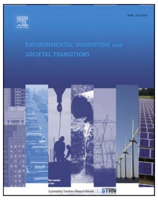

Research article

Collaboration or competition? Interactions between floating and fixed-bottom offshore wind in Norway

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ABSTRACT

Fixed-bottom offshore wind is exploited as a maturing technology in many European countries. Floating wind has impressive potential for deep waters but needs technological and market development. How these two partially related technologies interact remains unclear. We address the ambiguity of these interactions to investigate floating offshore wind's development. The interactions are divided into technological or market and can be negative (*competition* and *resistance)* or positive (*collaboration* and *diversification)*. We analyze these interaction types through a case study of offshore wind in Norway. Many positive interactions were observed, including knowledge overlaps and infrastructure compatibilities. Negative interactions include competition about future space constraints at ports, labor availability, and resistance by incumbent wind turbine manufacturers. Further, market and technological interactions are mutually influential, creating important feedback loops. Technologies can no longer be simply categorized as 'niche' or 'regime', but rather 'niche-like' (emerging) and 'regime-like' (maturing); hence, both emerging-emerging and emerging-maturing interactions occur.

1. Introduction

Europe is undergoing a significant energy transition, with continent-wide targets to mitigate climate change effects and reduce greenhouse gas emissions (Belardo, 2021). Most crucially, renewable energy (RE) needs to be deployed at massive scale. One of the most promising RE technologies with impressive installation and growth prospects is offshore wind energy, with nearly 30 gigawatts already installed in Europe alone, rising to 70–100 GW by 2030 and 400–500 GW by 2050 (Esteban et al., 2011; WindEurope, 2019). Currently, the offshore wind market is dominated by fixed-bottom foundations in shallow waters using three-bladed upwind turbines (WindEurope, 2020). Fixed-bottom offshore wind (FBOW) is hence maturing and becoming a staple of the European energy system. FBOW is expected to continue to grow and serve as a cornerstone of many coastal European countries' energy mixes, such as the Netherlands and the United Kingdom (deCastro et al., 2019; Jansen et al., 2020). This is enabled by the establishment of a dominant design, common practices, and a fully-fledged supplier industry, allowing FBOW to benefit from economies of scale and build long-term confidence with a focus on process and incremental innovation (Dedecca et al., 2016; Durakovic, 2021; Rodrigues et al., 2015; van der Loos et al., 2020b). Due to this maturing state of the technology, FBOW has also been labelled one of the "modern" renewables (Strauch, 2020).

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However, large sea areas in Europe and around the world, such as the Mediterranean Sea, the Norwegian part of the North Sea or the west coast of North America, are characterized by deep waters (60–2000 meters) that are unsuitable for conventional FBOW, but significant wind energy potential (European Commission, 2021). Therefore, a new offshore wind technology, floating offshore wind (FLOW), has started to emerge (Bosch et al., 2018). Currently there are only a handful of full-scale FLOW pilot projects, testing out different engineering principles. FLOW is therefore in a juvenile stage of development, both technologically and commercially. Interestingly, FLOW is populated by both incumbent FBOW actors as well as numerous startups seeking to establish designs for the foundation, the turbine, unique manufacturing processes and bespoke installation techniques. Hence, FLOW partially, but by no means entirely, overlaps with its more mature FBOW counterpart. What this means for the interaction between these two technologies has not yet been studied and constitutes the focus of this paper.

Previous studies have focused on the interactions between related or contextual socio-technical systems through the lens of the multi-level perspective, claiming that nascent and emerging technologies or "niches" either interact with other niches or they interact with mature technologies or "regimes", both of which can be positive or negative in nature (Diaz et al., 2013; Mylan et al., 2019; van Rijnsoever and Leendertse, 2020). Collaborative efforts can increase the availability of supporting resources, such as subsidies, and/or increase legitimacy for renewables (Markard and Hoffmann, 2016; van Rijnsoever and Leendertse, 2020). Early engagement by established actors with related skillsets can also act as an example of positive diversification (Mäkitie et al., 2019; Raven, 2007; Schot and Geels, 2008; van der Loos et al., 2020a). Conversely, competition can occur for overlapping resources, such as permits, available subsidies, political priorities or labor (Bergek et al., 2015). Established actors may also work to inhibit niche breakthroughs, as they can threaten their prevailing market (Andersen and Geels, 2023; Geels, 2014; van Mossel et al., 2018; van Rijnsoever and Leendertse, 2020).

More recently, it has become clear that actor configurations and development dynamics around technologies cannot easily be clearly delineated; rather, nascent and emerging technologies often follow a pattern of maturation in which they gradually adopt more mature 'regime-like' features (Strauch, 2020). This means that the interaction between two technologies will exhibit traits stemming from both technological maturity and market diffusion. The more a technology matures and diffuses in a market, the more the interaction will exhibit regime-like characteristics vis-à-vis the niche with which it interacts. As such, how two partially related technologies at different levels of maturity positively or negatively interact remains unclear. As the energy transition unfolds, such interactions are likely to become more commonplace and thus important for sustainability transition scholars to understand.

Fundamentally, we consider FBOW and FLOW as two related yet distinct technologies. While some components and services are similar (e.g., electrical cables, geotechnical mapping, wind resource assessments), others are different (e.g., the foundation, stabilizing components, sometimes the wind turbine). This means that some actors, institutions, knowledge bases, and infrastructure overlap while others are unique to each technology. Lastly, as FLOW remains technologically immature whilst FBOW is in a phase of incremental innovation and rapid upscaling, the gap in fundamental technological engineering principles, tailored institutions, relevant actor groups and so forth may continue to grow.

A compelling empirical case is Norway, which has a large coastline with deep waters, thereby limiting the use of FBOW technologies (Arapogianni and Genachte, 2013; European Commission, 2021), while the potential for FLOW is tremendous. Norway is also a frontrunner in the technological development of FLOW, with (limited) deployment in Scotland and Norway (Afewerki and Steen, 2022; MacKinnon et al. 2022)). Furthermore, Norwegian incumbent firms are well-established in the global FBOW industry, capitalizing on their long standing experience in the offshore oil and gas and maritime industries (Mäkitie et al., 2018, 2019; Normann, 2015; Steen, 2016; van der Loos et al., 2022).

Our research question is hence:

How do positive and negative interactions between emerging floating and maturing fixed-bottom offshore wind affect the development of the nascent floating wind technology in Norway?

