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Does participation in knowledge networks facilitate market access in global innovation systems? The case of offshore wind

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ABSTRACT

This article explores how knowledge networks function as structural couplings in global innovation systems (GIS). Based on a unique dataset we investigate the effects of Norwegian offshore wind firms' participation in different knowledge networks on international market access. The results show that international knowledge networks facilitate access to market resources in a GIS under certain conditions. First, participating in pilot and demonstration projects positively affects firms' access to international markets. Second, participation in R&D projects has only a positive effect on international market access when R&D collaboration involves international partners. This effect is stronger when collaborators come from countries with a domestic market. Our results show that knowledge networks can function as one type of structural coupling (between a country and the GIS), which can facilitate another type of coupling (between knowledge and markets). The extent of coupling depends on the innovation mode and geographic scale of the knowledge networks. An implication for policy is that knowledge resources can be leveraged through incentives for international collaboration, and support for pilot and demonstration activities.

1. Introduction

Many countries see opportunities to build up national industries based on renewable energy technologies, driven by ambitions to align economic and climate objectives (Geels et al., 2016; Kern et al., 2014; Lauber and Jacobsson, 2016). These ambitions are often accompanied by public policies that support research and development (R&D) and pilot and demonstration plants (PDP), combined with publicly created markets. However, there are different national preconditions, and thus different rationales, for the introduction of such policies (Coenen et al., 2012). Countries differ in industrial capacity, knowledge pools and conditions for market formation (Kern and Markard, 2016). The latter can depend on renewable energy production capacity and prospects for job creation (Raven et al., 2016). Considering that supporting both knowledge creation *and* market formation is costly, some countries may decide to not invest in both types of policies, but rather opt for strategies to exploit resources, such as markets, abroad (Peters et al., 2012; van der Loos et al., 2020).

Despite territorial differences, renewable energy industries are largely international in terms of firms, knowledge networks, and markets (Carlsson, 2006; Ćetković and Buzogány, 2016; Quitzow, 2015). Actors based in one territory may attempt to exploit markets or knowledge resources elsewhere (Binz et al., 2014; Wieczorek et al., 2015). While such international resources offer opportunities, the access to them is not given (Coenen et al., 2012). Especially in industries characterised by technological complexity and non-standardized markets, resources can be embedded in certain territories (Huenteler et al., 2016; Malhotra and Schmidt, 2020).

Due to the territory-specific conditions, national policies can be set up to support specific areas, such as knowledge development, as a strategy to support industry development even in the absence of a local market (Gosens et al., 2015). In such cases, the strategy would be to invest in certain system resources and compensate for a lack of access to other resources by connecting to the global innovation system (GIS). This connection depends on so-called structural couplings between national resource formation and the GIS (Binz and Truffer, 2017). The functioning of a GIS therefore relies not only on coherent subsystems, but also on the structural couplings which connect subsystems in the GIS.

The notion of structural couplings is useful to conceptualise how networks can connect different subsystems within the GIS, and thus facilitate access to resources not available locally. However, the

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processes that facilitate structural couplings and how countries couple on to a GIS remain under-explored (Binz and Truffer, 2017). Our aim is to explore how countries can create structural couplings in a GIS linked to complex technologies, when only some of the necessary resources for industry development are present within that country. More specifically, we address the gaps identified by Binz and Truffer by investigating the structural couplings between two key resources – knowledge creation and market access – *and* couplings between a territorial subsystem and the wider GIS. The specific question we investigate is *how does participation in different types of knowledge networks facilitate structural couplings between knowledge creation and market formation subsystems?*

Participation in knowledge networks can in different ways connect firms to market resources, for instance to customers in PDPs (Mossberg et al., 2018) or through R&D collaborations with actors based in countries with existing markets (Bayona et al., 2001). In this paper, we test how these different knowledge creation activities facilitate the entry to international markets, and thus the creation of structural couplings, by distinguishing between R&D projects and PDPs.

Empirically, we explore the case of offshore wind power, which is an emerging technology targeted by national and EU policy. To perform our analyses, we use a unique combination of datasets on large-scale offshore wind farms (market), participation in PDPs, and subsidized R&D projects (knowledge). We investigate how one national subsystem (Norway) can create structural couplings to the offshore wind GIS. Norway has no domestic offshore wind market, but hosts actors and knowledge bases that are relevant for an international offshore wind market (Normann and Hanson, 2018). This is therefore a well-suited case to explore structural couplings. Offshore wind is also regarded as a complex and design-intensive industry with project-based markets. In such industries, resource formation is spatially sticky and structural couplings are therefore particularly important (Binz and Truffer, 2017). While Norway is a unique case, the focus on structural couplings between knowledge creation and market formation is of broader relevance, given that other countries may also seek to boost new industries by fostering knowledge creation, while having no, or limited, co-located market resources.

We have structured the paper in the following way. Section 2 discusses the theoretical background and develops a set of hypotheses to explore structural couplings. Section 3 presents the case, data and methods used to test our hypotheses, while the results are presented in section 4. Finally, section 5 discusses the conceptual and policy implications of our findings on the role of structural couplings between knowledge and market resources, and under what conditions such couplings between resources link territorial subsystems to the GIS.

2. Theoretical background and hypotheses

2.1. Structural couplings in global innovation systems

A principle idea in the literature on technological innovation systems is that actor networks determine the structure of the innovation system. When the system is delineated around a technology the boundaries are not territorially constrained but span regions and countries. A technological innovation system (TIS) is thus likely to take on global dimensions. The functioning of a TIS depends on the successful development of key system resources and the interplay between such resources. The seminal contributions to the TIS literature identified seven resources (Bergek et al., 2008; Hekkert et al., 2007). Akin to the TIS approach the global innovation system perspective can be used to study the development of technologies and industries, but focuses on four key resources: *knowledge creation, market formation, investment mobilisation,* and *technology legitimation* (Binz and Truffer, 2017).

For analytical purposes, GISs have been conceptualised to be comprised of nested subsystems (Binz et al., 2014). The functioning of the GIS depends on successful interaction between subsystems and on actors' ability to access resources outside of their own territory (Bergek et al., 2015). We refer to the interaction between these subsystems as structural couplings (Binz and Truffer, 2017). Subsystems can be delineated around territories or resources. Thus, following Rohe (2020), we distinguish between vertical couplings that link territorial subsystems (e.g. national and transnational) and horizontal couplings that link subsystems developed around specific resources (e.g. knowledge creation and market formation). Structural couplings can be established (1) when one actor is present in two (or more) different resource subsystems (functions) in the GIS, (2) when networks connect different subsystems, or (3) when one actor (multinational) is present in several territorial subsystems (Bergek et al., 2015). Fig. 1. illustrates how an actor's participation in the knowledge subsystem - either nationally or globally - can facilitate this actor's access to the market subsystem (missing from its territorial subsystem) and through that establish a horizontal structural coupling.