The remainder of this paper is structured as follows: Section 2 elaborates on how technology interaction can occur between emerging and maturing technologies via the frameworks of technology interactions, and niches and regimes. Section 3 describes how the interactions are operationalized and analyzed. Section 4 describes the empirical results of the analysis of the interactions. Section 5 describes the contribution to further understanding interactions when technologies are partially related and yet at distinct levels of maturity.

2. Theory

2.1. Technology interaction

A mature technology comprises interdependent social (e.g., organizations, practices, institutions) and technical elements (Carlsson et al., 2002). These elements, consolidated in a socio-technical system, are at the core of any interaction. "Socio-technical systems consist of a cluster of elements, including technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks and supply networks" (Geels, 2005, p. 446). In the development of a socio-technical system, maturation is characterized by the establishment of a cohesive network formed through the integration of constituent elements and their interconnecting linkages. When nascent, these elements are still in early development.

During processes of transition, which can occur either incrementally or due to severe shock, many dynamic interactions ensue within or between socio-technical systems. Additionally, technologies can also be at different maturity levels. The maturity and structure of socio-technical systems vary and thus influence the technology interaction. First, interactions between two emerging technologies are scrutinized.

2.2. Interactions between two emerging technologies

Competition between two emerging technologies that require similar resources or complementary assets can occur in different ways, for example over market shares, human capital, subsidies, legitimacy, or land use (Bergek et al., 2015; Sandén and Hillman, 2011). Thus, if resource scarcity arises, competition can occur. As two technologies rapidly emerge, the lack of specialized human resources for services such as installations and maintenance can lead to competition, as new personnel need to be recruited and trained (Foxon et al., 2005; Negro et al., 2012a).

Furthermore, technologies with (partly) overlapping socio-technical systems often compete for market diffusion at an early stage. If technologies are competing in related markets, they may also overlap in customer groups. In the early 2000s, this competition occurred between High Definition and Blue-ray discs to replace classic DVDs (den Uijl and de Vries, 2013; Negro et al., 2012a). This competition may impede both technologies' development. Emerging technologies often do not succeed under prevailing market conditions because they struggle to compete on cost and efficiency (Kemp et al., 1998). According to Markard (2020), the formative or nascent phase of a technology typically displays a structure with few actors in which the first ties with the socio-technical system begin to emerge. Later, the formation of structures and markets around the technology occurs in which ties with the environment multiply and formalize.

Conversely, although technologies might compete for market shares, overlapping elements in their systems or similar demand groups may incentivize actors to collaborate to challenge established technologies. To gain sufficient momentum to challenge prevailing technologies, structural coupling by collective action in institutional complementarity or shared elements like actors, infrastructures, or prevalent institutions can occur (Bergek et al., 2015; Markard, 2020).

Thus, positive interaction between two technologies can constitute a form of symbiosis, as the technologies support each other to create a new market in which both technologies are present (Sandén and Hillman, 2011). For example, collective lobbying is a strategy employed to strengthen several technologies or destabilize the incumbent system (van Mossel et al., 2018; van Rijnsoever and Leendertse, 2020). Consequently, the development of related technologies can also lead to higher availability of resources, such as subsidies or legitimacy (Markard and Hoffmann, 2016; Sandén and Hillman, 2011). In the case of French agriculture, public recognition for a few pilot initiatives within alternative agriculture sparked a wider and public interest and eventually comforted the local authorities to support these 'niche' initiatives (Bui et al., 2016; Ingram, 2018). Here, a 'tipping point' occurred and the (agricultural) niche was reinforced (Geels and Ayoub, 2023). A (marginal) change in a novel or even more mature socio-technical system can eventually be a substantial event in a social-technical transition. When the socio-technical system passes a certain critical threshold, positive feedback loops and momentum can lead to rapid maturing of the technology (Geels and Ayoub, 2023).

The maturation of a socio-technical system becomes apparent, and the technology becomes widely adopted. Eventually, new emerging technologies try to challenge this establishment of socio-technical systems and other types of interactions occur. Often, the literature on the multi-level perspective (MLP) is used to describe the interactions that are part-and-parcel of such transitions.

2.3. Interactions between niches and regimes

The multi-level perspective (MLP) understands socio-technical transitions through the interplay of niches, a socio-technical regime, and a broader exogenous landscape (Geels, 2002; Geels and Schot, 2007). Emerging or nascent technologies are often developed in niches, while mature technologies are part of the regime (Jansen et al., 2020; Markard and Truffer, 2008). Mature and fully commercialized or diffused technologies are part of the regime, often understood as "a semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of socio-technical systems" (Geels, 2005, p. 5).

The more a novel technology and its market matures, the more regime-like characteristics it will develop, such as dominant designs, a strong supply chain and bankability (Geels et al., 2008). The structural elements of the socio-technical system in regimes are relatively steady and the actor base remains similar (Nevzorova and Karakaya, 2020). These structural elements allow for the technology to become adopted and hence contribute to the continuation of the regime by reinforcement of the structure. Here, a 'lock-in' of technologies can occur due to co-evolution between technological and societal conditions (van der Loos et al., 2020), as well as benefitting from economies of scale and increasing returns (Arthur 1994).

Regimes

A well-observed regime characteristic is resistance to change, because of established dominant practices and the lobbying power of incumbent actors embedded in well-established networks (Lockwood et al., 2019). Innovation is mainly incremental and interactions from the regime-perspective are served to preserve and strengthen the status quo (Markard and Truffer, 2008). Regime actors engaged in established technologies often defend their market and may employ tactics to inhibit niches, such as lobbying over safety concerns, technological performance, or loss of labor opportunities. When an external shock occurs, the current socio-technical system may become vulnerable to change, giving niches the opportunity to break through. Here, a regime can temporarily 'destabilize', providing exposure to the entrance of niches, and 'restabilize' again with the inclusion of the matured niches (Geels, 2005). The niche can be inhibited by lobbying for favorable or protective legislation by regime actors seeking re-stabilization (Tongur and Engwall, 2017; van Rijnsoever and Leendertse, 2020). Additionally, regime actors can incrementally innovate to resist challenges, creating an even more stable and entrenched system and locking out new technologies (Berggren et al., 2015; Geels and Schot, 2007; Sandén and Hillman, 2011). Established actors can also delegitimize emerging niches if the emerging technology begins to diffuse and competition over market share occurs (Bergek et al., 2015; Mäkitie et al., 2018).The oil and gas sector's initial resistance to the emergence of renewable energy technologies or car manufacturers' resistance to electric vehicles are two classic examples of regime resistance (del Río and Unruh, 2007; Wesseling et al., 2014).

Table 1
Summary of the theoretical technology interactions.

Relation	Interaction	Interaction types	Andersen & Markard (2020)	Sandén & Hillman (2011)	Bergek et al. (2015)	Geels & Schot (2007); Raven (2007)	van Mossel et al. (2018)	van Rijnsoever & Leendertse (2020)
Emerging/ Emerging technology	Negative	Competition		Competition	Competition			
	Positive	Collaboration		Symbiosis	Complementing		Follow in niches	Destabilizing the incumbent system
Emerging/ maturing technology	Negative	Resistance	Defensive	Amensalism[1]			Delay the transition	Stabilizing the regime / Resisting the niche
	Positive	Diversification	Proactive	Commensalism[1]		Hybridization/ Diversification	First to enter niches	Strengthening the niche system

[1] Sandén & Hillman (2011) describe *Amensalism* and *Commensalism* as a negative/neutral and positive/neutral interaction, therefore not perfectly overlapping with this created framework. However, elements mentioned in the study of Sandén & Hillman (2011) do overlap with the interaction concepts of *resistance* and *diversification* and are therefore considered a valuable addition.

Furthermore, amensalism can also occur, in which the emerging niche is inhibited without an apparent effect on the established regime technologies (Sandén and Hillman, 2011). Regime actors can (marginally) invest in these emerging technologies to keep them 'on a leash' and thus still keep them from breaking into the market (Smink et al., 2015; van Mossel et al., 2018).

Niches

Radical innovations are needed to induce a shift in extant (unsustainable) socio-technical systems Niches are defined as socio-technical environments that shield nascent and emerging innovation dynamics from regime selection environments (Hoogma et al., 2000; Negro et al., 2012b). Niches encompass nascent technologies, indicated by a low 'technological readiness level' (Nakamura et al., 2013). Niches are purposefully created by actors, and often rely on government support to develop and gain momentum (Markard and Truffer, 2008). Local or transnational governments can provide funding to private firms or research institutes to promote the development of specific technologies (Wieczorek et al., 2013). For example, the emergence of the car in the early 20th century was supported by specific sectors and institutions (Geels, 2005). In niches, the potential advantages are uncertain, alignment amongst actors is weak, and a dominant design has yet to emerge (Hoogma et al., 2002). The alignment between a niche and the regime is crucial to develop the niche and its possible breakthrough in a market. Socio-technical systems in niches that become well-aligned or compatible with the regime generally have a higher chance of diffusion (Elzen et al., 2012). In the trajectory of a socio-technical transition, niches can get adopted in the newly shaped socio-technical regime (Haley, 2015). Conversely, while regime actors often resist change, there are also instances of positive interaction. One strategy to strengthen the niche is to attract established actors (van Rijnsoever and Leendertse, 2020). If promising niches have a similar value chain or operate in the same sector, they often comprise related or complementary infrastructures, specialized knowledge or services to the matured technology (Bergek et al., 2015). Hence, niches can often benefit from the fungibility of existing resources, as an overlap in sector-related knowledge is present (Mäkitie et al., 2018). Therefore, incumbent sectors' knowledge base often serves as a starting point for an emerging technology, known as 'commensalism' (Sandén and Hillman, 2011; Steen and Weaver, 2017).

Moreover, while regime actors are often depicted as merely defending dominant technologies, they often proactively engage with emerging technologies and play an essential role in multi-technology interactions Andersen and Markard, 2020), especially if the emerging technology offers promising business opportunities (Lieberman and Montgomery, 1988; Mäkitie et al., 2018; van Mossel et al., 2018). Partnering with regime actors is also beneficial for niches, as 'piggy-backing' on the regime actor can occur, which helps the niche access international markets, allowing the technologies to develop and mature (Steen and Weaver, 2017; van der Loos et al., 2020). For example, video rental store diversification to DVDs and Blu-ray discs from traditional VHS tapes was a small diversification strategy that supported a niche technology while maintaining its core business model. More recently, some oil and gas developers have taken an interest in the development of large-scale renewable energy projects, such as offshore wind (Mäkitie et al., 2018; van der Loos et al., 2021).

Lastly, there is also a possibility of no interaction between technologies. This often occurs when different services are provided, different resources are needed, or when "a common resource is a non-exclusive good, such as non-specialist codified knowledge, or is in abundant supply" (Sandén and Hillman, 2011, p. 407). Neutrality in interaction can also occur when the two technologies are geographically separated and thus do not compete in the same market. Neutral interaction has a limited contribution to this study and, therefore, will be excluded from further analysis. Table 1 summarizes the theoretical concepts mentioned above from prevailing literature in relation to the four interaction types: *competition, collaboration, resistance,* and *diversification.*

Classically, there is a clear distinction between two emerging technologies (emerging/emerging) and one emerging and one maturing (emerging/maturing) technology, with specific interaction types depending on whether the interactions in question occur between two emerging technologies or between an emerging/maturing technology. For example, emerging alternative fuels such as hydrogen, e-fuels or biofuels are developed in multiple niches and strongly interact with each other, both competitively and collaboratively (Hillman and Sandén, 2008). Other research is focused on emerging- and matured technologies, through the lens of niche-regime dynamics, such as emerging agri-food niches embedded within dominant agri-food systems (Bui et al., 2016; Geels, 2012).

More recently and following from the previous sections, this cut-and-dry delineation has become more nuanced: as technologies develop and mature, the more stabilized the socio-technical structure becomes, and thus the technologies begin to exhibit increasingly dynamic 'regime-like characteristics while also still exhibiting 'niche-like characteristics. Strauch (2020) argues that the transition from niche-scale to regime-scale involves a tipping point. Characteristics or indicators for a regime-scale technology are *readiness to scale*, in e.g. a dominant design of the technology (technological) or a commercial and bankable product (market), and *scaling support*, which includes establishing actors network e.g. supply chain actors (technological and market) or policy support (market) (Strauch, 2020). For example, first a dominant design of the technology is established by which a strong supply chain can be created and eventually market share can be increased due to a commercialized product (Geels et al., 2008).

Thus, before a technology can become regime-scale, it needs to co-develop and mature both technological and market components. Hence, if a technology develops and starts to interact with other technologies, these interactions can involve dynamics of the technology maturity or market maturity (i.e. market diffusion) of the technologies.