Structural couplings are important not only for system performance, but also to firms. Resources tend to develop unevenly within the GIS, given differing territorial preconditions for e.g. knowledge development (Binz et al., 2014; Coenen et al., 2012). Due to this uneven distribution of resources, firms may not have local access to all system resources (Gosens et al., 2015). Firms will therefore need to establish extra-territorial couplings to gain access to other system resources in the GIS (Binz and Truffer, 2017). For national industry development, it can make sense to build up certain system resources, as long as firms have access to other resources in the GIS (Binz et al., 2016; Gosens et al., 2015). For instance, actors in countries or regions without markets can sell their products in other territorial subsystems of the GIS (Binz et al., 2014). Access to resources in the GIS can, thus, compensate for the lack of such system resources at the regional or national level (Wieczorek et al., 2015). However, access to markets in other territories can be challenging in industries where the markets are project based and the customers require non-standardised solutions (Huenteler et al., 2016). In such industries, market access will require collaboration and embedding in international networks. Networks are therefore a type of structural coupling that can be particularly important in industries that demand customised products and services.

2.2. Networks as structural couplings between knowledge and market resources

Our focus is on how actor networks linked to one resource (knowledge) can facilitate the formation of structural couplings to another (market formation). This focus is motivated by the following. Knowledge creation and market formation underpin two overarching purposes of an innovation system, namely the development *and* diffusion/use of technology (Carlsson and Stankiewicz, 1991). Knowledge creation is essential for innovation and system performance (Bathelt and Glückler, 2005; Bergek et al., 2008). Moreover, firms rarely innovate in isolation, but interact and collaborate with other actors, such as customers, suppliers and knowledge institutions (Kline and Rosenberg, 1986). These collaborations entail that actors are embedded in knowledge networks, which in turn can be expected to facilitate structural couplings to market formation subsystems.

The characteristics of knowledge networks influence the spatiality of GISs and therefore the importance of structural couplings (Binz and Truffer 2017). The dominant innovation mode varies across industries. Some industries rely mostly on research-based and codified knowledge (Science, Technology, Innovation - STI), while other industries rely mostly on knowledge created through interaction between actors (Doing, Using, Interacting - DUI) (Jensen et al 2007). When firms engage in knowledge creation via DUI, it by definition implies close user-producer interactions, and thus a potential coupling between knowledge creation and market formation. Although tacit knowledge developed via the DUI mode is territorially embedded, firms can be motivated to invest in collaboration with geographically distant partners to foster the transfer of tacit knowledge (Bathelt et al., 2004). When

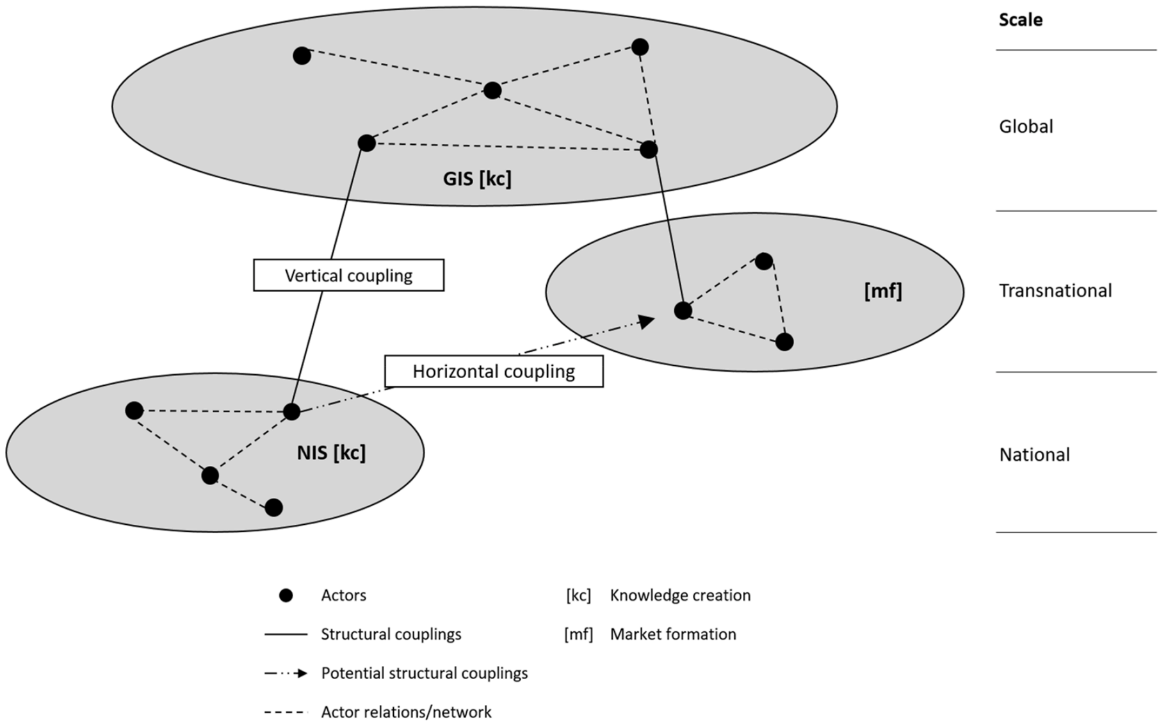

Fig. 1. Generic structure of section of a hypothetical global innovation system. The vertical coupling connects the national and global knowledge subsystems. The horizontal coupling represents potential linkages between territorial subsystems based around knowledge creation and market formation respectively. (Figure based on Binz and Truffer, 2017).

markets are geographically distant, such couplings across territorial sub-systems are important.

For STI, the participation in knowledge networks through R&D collaboration enhance firms' competitiveness and innovation (Colombo et al., 2016), correct or prevent market failures (Choi and Lee, 2017), and lower market entry barriers (Aristei et al., 2017). Moreover, firms use R&D collaborations to broaden their scope of activities through their partners, and enter new market segments while lowering the spending of precious resources (Berchicci, 2013; Hagedoorn et al., 2000). Although the purpose of R&D is to develop technological knowledge, firms also collaborate in R&D activities with the objective to identify new opportunities and to achieve greater market share (Berchicci, 2013). R&D collaborations allow firms to acquire technological and market knowledge, and access to larger domestic and/or foreign markets. For this reason, firms seek R&D collaborations with firms that are already present in domestic or international markets (Bayona et al., 2001).

In summary, firms engage in PDP and R&D projects for several reasons. Through these knowledge creation activities, firms participate in both national and international knowledge networks. The latter creates vertical structural couplings. We assume that by connecting with new actors from other domains, firms will also aim to gain access to international markets. By linking up to these markets through repeated successful commercialisation activities, firms establish horizontal structural couplings. In the following, we hypothesize how different knowledge networks can facilitate the creation of such horizontal couplings between the knowledge creation and market formation subsystems.

2.3. Hypothesising the role of different knowledge networks for structural couplings

2.3.1. Participation in international pilot and demonstration plants (PDPs)

Firms` participation in PDPs can support DUI learning (Frishammar et al., 2015). Hellsmark et al. (2016) suggest that PDPs play important roles in bridging basic knowledge development and market adoption. Particularly during formative phases of GIS, experimentation with different solutions is important, and PDPs offer opportunities for such experimentation. PDPs create 'windows of opportunity' in the existing innovation system (Farla et al., 2012; Shove and Walker, 2010), and have two key functions: (1) They contribute to reduce risks linked to technical, market, organisational and institutional uncertainties. (2) They facilitate different learning processes depending on the type of PDP. While some, such as lab-scale PDPs only have limited actor networks, industrial verification PDPs and deployment PDPs involve more complex networks (Hellsmark et al., 2016).

Depending on the type of PDP, a large number of different types of actors can be involved. The types of actors and their roles in PDPs also differ (Mossberg et al., 2018), of which several can be expected to be useful to connect with for market access. Infrastructural managers connect and coordinate actors and resources in a PDP, and therefore are highly connected and likely to have access to experienced operators. Users and customers play central roles, not only in providing user feedback, but also in relation to future market access. Indeed, based on a descriptive case analysis, van der Loos et al. (2020) suggest that PDP participation can support firms' international market access. When firms based in one country participate in international PDPs and achieve market access, structural couplings are established. This leads to our first hypothesis:

H1: Participation in international pilot and demonstration plants (PDPs) positively affects the participation of firms in international markets.

2.3.2. Participation in R&D projects

While DUI is important, firm innovation and market presence may require STI learning. One of the most frequent indicators of STI mode of learning is knowledge development through the intensity of participation in collaborative R&D projects (Colombo et al., 2016). Through R&D collaborations, firms create R&D collaboration networks (Hagedoorn et al., 2000). Networks are formed to link and exploit the different competences existing in the GIS. These strategic R&D collaborations help maximize the collective resources and increase the performance of individual firms, especially in new market environments with high uncertainty. In this way, R&D networks allow firms to pool resources in projects that are too large for firms to accomplish themselves, achieving economies of scale (Hagedoorn et al., 2000; Wanzenböck et al., 2013), and establishing trust (Dyer and Chu, 2011; Tsouri, 2019).

Especially in emerging markets with a high degree of uncertainty, few firms acquire the necessary knowledge through internal R&D activities (Bayona et al., 2001). Therefore, firms engage in R&D collaboration, not only for enhancing their innovative performance, as argued above, but for gaining access to the international market (Bayona et al., 2001; Hagedoorn et al., 2000). Firms aim to gain market access, based on the resources and trust created through their R&D collaborative networks. We explore whether the extent of participation in domestically and internationally funded STI-type projects (R&D) influences firms' participation in the international markets for an emerging technology with the following hypothesis:

H2: Participation in more R&D projects positively affects the participation of firms in international markets.

2.3.3. Domestic and international R&D collaboration

Due to the uneven geographical distribution of knowledge, firms create, diffuse and utilize knowledge in collaboration with actors located in the same territory (Boschma, 2005) or they collaborate with international actors (Bathelt et al., 2004).

On the one hand, as emerging technological fields are characterised by uncertainty, actors prefer to source knowledge locally through R&D collaborations with actors in the same territorial and institutional contexts (Bathelt and Glückler, 2005; Tsouri, 2019). According to Grillitsch and Trippl (2014), knowledge sourced nationally can be beneficial and important for firm collaboration and innovation. Firms may collaborate with other domestic firms, particularly large established firms, that have direct access to the international market through existing networks. Firms that previously have lacked this access can, however, gain access through collaboration with those domestic firms that already have an international market presence (van der Loos et al., 2020). It is therefore relevant to explore whether national R&D collaboration leads to international market access.

On the other hand, relying only on national knowledge sourcing may lead the knowledge development into a lock-in situation, as the knowledge would not be renewed by external sources (Boschma and Frenken, 2011). Since new knowledge is a rare resource, firms have to increase their R&D collaboration, tapping into a variety of actors, sometimes distant, to obtain the desired knowledge resources (Robinson et al., 2013). International knowledge sourcing is important due to the heterogeneity of the knowledge and competences required (Trippl et al., 2009; Un and Rodríguez, 2018). The generation of knowledge in an emerging technological field therefore also relies on the ability of actors to access and use knowledge that cannot be found locally or even inside the borders of the country (Aarstad et al., 2016).

Given that R&D collaboration with both domestic and international actors is important for firm innovation, and potentially market access, we propose the following hypotheses to examine the relative importance of domestic and international R&D collaboration for firms' participation in international markets:

H3a: Having more international R&D collaborators positively affects the participation of firms in international markets.

H3b: Having more domestic R&D collaborators positively affects the participation of firms in international markets.

2.3.4. R&D collaboration with partners in countries with a market

Firms without access to a domestic market use strategic R&D collaborations as one way in which they can exploit existing (related) assets to target international markets. R&D collaboration is a cost-efficient way of partnering with firms that have a presence in target markets (Hottenrott and Lopes-Bento, 2014). In a "sticky" GIS, where markets demand customized products and services, collaborations with actors based in countries with home markets can therefore be expected to be important (Binz and Truffer, 2017). In this paper, we therefore theorize that international collaboration with actors from countries with existing home markets will be of particular importance since they may have experience and pre-existing networks from their domestic market. This leads us to the following hypothesis:

H4: Having more R&D collaborators from countries with a domestic market positively affects the participation of firms in the international markets.