2.4. Interaction types between emerging and mature technologies and markets

When a technology is developing, a differentiation can be made between technological maturity and market diffusion. Simplified, an emerging technology first needs to technologically mature (sufficiently) before it can enter the commercialization and market diffusion phase (Peres et al., 2010). A certain degree of technological maturation is thus imperative prior to developing a mature market, particularly if a novel technology is disruptive in an existing market.

Therefore, the type of interactions between technologies will likely dynamically exhibit characteristics from both emerging/emerging technologies as from emerging/maturing technologies, depending on the relative degree of technological maturity and market diffusion of the technologies in question. For example, the interaction dynamics that occur for the emergence of the electric bicycle are dependent on 1) its relative technological maturity; and 2) on the maturity of the traditional bicycle market. The interaction between electric bicycles and traditional bicycles is thus dependent on both technical and market characteristics, and the interaction can be both positive and/or negative in nature. These characteristics will at times be more closely aligned with characteristics from interactions stemming from emerging/emerging technologies, for example collective lobbying to support better bicycle infrastructure in general to encourage a more sustainable mobility system; contrarily, there may be emerging/maturing characteristics if traditional bicycle lobbying attempts to discredit the sustainability advantages of e-bicycles due to, for instance, e-waste.

To that end, we combine and nuance the notion of emerging/emerging and emerging/maturing interaction types and create a distinction between technological and market maturity for two, in this case partially related, technologies. As the literature regarding technologies (and their systems) in distinct phases of maturity is underexplored, the differentiation of an emerging and a maturing technology in this regard is rather blurry. Hence, we seek to shed light on these interactions with our case study of floating wind versus fixed-bottom offshore wind in Norway. These two distinct technologies share certain characteristics while are unique in other ways (see Section 4.1). Hence, FBOW and FLOW in Norway are expected to display both emerging/emerging- and emerging/maturing interaction dynamics because FBOW has a rapidly growing market in some countries, clear dominant design and well-established industry whilst FLOW has neither a market, except for a few pilot projects, nor a dominant design.

3. Methods

To explore interactions between two partially related technologies at different maturity levels, we employ a qualitative, interview-based research design. The framework comprises prevalent emerging/emerging- and emerging/maturing technology interactions in combination with classical technology interaction types. Our first step was desk research to map socio-technical system elements (core actors, institutions, networks, technologies) based on secondary data (reports, media, company websites, previous research).

For the in-depth analysis of the four interaction types (*competition, collaboration, resistance, diversification*) and their rationales, we conducted 19 semi-structured interviews in the period April-May 2022 with a wide variety of Norwegian stakeholders engaged in FLOW and/or FBOW. These interviewees were identified through stratified purposive sampling: subgroups based on relevant criteria. The interview questions explicitly distinguished between technological and market characteristics to provide greater nuance into specific interaction dynamics. The interviewees comprised five established firms with interest in both floating and fixed-bottom offshore wind [FBF], two established firms only with an interest in floating [FLO], three governmental agencies [GOV], three research institutes [RI], four floating wind start-ups [SUP] and two offshore wind associations [ASC]. Please see Appendix 1 for an overview.

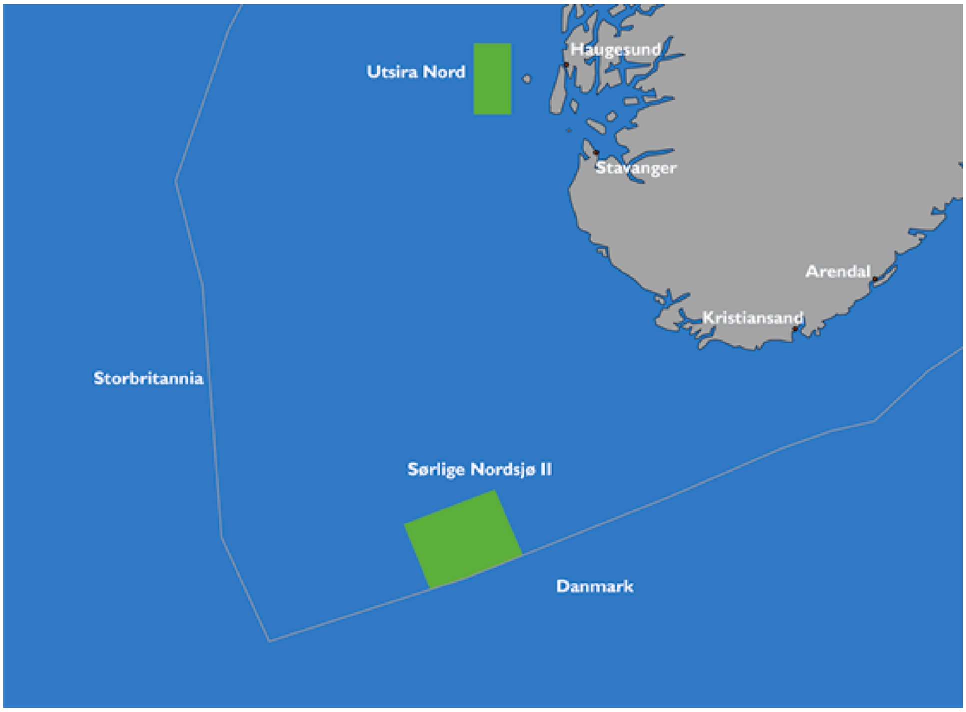


Fig. 1. Locations for offshore wind production in Norway (adopted from (Ministry of Petroleum and Energy (2020)).

Transcribed interviews were first inductively open-coded using NVIVO software, creating individual relevant nodes or concepts. Next, during the axial coding process, these nodes were abductively divided under the four interaction types created in the theoretical framework (please see Table 1), i.e., *competition, collaboration, resistance* and *diversification*. Consequently, through selective coding, these interaction types were analyzed to find patterns or rationales of maturation. All the concepts were then analogously critically re-evaluated to ensure internal validity throughout the coding process. Quotes from the interviews used in this study were anonymized and verified by the interviewee.

4. Results

4.1. Background

In some European countries, such as the UK, the Netherlands or Denmark, fixed-bottom offshore wind (FBOW) is becoming a substantial part of the energy system as the technology and the market are maturing (WindEurope, 2020). Indeed, it has surpassed the formative phase development in terms of its contribution to the electricity system in these countries (Bento and Wilson, 2016; Wilson, 2012). In other European countries, such as Norway or France, the FBOW market has not yet developed. Norway is unique as it strongly participates in the European FBOW market, based on international operations and services despite not having its own market, similar to that of the Netherlands in the early 2000s (Normann and Hanson, 2018; van der Loos et al., 2021).

Floating offshore wind (FLOW) offers a solution for countries with deep waters. Many designs for FLOW foundations are under development, including tension-leg, semi-submersible and spar buoy (Caglayan et al., 2019). The potential capacity of FLOW is substantial, with over a quarter of the total installed offshore wind capacity in Europe in 2050 expected to be floating (WindEurope, 2020, 2021). Nevertheless, the current global installed capacity is around 100 MW, with only a handful of full-scale demonstration projects. FLOW has both an immature market and technology. Interestingly, the Norwegian oil and gas (O&G) company Equinor was the first to install a single full-scale floating wind turbine (Hywind) in 2009, developed the first and largest operational FLOW project, consisting of five turbine equaling 30 MW (Hywind Scotland) in 2017, and recently completed the 88 MW Hywind Tampen project, the world's largest floating windfarm in Norway (Memija, 2023). Many Norwegian suppliers and R&D institutes have been involved in this development (Afewerki et al., 2019).

In 2020, the government of Norway announced an expansion of the offshore energy law and consequently announced that two fields in Norway would be opened for offshore wind (see Fig. 1) (Ministry of Petroleum and Energy, 2020; Regjeringen, 2021). The first area, '*Sørlige Nordsjø II*', has an average water depth of 60 m and an estimated power capacity of 3 GW (Fjellberg, 2021). Because of the (relatively) shallow waters, this field envisions FBOW foundations. The second area, '*Utsira Nord*', has an average water depth of 267 m and an estimated power capacity of 1.5 GW, therefore targeting floating solutions (Nilsen, 2019).

4.2. Market interactions

Given that Norway has neither an established market for offshore wind – FBOW or FBOW – we mostly observe market interactions between two emerging technologies: competition- and collaboration-like interactions.

4.2.1. Competition

FBOW and FLOW will directly compete over the same geographic areas in intermediate waters of 60–100 meter depth [ASC1] (Buljan, 2022a; Memija, 2022). Recently, a combination of FBOW and FLOW was announced to aim for waters up to 100 m (Durakovic, 2022b). There might be even FLOW and FBOW turbines next to each other, as [FBF4] states:

We could even see that in the same area one developer chooses to go for fixed-bottom and next to it a developer is choosing for floating wind. […] But most developers engage in both technologies so for them is not really a competition, it is more what is most economic for that project. But for the supply chain, it can be competition!

We will likely see competition for resources, land-use and subsidies as these two markets begin to emerge. If the government exclusively focuses on FLOW, resistance will emerge from actors bound to the fixed-bottom market [ASC2]. This interaction would also occur vice versa: if only FBOW parks were to be announced, the development of the market niche of FLOW would stagnate [ASC2].

Furthermore, considering the resources necessary for developing and deploying both technologies, other dimensions of competition materialize. This includes for example access to port infrastructure for component manufacturing and assembly [FBF5] (Durakovic, 2022a). FLOW may also compete with yards that conventionally cater to the O&G sector, which uses similar facilities to assemble and transport floating structures [FBF4]. Lastly, relevant actors compete for similar resources. Many actors are promoting growth and support for both markets, but there is a possibility that developers will diverge into one of the two markets as they start to emerge. As [FBF5] argues:

Maybe if we win Sørlige Nordsjø II and some other fixed-bottom wind parks, I guess with our expertise, we are kind of going in one direction. And the same goes for floating. But our strategy, for now, is to aim for both floating and fixed-bottom parks.

As these projects need substantial capital, allocation of a project for one distinct technology can lead to focusing on one respective market niche to maximize further profits and scale up [FBF1, FBF3, FBF5, FLO2]. Hence, a feedback loop can emerge, in which the mobilization of resources in the direction of one technology limits the remaining resources for the technology and market development of the other technology [FBF5]. Additionally, accessing a limited pool of subsidies or a sufficiently large labor force may also drive competition between these two emerging markets.

4.2.2. Collaboration

We find that *consortia* and *lobbying* play a key collaborative role in the market formation of FBOW and FLOW. Most actors want to apply for both recently announced tenders for offshore wind in Norway. Positive complementary interaction is observed since certain tendering zones can be exploited by both technologies.

Nearly all relevant actors are involved in consortia engaged in both technologies for three key reasons. The first is that companies occupy various parts of the value chain, thus providing complementary expertise [FBF1, FBF4, SUP1]. For example, in the Aker Offshore Wind-Ocean Winds-Statkraft consortium, expertise includes offshore development and marine operations, developing and operating global offshore wind farms, and delivering renewable energy to the market, respectively (Statkraft, 2021).

As offshore wind turbines are massive structures, testing the new FLOW designs first occurs on smaller-scale demonstrators. However, these demonstrators still need significant scales to create a realistic testing environment [RI1]. Therefore, especially for young and smaller companies, it is essential to join forces with external companies to finance the initial investments [FLO2]. These financers often comprise companies already active in the global offshore wind market, providing market knowledge to foster the market diffusion in Norway.

Furthermore, as FBOW is commercially competitive throughout Europe, legitimacy for offshore wind is present (Jansen et al., 2020). Actors are eager to join forces with actors present in the European market to establish trust for the other stakeholders to establish a market in Norway [FBF1, FBF3]. Therefore, first participating in FBOW can lead to trust to secure contracts in FLOW [SUP3]. Through this rationale, new or diversifying companies focusing on the domestic market gain experience and trust through foreign markets to eventually prevail or gain competitive advantage [FBF1].

Additionally, partnering up with firms covering other aspects of the value chain can also lead to sharing valuable information. A reciprocal benefit can occur when a company that designs a floating foundation enters long-term strategic partnerships with a turbine manufacturer to optimally design the control system between the foundation and the turbine [FBF2, FLO1, SUP2, SUP4]. This also applies to other stakeholders, such as investors or insurance companies [FBF2–4, FLO1].

Lobbying also plays a strong role in the emergence of a market in Norway, which primarily occurs through various project development consortia. A distinction can be observed in the goal of lobbying: lobbying for societal and cross-sectoral legitimacy and lobbying the government for clear ambitions and the creation of the offshore wind market.