3. Data and methods

3.1. The offshore wind industry in Norway

To test our hypotheses, we explore the participation of Norwegian offshore wind firms in the international offshore wind market. Europe is the most mature market for offshore wind globally, and until recently the majority of projects have been in the North Sea and Baltic Sea (BVG Associates, 2019). The offshore wind GIS[1] has been considered as spatially sticky (Binz and Truffer, 2017), characterized by DUI mode of innovation with territorially embedded knowledge creation and market formation. However, the supply chain for offshore wind consists of a wide variety of firms that deliver products and services such as components and designs for foundations, installation, subsea surveillance, crew transfer, engineering, and operations and maintenance (Normann and Hanson, 2018). Moreover, a vast majority of the firms that deliver to offshore wind have a background in the oil and gas supply industry (Hanson et al., 2019; Steen and Weaver, 2017), which is an industry that leans on both STI and DUI modes of innovation (Simensen and Thune, 2018). Thus, whilst DUI is likely to be the more important mode of innovation, we expect that offshore wind suppliers also to some extent engage in STI modes of innovation.

The Norwegian offshore wind industry is a special case. The development of an internationally oriented offshore wind supply industry has been identified as a priority area for Norwegian policy (Energi21, 2011, 2014). However, because close to 100 per cent of mainland electricity is renewable (mainly hydropower), there have been weak incentives for stimulating domestic market formation (Wicken, 2011). Consequently, except for a single demonstration turbine commissioned in 2009, there is no domestic market for offshore wind in Norway. Instead, the government's strategy for offshore wind has been to support Norwegian firms' access to international markets through various R&D incentives (Meld. St. 25, 2015-2016; St.prp. nr 1 2007-2008, p. 16).

The Norwegian offshore wind industry provides a unique opportunity to analyse structural couplings between the knowledge creation and market formation subsystems. The Norwegian offshore wind industry is a subsystem of the offshore wind GIS. This system has been based on existing technological competences and publicly supported R&D activities, contributing to local knowledge creation. However, the Norwegian subsystem has had to rely on access to market formation in the GIS. Previous studies of the offshore wind GIS has described how certain resources have developed in certain places, and that structural couplings can provide access to resources in other territories (Wieczorek et al., 2015). The Norwegian case provides an opportunity to study how and when these structural couplings fulfil this role.

3.2. A combination of datasets

In this paper, we combine data from three datasets: the 4C Offshore database of offshore wind farms, the CORDIS database of EU-funded

[1] In this study we refer to the creation of structural couplings between the Norwegian subsystem and the offshore wind GIS. In this case the GIS is not fully global, but it is concentrated in Europe, with clusters in specific countries, which have large-scale offshore wind farms in their territory.

R&D projects, and the Research Council of Norway (RCN) R&D projects database. Our focus is on Norwegian firms that participate in at least one of the three datasets (i.e. in R&D or/and market projects – small or big scale).

The 4C database includes all offshore wind farm projects constructed, under construction, planned, authorized, and dormant or cancelled. It includes both large- (≥50 MW) and small-scale projects. It provides information on the state of construction, date of authorization, date of construction initiation, date of first power production, capacity and other characteristics of the wind farms, as well as the stakeholders' name, location and type. The database provides annual data from 1990 until 2018.

We define the market to only include large-scale (≥50 MW) offshore wind farms that are either fully commissioned, partial generation, under construction, or preconstruction phases, as not all the proposed and authorized projects can be expected to materialize. The market is concentrated mainly in Europe (Germany, the United Kingdom, the Netherlands, Denmark, Belgium, and Sweden), while there are a few large-scale projects in Asia[2].

Fig. 2 presents the distribution of the offshore wind market across countries and the market share according to which countries the offshore wind firms are located. The largest share of both offshore wind farms and firms is in the United Kingdom, followed by Germany. Denmark and Belgium both host approximately six per cent of the offshore wind farms, and they have a similar share of firms active in the international market, while Sweden has one per cent of both actors and windfarms. The Netherlands is home to eleven per cent of the firms active in offshore wind farm construction, even though only five per cent of the international market is in the Netherlands. Finally, although Norway has no domestic market, approximately three per cent of firms active in the international market are Norwegian.

In addition to participating in the construction of large-scale offshore wind farms, firms may acquire DUI type of learning by participating in the construction of small-scale (<50 MW) offshore wind. Most of these projects are PDPs. Ten per cent of the small-scale projects have later been developed into large-scale projects. However, the large-scale projects have consisted of different groups of contractors, and we treat these as separate projects. Fig. 3 presents the shares of existing (completed or planned for construction) small-scale offshore wind farms and of the firms participating in their construction for the countries that have a domestic offshore wind market, plus Norway. The percentages refer to the global population of small-scale offshore wind projects and the actors participating in their construction. When compared with large-scale projects (Fig. 2), we can observe a higher share of projects in Scandinavian countries.

The CORDIS database of EU-funded R&D projects is the official database of the European Commission, containing information about all the R&D activity that takes place under the EU research frameworks. We use R&D projects funded by the last four frameworks (FP5, FP6, FP7 and Horizon2020), spanning the period from 1998 until 2018. The CORDIS dataset contains information about the name and duration of every project; the funding scheme; an abstract of the project; and the name, location and activity type of the participants. To identify the projects related to the offshore wind industry, we filtered the project abstracts by keywords (offshore wind, wind power, wind energy, wind turbine, wind park, windfarm, and turbine blade in combination with the words offshore and floating). We subsequently performed a content analysis on the filtered abstracts.

Fig. 4 shows the participation of single actors in EU-funded R&D projects on offshore wind according to the home country of the organization. The R&D projects on offshore wind are dominated by actors located in the United Kingdom, Spain, Germany, Denmark, and the Netherlands. A considerable percentage of Norwegian actors participate in R&D projects.

Our third dataset includes R&D projects funded by the Research Council of Norway (RCN). The information and structure of the data are similar to those of CORDIS. This dataset includes projects funded from 2000 until 2017 in all fields of research. We followed the same procedure for abstract filtering as for CORDIS to isolate the projects relevant to offshore wind. In this dataset, the majority of the actors are located in Norway (85 per cent). The other actors are mainly located in the United Kingdom, Germany, Denmark and the Netherlands.