Interviewees acknowledge that if FLOW matures and manages to become cost competitive, actors might have a good argument to justify the market diffusion of FLOW over FBOW, as they can generally be placed further away from shore. This would allow for even greater economies of scale and less public opposition due to visual pollution. Hence, a more competitive lobby may arise in the future [FBF5, SUP1].

Offshore wind in Norway has strong linkages to the petroleum industry (Andersen and Gulbrandsen, 2020; Mäkitie et al., 2019; Steen and Hansen, 2018). The new Norwegian government has said they will still seek growth in the petroleum industry, but with a significant focus on reducing CO_2 emissions [ASC1, GOV2]. The petroleum industry collectively lobbies for an offshore wind market as an opportunity to electrify O&G platforms [FBF1, SUP2].

Lobbying also occurs to develop a more comprehensive and standardized regulatory system, which is currently lacking. While FBOW has experienced over 20 years of institutional finetuning around Europe, developers in Norway complain about the difficulties to get approval to test and exploit projects as each needs to go through a customized assessment [SUP2].

The institutional set-up of the framework is immature and lacks clarity; there is also a concern that the regulations may become too strict if the government adopts the institutional framework of O&G. As [FBF5] says:

I can only speak for Norway, but I do not think we have established rules for either technology. So, I guess the rules from fixed-bottom will also come from fixed oil and gas installations. But I know other countries have more developed rules than we do…So, for example if you want to do floating in Denmark, where bottom fixed is very common, I would assume that they would base that on the established bottom fixed because they don’t have a big oil and gas industry.

Another company [FBF4] mentions:

The standard for floating is mostly based on O&G right now. And that is not a good idea because there is a lot less risk involved in floating than in O&G. Floating wind turbines are not manned structures (only during maintenance), and if something goes wrong, you are not going to have huge oil spills.

A problem observed by all interviewees is that actors will not substantially mobilize resources and investments to develop a supply chain if it remains unclear what the future growth prospects are and what the institutional and support mechanisms in Norway will look like [FBF5, ASC2]. The development of the technologies and local markets is coupled with high risks and costs, and without solid market support and government ambition, the confidence of the industry to mobilize these resources is missing [GOV1, RI1, SUP2, ASC2]. Therefore, the offshore industry lobbies for the government to reduce risks and create a more accessible market through strong support mechanisms for both FBOW and FLOW.

4.3. Technological interactions

Given that FBOW has a well-established dominant design that engages predominantly with incremental and process innovation while FLOW is still very much in an experimental phase, technological interactions more closely resemble interactions between an emerging and a mature technology, i.e., resistance and diversification.

4.3.1. Resistance

The most prominent technological resistance was observed from the turbine manufacturers. Offshore wind emerged out of onshore wind: first, turbines were placed onshore, then they were incrementally diffused and optimized nearshore and then farther offshore. Thus, the technologies of onshore wind and FBOW are highly related [FBF5]. As [RI2] states:

The whole bottom fixed and floating have a very different way of thinking because fixed-bottom has just taken the land-based turbines and moved them offshore. Then, those who are familiar with turbines have done calculations for the tower and turbine and then some marine people have done calculations for the foundation and the loads on it, and they just exchanged some information for the intersection. So basically, you kept the same principle.

This statement simplistically emphasizes that current FBOW was designed to be complementary to ordinary onshore wind turbines. The offshore turbines are largely produced by just a few manufacturers (Siemens-Gamesa Wind Energy and Vestas). However, these standardized turbines are not optimal for FLOW foundations, as the motions of the foundation influence the turbine and vice versa. Therefore, the control systems need substantial adaptation, become fundamentally different or radical turbines need to be developed [SUP1, SUP3]. Turbine manufacturers are not cooperative because they would need to disclose valuable and sensitive information about the motions of the turbines to optimize the interplay between the turbine and the floating foundation [FBF1, FBF4, FBF5, FLO3]. Supplying standardized wind turbines further reduces risks and creates even better economies of scale, which resists the emergence of wind turbines based on fundamentally different engineering principles [SUP2, GOV2]. Therefore, turbine manufacturers prefer to focus on incremental innovation which can be applied on both onshore and FBOW foundations [RI3], thus strengthening the industry in which they are engaging.

Passive resistance is also observed from companies with specialized assets applicable to only one of the technologies, such as jack-up vessels or specialized equipment used to install wind turbines on FBOW foundations [FBF5, GOV3, GOV2]. These incumbent actors strengthen their market position by incrementally innovating these limiting assets, such as larger vessels suitable for larger and heavier monopiles [FLO2] (Buljan, 2022a; Memija, 2022).

4.3.2. Diversification

We observe that diversification occurs via complementary technologies, opportunities for FLOW and co-existence with other technologies or sectors.

FLOW has a much larger technical potential in Norway’s deep waters and is hence the dominant focus of the government and the industry [FLO1, GOV1, GOV2, ASC2]. Established actors in FBOW often engage in FLOW, as there are many complementary assets, such as operations and maintenance, services, and vessels, but also licenses to operate, human resources and knowledge. A key stimulus is that with a domestic market for offshore wind, more local content can be created in Norway [FLO1, FBF5] (Buljan, 2022b). However, with a FLOW foundation, the proximity of the suppliers is less crucial, as FLOW foundations are towed to the installation location, and maintenance occurs in harbors or quays [FBF2, SUP4]. Furthermore, FLOW foundations are often locally assembled [FLO1, FLO2]. There is therefore an opportunity to develop local content capacities.

While the adjacent development of both technologies can be a source of competition, interviewees state that they expect it to stimulate the market and supply chain of both technologies [SUP4]. Furthermore, FBOW has already addressed many challenges that can also be relevant to FLOW, thus reducing certain risks [GOV1, GOV2, SUP3].