3.3. Treatment of data and variables

The number of firms based in Norway that participate in at least one of the three datasets is 178. We recorded the participation in projects and the number of collaborators for all firms for every year from 2002 to 2017, which resulted in a balanced panel. There were no large-scale wind farms constructed before 2002. We used the following variables: market participation, international PDP participation, participation in EU projects, participation in RCN projects, foreign collaborators in EU projects, domestic collaborators in EU projects, foreign collaborators in RCN projects, domestic collaborators in RCN projects, and collaborators from domestic market countries. We used size, age, and involvement of the firm in oil and gas (O&G) activities as control variables.

We explore whether Norwegian firms that lack a domestic market benefit from previous participation in DUI and STI based knowledge networks to acquire access to the international market. We take into consideration the cumulative nature of knowledge (Castellacci and Zheng, 2010). Firms maintain knowledge and connections accumulated through DUI and STI learning after the end of a project. Therefore, we do not consider participation in projects or interactions with other actors in a specific moment back in time, but the sum of these elements for larger periods in the past. We therefore control the cumulative data for past periods of three, five and ten years (cumulative time lags).[3] To express these time lags, we use the sum of the projects in which Norwegian actors have participated for the last three, five, and ten years to form the variables that describe project participation (PDP and R&D). To measure the number of collaborators, we use the total number of collaborators (foreign or domestic) that a Norwegian actor has for every aforementioned period.

Market participation: We define a market (see section 3.2) as the offshore wind farms that currently or soon will produce energy ('fully commissioned', 'under construction', 'pre-construction', or 'partial generation'). We only include large-scale (≥50 MW) offshore wind projects. We exclude projects with no evidence for when or if their construction will start ('cancelled', 'concept/early planning', 'consent authorized', 'dormant', 'development zone', 'consent application submitted'). Market participation is the dependent variable of the model. In the first version of the model, we operationalize the dependent variable as a count variable (0,1,2,3…), defined as the number of large-scale offshore wind farm construction projects every firm participated in every year. It can be interpreted as 'no, less, or more' participation in market projects. In order to simplify the interpretation of our results, we introduce a second version of the same model with the dependent variable operationalized as binary (0/1), representing 'participation or not' in the market for every year. In the models, market participation is

[2] The market of China consists of so-called "near to shore" wind farms. They are at water depths of only a few meters and so close to the shore that it is questionable to what extent they can be considered proper offshore wind farms.

[3] To avoid the overlapping of the dependent variable year and the explanatory variable cumulative time lag, as well to secure the directionality of our empirical research, we make sure that we consider in the cumulative time lag of the explanatory variables the period until the previous year before the year considered in the dependent variable. E.g. when we examine the market participation of year 2016, we take into consideration the five-year lag of the explanatory variables for 2011-2015

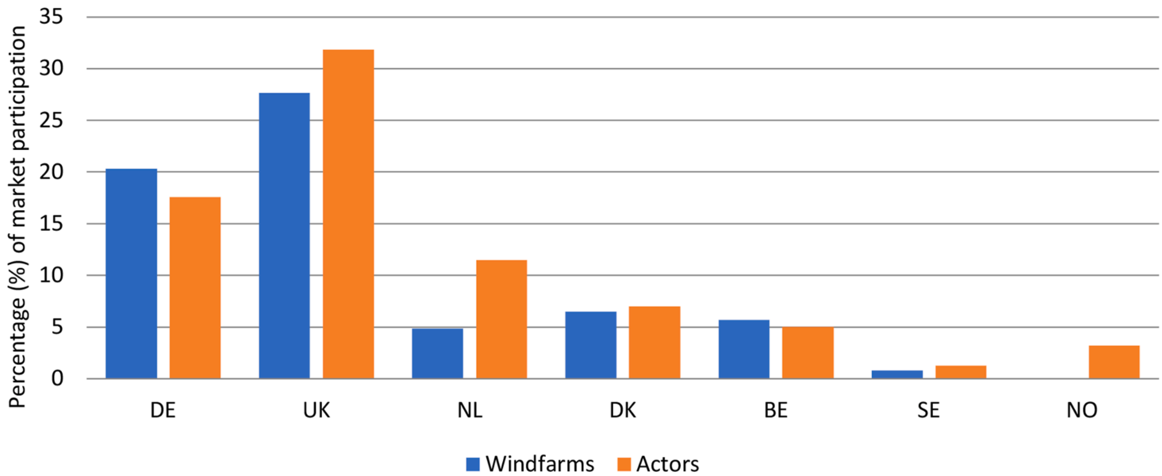

Fig. 2. Percentage of participation in the international offshore wind market according to the location of the offshore wind farms ("Windfarms") and the location of the participating firms ("Actors") (source: 4C Offshore database).

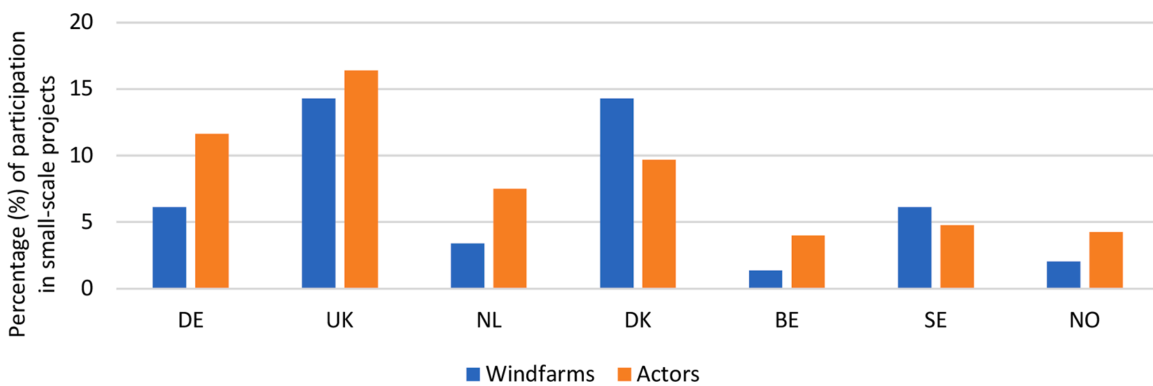

Fig. 3. Percentage of participation in small-scale projects according to the location of the offshore wind farms and the location of the participating actors for countries with domestic markets plus Norway (source: 4C Offshore database).