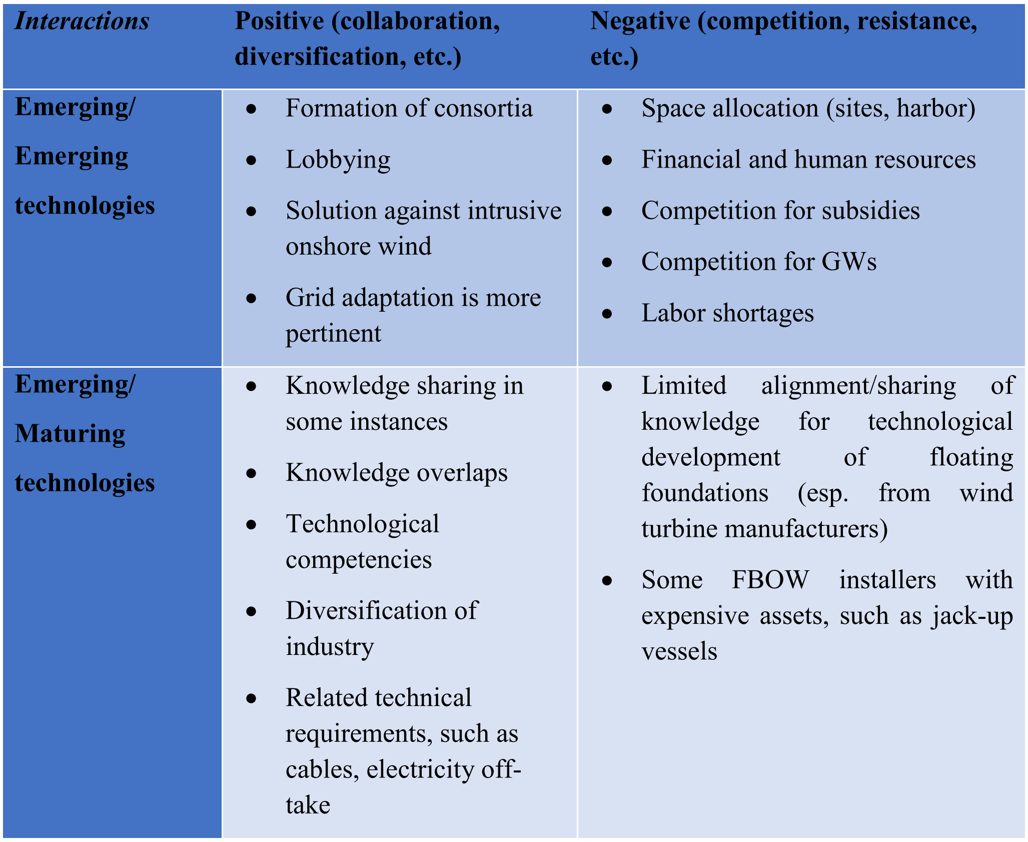
Moreover, insights and innovations resulting from the development of FLOW can also spill back over to FBOW development, leading to further cost reductions [FLO2, ASC2]. Technological applications therefore overlap, so research and development can be valuable for either technology [GOV2, GOV3]. For example, long-distance subsea export- or inter-array cable innovations for FLOW can also be applied to FBOW [FBF4].

By also engaging in FBOW, actors gain legitimacy to enter FLOW [SUP4]. For example, companies join forces with turbine manufacturers to limit technological complexity [SUP2]. While we previously found that turbine manufacturers prefer to deliver turbines for FBOW foundations due to the level of standardization and large order book, there is remarkably a reversed rationale observed for foundations. For FBOW foundations, the maximum size of the turbine is limited. The width of the FBOW foundation exponentially increases as the turbine dimensions increase, making foundation installation challenging [FBF4, FLO2]. FLOW foundations have fewer difficulties scaling their design and therefore do not experience this limitation [FLO1, SUP1]. A larger turbine is preferable, both from an energy production capacity and cost perspective. Some specialized companies, such as installers, may therefore attempt to diversify into FLOW from FBOW. In other words, FLOW addresses certain technical limitations of FBOW, leading to more legitimacy and interest from established actors. Diversification into FLOW opens more possibilities to co-exist with the O&G industry. As many O&G platforms are floating in deep waters, FLOW turbines open possibilities to provide electricity to the platforms [SUP1].

While there are some specialized networking events for FLOW, such as conferences regarding dynamic subsea cables specifically for floating structures, most knowledge exchange sessions are with actors interested in both FLOW and FBOW [FBF1-FBF4, SUP3, GOV1]. As certain elements are similar for both technologies, such as onshore grid connections, knowledge can easily spill over. Additionally, studies regarding the wake effect, for example, are applicable to both technologies [RI, RI2].

The observed positive and negative interaction types between floating and fixed-bottom wind in Norway are organized and summarized in Table 2.

Table 2
Positive and negative interactions between floating and fixed-bottom wind in Norway (not exhaustive).



Interactions	Positive (collaboration, diversification, etc.)	Negative (competition, resistance, etc.)
Emerging/ Emerging technologies	• Formation of consortia • Lobbying • Solution against intrusive onshore wind • Grid adaptation is more pertinent	• Space allocation (sites, harbor) • Financial and human resources • Competition for subsidies • Competition for GWs • Labor shortages
Emerging/ Maturing technologies	• Knowledge sharing in some instances • Knowledge overlaps • Technological competencies • Diversification of industry • Related technical requirements, such as cables, electricity off-take	• Limited alignment/sharing of knowledge for technological development of floating foundations (esp. from wind turbine manufacturers) • Some FBOW installers with expensive assets, such as jack-up vessels

5. Discussion

Current literature on technology interaction often describes how emerging technologies develop in niches and challenge the regime, while the regime opposes radical change. Thus, most studies investigate interactions and dynamics between two emerging technologies or one emerging while the other is already mature.

However, we find that the contrast between the interaction mechanisms of two emerging technologies versus an emerging and a still maturing technology can become blurry in a dynamic environment, considering the fast development of technologies, their maturity, degree of relatedness to other technologies and relative participation and characteristics of the respective country(ies). Interactions can be positive or negative depending on what benefits them the most: collaboration occurs between two emerging technologies when it is mutually beneficial to co-evolve and collectively destabilize the regime; emerging/maturing technology interactions occur when cooperation is beneficial, for example when the prospects for diversification appear promising. Negative technological interactions may develop to slow down potentially disruptive innovation. The divergence between the concepts gets even more complex when the technologies are partially, but not fully, related and market maturity differs on a local level.

Floating offshore wind (FLOW) is technologically immature and has no commercial market diffusion globally. Fixed-bottom offshore wind (FBOW) is showing mature or regime-like characteristics, by establishing a dominant design, mostly undergoing incremental innovation and having a rapidly growing market. However, market diffusion remains nearly absent in many other countries, such as Norway.

As partially related technologies with partially overlapping actors, policies, and networks, this indicates a complex relationship demonstrating multiple dynamic interactions. Because of this complexity and dynamic nature, divergent interaction rationales are present. Classic to interaction literature, we observed that collaborative efforts arise to help the government create optimal, clear, and strong market conditions for both FBOW and FBOW. A lack of coherence and long-term vision is a classic sign of a poorly performing socio-technical system; thus, collaboration can break the negative cycle. The maturation of the market may also have a strong influence on the technological pathway that FLOW will follow. It remains to be seen whether there will be many phases of engineering experimentation, such as for radical turbines, or whether rapid upscaling policies will pre-emptively force certain incremental design principles (van der Loos et al., 2024). As these markets begin to grow, resource scarcity will also play a strong negative role, potentially creating negative feedback loops.

We also witness proactive diversification from FBOW to FLOW by many incumbent actors. These interactions were observed through the diversification of established actors already engaging in the maturing FBOW market in Europe. They leverage their experience and prior knowledge, capital, and supply chain of FBOW to FLOW, similar to diversification from O&G into offshore wind (Mäkitie et al., 2019). This supports the notion of 'pluralizing incumbencies', whereby established actors guide the development of FLOW technology in ways that enable emerging niche projects while allowing incumbents to capitalize on existing knowledge and resource bases Turnheim and Sovacool, 2020).

Nonetheless, we see examples of resistance, particularly from the incumbent turbine manufacturers, which prefer large-scale contracts for FBOW, allowing for economies of scale, reduced risk, and incremental innovation. They, therefore, resist technological developments in turbine designs that may more optimally suit FLOW. Additionally, existing FBOW-specific policies can unintentionally hamper the development of FLOW, hence creating increasingly path-dependent processes. Space constraints and labor shortages may also play a significant role as FLOW scales up, leading to greater competition between the two technologies.

The phenomena observed in this research can likely be applied elsewhere as technologies and markets develop and mature simultaneously and in parallel in different geographies. One example could be the emergence of concentrated solar power (CSP) and conventional photovoltaic (PV) solar systems. PV is a 'modern renewable' that has achieved enormous market reach in many countries while CSP is still in the nascent phase of development. It will be likely a combination of positive and negative interactions between PV and CSP depending on the institutional set up in a given country, presence of actors and technological maturity. Another interesting case could be the interaction between electric bicycles and traditional bicycles depending on the relative institutional embeddedness and market share of traditional bicycles.

Additional investigations into the dynamics of FLOW in countries where there is an established FBOW market, such as the United Kingdom, could further nuance these interaction types. While we expect to observe fundamental positive and negative interactions, how and why they occur will likely change and depends on many elements, such as the phase of technological maturity and market diffusion in question. France would provide a particularly interesting case of a country with no established market but substantial technical potential and targets for both FBOW and FLOW. This means that both technologies will experience rapid growth and upscaling at the same time, potentially leading to substantial competition.

6. Conclusion

This research aimed to explore the unique interactions between the emerging technology of floating offshore wind (FLOW) and the maturing of fixed-bottom offshore wind (FBOW) technologies in Norway. FLOW is an immature technology with no established market, heavily dependent on experimentation, institutional alignment and concerted market formation policies. FBOW is a maturing technology that has developed a dominant design and has been growing its market share around the world. However, there is no established market for FBOW in Norway despite several Norwegian companies partaking in international offshore wind markets.

Therefore, this research focused on understanding market and technological interactions for two partially related technologies, exploring four distinct interaction types. Negative interaction can occur as competition or resistance, whereas positive interaction types include collaboration and diversification. While these interaction types were originally conceptualized as either between two emerging technologies or between an emerging and a mature technology, we observe that all interaction types occur; how they occur depends on the relative maturity of the two technologies in question and whether the focus is on market development or technological characteristics. Hence, this research contributes to our understanding of how interactions occur between technologies at different levels of maturity.

We primarily observed positive interactions between the technologies. Prior knowledge originating from FBOW can be used for the development of FLOW; therefore, many actors engage in both technologies. Knowledge development in either technology is often beneficial for the other technology. The offshore wind industry actively lobbies the government to create an industry-wide institutional framework. In the non-existent offshore wind market in Norway, the market interactions for both technologies are thus primarily positive, as they have a mutual interest in the formation of supporting policies.

Negative interactions currently arise from the turbine manufacturers, who favor supplying wind turbines to large FBOW projects as the interplay between the foundation and the turbine is less complex, and they can capitalize on economies of scale and fewer financial risks. Many other negative interactions are foreseen for the future – such as financial, space and labor scarcity.

To answer the research question: "How do positive and negative interactions between emerging floating and maturing fixed-bottom offshore wind affect the development of the nascent floating wind technology in Norway?" and to conclude, FBOW is, at times, an enabler of FLOW, which has high prospects for deployment in deep waters. As many of the elements required for FLOW to develop are related to the maturing FBOW technology, a co-development is likely to occur; however, resistance and competition may emerge, particularly as space constraints and labor shortages become more acute. Hence, developing a strong market support system and clear ambitions from the Norwegian government, while taking advantage of strong industrial overlaps, are recommended for Norway to become a dominant domestic and international player in floating offshore wind.

CRediT authorship contribution statement

Hylke C. Havinga: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **H.Z. Adriaan van der Loos:** Writing – review & editing, Writing – original draft, Supervision, Resources,

Methodology, Conceptualization. **Markus Steen:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

Data availability

The data that has been used is confidential.

Appendix 1. List of interviewees

Interview code	Type of actor	Date of interview
fBF1	Established firm with interest in both Floating (FLOW) /Fixed-bottom (FBOW)	3–4–2022
FBF2	Established firm with interest in both FLOW/FBOW	21–4–2022
FBF3	Established firm with interest in both FLOW/FBOW	9–5–2022
FBF4	Established firm with interest in both FLOW/FBOW	20–5–2022
FBF5	Established firm with interest in both FLOW/FBOW	23–5–2022
FLO1	Established firm with interest in FLOW	26–4–2022
FLO2	Established firm with interest in FLOW	19–5–2022
GOV1	Governmental agency	6–4–2022
GOV2	Governmental agency	9–5–2022
GOV3	Governmental agency	10–5–2022
RI1	Research Institute	22–4–2022
RI2	Research Institute	10–5–2022
RI3	Research Institute	13–5–2022
SUP1	Startup FLOW	25–4–2022
SUP2	Startup FLOW	29–4–2022
SUP3	Startup FLOW/FBOW	29–4–2022
SUP4	Startup FLOW/FBOW	10–5–2022
ASC1	Industry association	29–4–2022
ASC2	Industry association	11–5–2022

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