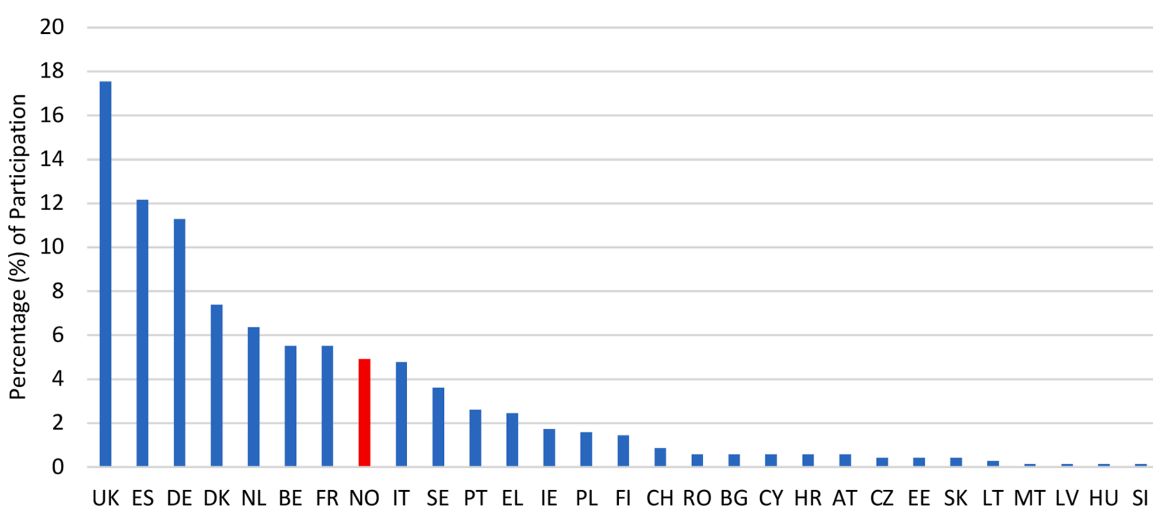

Fig. 4. Participation (%) of actors in offshore wind R&D projects funded by the EU distributed across EU/EAA countries.

interpreted as the establishment (binary variable) and reinforcement (count variable) of a horizontal structural coupling.

International PDPs: As a variable portraying an aspect of DUI-based networks, we use the number of materialized small-scale (PDPs) offshore wind projects (<50 MW) Norwegian firms participate in each year in the 4C Offshore dataset. As Norway has only one PDP project in its territory, we consider only the international PDPs. International PDPs constitute vertical DUI based structural couplings.

To measure the participation in STI-based networks, we use the two datasets of R&D projects (EU- and RCN-funded projects). Out of the two datasets, we construct three different sets of variables for the number of projects, the number of foreign collaborators, and the number of domestic collaborators of Norwegian firms every year. These variables are expressed with the cumulative lag. Participation in R&D projects operationalizes the concept of vertical STI based structural couplings.

Number of projects participated in: *EU projects* measures the number of projects funded by the EU in which a firm participates during a past period. *RCN projects* is the number of projects funded by the RCN in which an actor participates during a past period.

Number of foreign collaborators: This set of variables represents the sources of foreign knowledge that Norwegian actors have access to during a past period. *EU foreign collaborators* includes the number of non-Norwegian collaborators that a Norwegian firm has in EU-funded R&D projects. *RCN foreign collaborators* includes the number of non-Norwegian collaborators that a Norwegian firm has in RCN-funded R&D projects.

Number of domestic collaborators: This set of variables represents the sources of nationally circulated knowledge to which a Norwegian firm has access during a past period. *EU domestic collaborators* includes the number of collaborators based in Norway that a Norwegian firm has in EU-funded R&D projects. *RCN domestic collaborators* includes the number of collaborators based in Norway that a Norwegian firm has in RCN-funded R&D projects.

As a second step, we modified the model to understand the role of knowledge originating from countries with a domestic offshore wind market. We replaced the set of variables of foreign collaborators with the variable *Collaborators in domestic markets*. This variable refers to the number of collaborators of Norwegian firms during a past period that are based in a country with a domestic offshore wind market and constitutes a subset of the number of foreign collaborators.

Finally, to control for the effects of the capacity of the firms to enter the market according to their resources to face trade barriers (Castellacci, 2010), we added three control variables, namely, *Age, Size* and *O&G* involvement of the firms. *Age* is measured in years since the foundation of the firm. For *Size*, we used the classification of the European Commission to define micro, small, medium, and large firms, in an ascending scale (1 = Micro <10 employees, 2 = Small <50 employees, 3 = Medium < 250 employees, and 4 = Large > 250 employees). For *O&G* involvement of the firm, we employ a dummy variable (0/1) (Table 1).

Table 1
Descriptive statistics from the panel data variables (overall).

	Three years lag		Five years lag		Ten years lag	
	Observations: 2,492 Number of firms: 178 Years: 14		Observations: 2,132 Number of firms: 178 Years: 12		Observations: 1,246 Number of firms: 178 Years: 7	
	Mean (Std. Dev)	Min - Max	Mean (Std. Dev.)	Min - Max	Mean (Std. Dev.)	Min - Max
Market participation (count)	0.068 (0.344)	0-4	0.077 (0.367)	0-4	0.080 (0.374)	0-4
Market participation (binary)	0.048 (0.214)	0-1	0.054 (0.227)	0-1	0.056 (0.230)	0-1
International PDPs	0.031 (0.199)	0-3	0.050 (0.262)	0-3	0.112 (0.410)	0-4
EU projects	0.111 (0.621)	0-9	0.183 (0.960)	0-12	0.358 (1.547)	0-14
RCN projects	1.225 (2.807)	0-32	2.125 (4.546)	0-51	4.390 (7.772)	0-91
EU foreign collaborators	0.657 (4.033)	0-55	0.762 (4.341)	0-55	1.108 (5.288)	0-55
RCN foreign collaborators	0.543 (1.695)	0-14	0.633 (1.816)	0-14	0.872 (2.120)	0-14
EU domestic collaborators	0.058 (0.379)	0-5	0.067 (0.409)	0-5	0.104 (0.511)	0-5
RCN domestic collaborators	5.520 (12.571)	0-99	6.431 (13.362)	0-99	8.914 (15.535)	0-99
Collaborators in domestic markets	0.667 (2.513)	0-27	0.774 (2.695)	0-27	1.075 (3.190)	0-27
Age	19.057 (23.355)	0-151	19.904 (23.392)	0-151	22.199 (23.400)	0-151
Size	2.242 (1.345)	0-4	2.290 (1.304)	0-4	2.433 (1.175)	0-4
O&G	0.449 (0.498)	0-1	0.449 (0.498)	0-1	0.449 (0.498)	0-1

3.4. The general model

To examine the effects that DUI and STI modes of learning have had on Norwegian firms' access to the international market, we employ the following model in its general form:

$$Market_{it} = \sum_{p=(t-1\cdots t-k)} International\ PDPs_i + \sum_{p=(t-1\cdots t-k)} EU\ projects_i + \sum_{p=(t-1\cdots t-k)} RCN\ projects_i + \bigcup_{p=(t-1\cdots t-k)} EU\ foreign\ collaborators_i$$

$$+ \bigcup_{p=(t-1\cdots t-k)} RCN\ foreign\ collaborators_i + \bigcup_{p=(t-1\cdots t-k)} EU\ domestic\ collaborators_i + \bigcup_{p=(t-1\cdots t-k)} RCN\ domestic\ collaborators_i + Controls_{it}(age, size, O\&G)$$

In this model, for every firm i and year t, *Market* represents the number of offshore wind market projects in which a firm participates in the current year. $\sum_{p=(t-1\ldots t=k)}$ is the sum of the number of projects from 1 to k years that constitute a period p. The variable *International PDPs* is the number of small-scale offshore wind projects the firm participates in during the selected years. *EU projects* is the number of EU-funded R&D projects that the firm participates in for the selected period. Similarly, *RCN projects* is the number of nationally funded R&D projects in which a firm participates for the given period. $U_{p=(t-1\ldots t=k)}$ is the number of collaborators from 1 to k years that constitute the period p. *EU foreign collaborators* is the number of foreign collaborators in EU-funded R&D projects, *RCN foreign collaborators* is the number of foreign collaborators in nationally funded R&D projects, *EU domestic collaborators* is the number of Norwegian collaborators in EU-funded R&D projects, and *RCN domestic collaborators* is the number of Norwegian collaborators in nationally funded R&D projects that every firm has during the defined period p. The *Age* of firm i is measured in years from its establishment until year t, *Size* is the size of the firm according to the four ascending categories (1 to 4), and *O&G* is the dummy variable expressing firm's involvement in O&G activities.

4. Analysis of the results

To understand how different periods of cumulative DUI and STI knowledge matter, we try different time lags (three, five and ten years) and choose the period with the best fit (R-sq). The best fit of the model is found when we consider the cumulative projects in the last five years.

Table 2
Calculation of the main model with three-, five- and ten-year cumulative lags of the variables (fixed and random effects panel data).

Dependent variable:	Market participation (count)					
	OLS					
Cumulative time lag	**3 years**		**5 years**		**10 years**	
	FE	**RE**	**FE**	**RE**	**FE**	**RE**
International PDPs	0.197***	0.244***	0.215***	0.261***	0.082	0.122***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.259)	(0.002)
EU projects	-0.016	-0.022	-0.007	-0.015	0.015	-0.006
	(0.434)	(0.272)	(0.596)	(0.240)	(0.395)	(0.597)
RCN projects	0.005	0.006	-0.001	0.000	-0.006	-0.003
	(0.425)	(0.237)	(0.823)	(0.959)	(0.221)	(0.364)
EU foreign collaborators	0.013***	0.012***	0.013***	0.013***	0.017***	0.014***
	(0.006)	(0.005)	(0.005)	(0.004)	(0.003)	(0.007)
RCN foreign collaborators	-0.003	0.003	-0.006	0.001	0.037	0.017
	(0.663)	(0.707)	(0.522)	(0.887)	(0.111)	(0.138)
EU domestic collaborators	-0.129***	-0.133***	-0.139***	-0.142***	-0.188***	-0.167***
	(0.006)	(0.003)	(0.005)	(0.003)	(0.001)	(0.002)
RCN domestic collaborators	-0.001	-0.001	0.001	0.000	-0.000	-0.000
	(0.405)	(0.407)	(0.633)	(0.882)	(0.916)	(0.947)
Age (years)	0.005***	-0.000	0.002	-0.001	-0.001	-0.000
	(0.003)	(0.669)	(0.501)	(0.373)	(0.857)	(0.594)
Size		0.025***		0.027**		0.027
		(0.004)		(0.011)		(0.152)
O&G experience		0.083***		0.095***		0.105**
		(0.002)		(0.002)		(0.012)
N	2,492	2,492	2,136	2,136	1,246	1,246
R-sq	0.0079	0.0743	0.0501	0.0977	0.0172	0.0685

Dependent variable:	Market participation (binary)					
	Linear probability					
Cumulative time lag	**3 years**		**5 years**		**10 years**	
	FE	**RE**	**FE**	**RE**	**FE**	**RE**
International PDPs	0.115***	0.141***	0.075***	0.105***	0.035	0.043*
	(0.000)	(0.000)	(0.001)	(0.000)	(0.425)	(0.077)
EU projects	-0.004	-0.007	0.001	-0.004	0.007	-0.002
	(0.789)	(0.585)	(0.901)	(0.657)	(0.471)	(0.769)
RCN projects	-0.002	0.001	-0.003	-0.001	-0.000	0.000
	(0.668)	(0.734)	(0.296)	(0.714)	(0.991)	(0.991)
EU foreign collaborators	0.012***	0.012***	0.013***	0.013***	0.017***	0.015***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
RCN foreign collaborators	0.001	0.004	0.003	0.005	0.017	0.007
	(0.795)	(0.384)	(0.573)	(0.354)	(0.229)	(0.292)
EU domestic collaborators	-0.131***	-0.138***	-0.146***	-0.149***	-0.184***	-0.171***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
RCN domestic collaborators	-0.000	-0.000	0.001	0.000	0.001	-0.000
	(0.864)	(0.696)	(0.429)	(0.855)	(0.735)	(0.670)
Age (years)	0.004***	-0.000	0.001	-0.000	-0.002	-0.000
	(0.001)	(0.507)	(0.416)	(0.298)	(0.552)	(0.527)
Size		0.019***		0.019***		0.019
		(0.001)		(0.003)		(0.101)
O&G experience		0.058***		0.069***		0.084***
		(0.000)		(0.000)		(0.001)
N	2,492	2,492	2,136	2,136	1,246	1,246
R-sq	0.0083	0.0795	0.0258	0.0839	0.0060	0.0806

We repeated the analysis for both the operationalisations of the dependent variable, count and binary. Table 2 presents the three cumulative lags.

In both operationalisations of the dependent variable (market participation) we observe similar patterns to the significance and signs of the coefficients. When we consider the market participation as binary (participation or not), the five-years lag model best explains the variance of the dependent variable. Therefore, we use this time lag for our subsequent analyses. However, the operationalisation of the dependent variable both as binary and count, suggest the use of negative binomial and logit estimators respectively. Table 3 reports the results of the analysis with negative binomial and logit models, in comparison with their linear equivalents.

For all the examined estimations, the DUI-based knowledge gained in the past through participation in international PDPs positively and significantly affects firm participation in the international offshore wind market (confirming H1). In the case of more or less market participation (OLS and negative binomial), we observe that the effect peaks when we consider five years of cumulative participation in R&D projects and international PDPs, and decreases after this point (in terms of magnitude of coefficient) but remains a significant factor for firm participation in the market.

Unlike the participation in international PDPs, the amount of R&D projects a firm participates in does not imply more (or even) participation in the international offshore wind market. This applies to participation in EU- and nationally funded projects (rejecting H2). This does not necessarily mean that the STI-based knowledge developed in these projects has no effect on the ability of Norwegian firms to enter the international market but rather that the number of R&D projects in which a firm participates has no significant effect on the amount of market participation. Our results further suggest that the number of foreign collaborators a Norwegian firm has over time (joint number of foreign collaborators during the last three, five, or ten years) in EU-funded R&D projects positively affects the firm's participation in the international market (confirming H3a)[4].

The results show a negative and significant effect of the number of domestic collaborators in EU-funded R&D projects on Norwegian firms' participation in international markets (rejecting H3b)[5]. This suggests collaborations with foreign partners through participation in EU funded projects positively contributes to firms` access to international markets, while this is not the case for collaborations with domestic partners. Furthermore, when we consider only the cumulative period of three years, we find a small but negative and significant effect of the number of domestic collaborators in nationally funded projects on firms' participation in international markets. Thus, over shorter periods, the more domestic collaborators a Norwegian firm has in nationally funded projects, the less it participates in international markets. However, over longer periods (ten years), the number of foreign collaborators in nationally funded projects positively and significantly affects Norwegian firms' participation in international markets.

Finally, to account for collaborations with partners based in countries with domestic markets, we made a slight alteration to the original model. We replaced the foreign collaborators (in EU- and nationally funded projects) with the variable *Collaborators in domestic markets*. This variable is a subset of the aforementioned variables and includes only

[4] Neither the EU-funded projects and the collaborators in EU projects nor the RCN projects and the collaborators in RCN projects are highly correlated. Thus, there is not an issue of collinearity. We have performed robustness checks by controlling for high correlations and adding the variables separately to the regression, without changes to the significance levels and signs.

[5] There is not a high correlation between the foreign and the domestic collaborators, in either EU- or RCN-funded projects. We added the variables separately in the model, controlling for its robustness, and there were no changes to the significance levels and signs.

Table 3
Effect of DUI and STI knowledge on the market participation for offshore wind industry with five-year cumulative lag (linear, negative binomial, logit, fixed and random effects).

Dependent variable:	Market participation (count) OLS		Negative binomial		Market participation (binary) Linear probability		Logit	
	FE	RE	FE	RE	FE	RE	FE	RE
International PDPs	0.215***	0.261***	0.485**	0.702***	0.075***	0.105***	0.383**	0.764**
	(0.000)	(0.000)	(0.015)	(0.000)	(0.001)	(0.000)	(0.036)	(0.016)
EU projects	-0.007	-0.015	0.247	-0.082	0.001	-0.004	0.331	-0.039
	(0.596)	(0.240)	(0.427)	(0.719)	(0.901)	(0.657)	(0.356)	(0.873)
RCN projects	-0.001	0.000	-0.028	0.037	-0.003	-0.001	-0.094	-0.013
	(0.823)	(0.959)	(0.548)	(0.395)	(0.296)	(0.714)	(0.171)	(0.836)
EU foreign collaborators	0.013***	0.013***	0.116*	0.167*	0.013***	0.013***	0.197*	0.194*
	(0.005)	(0.004)	(0.081)	(0.056)	(0.000)	(0.000)	(0.095)	(0.051)
RCN foreign collaborators	-0.006	0.001	-0.235	-0.105	0.003	0.005	-0.095	0.082
	(0.522)	(0.887)	(0.102)	(0.334)	(0.573)	(0.354)	(0.677)	(0.624)
EU domestic collaborators	-0.139***	-0.142***	-2.160**	-1.604*	-0.146***	-0.149***	-3.343*	-3.370**
	(0.005)	(0.003)	(0.034)	(0.061)	(0.000)	(0.000)	(0.055)	(0.033)
RCN domestic collaborators	0.001	0.000	0.047	0.011	0.001	0.000	0.062	0.013
	(0.633)	(0.882)	(0.106)	(0.593)	(0.429)	(0.855)	(0.111)	(0.609)
Age (years)	0.002	-0.001	0.018	-0.014	0.001	-0.000	0.021	-0.013
	(0.501)	(0.373)	(0.400)	(0.134)	(0.416)	(0.298)	(0.556)	(0.272)
Size		0.027**		0.518***		0.019***		0.484**
		(0.011)		(0.002)		(0.003)		(0.010)
O&G experience		0.095***		1.990***		0.069***		2.717***
		(0.002)		(0.000)		(0.000)		(0.000)

Table 4
The contribution of incoming knowledge from countries with domestic markets for offshore wind.

Dependent variable:	Market participation (count) OLS		With collaborators in domestic markets		Market participation (binary) Linear probability		With collaborators in domestic markets	
	FE	RE	FE	RE	FE	RE	FE	RE
International PDPs	0.215***	0.261***	0.213***	0.261***	0.075***	0.105***	0.075***	0.105***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
EU projects	-0.007	-0.015	-0.004	-0.012	0.001	-0.004	0.002	-0.001
	(0.596)	(0.240)	(0.742)	(0.323)	(0.901)	(0.657)	(0.799)	(0.801)
RCN projects	-0.001	0.000	-0.004	-0.001	-0.003	-0.001	-0.004	-0.002
	(0.823)	(0.959)	(0.301)	(0.653)	(0.296)	(0.714)	(0.166)	(0.307)
EU foreign collaborators	0.013***	0.013***			0.013***	0.013***		
	(0.005)	(0.004)			(0.000)	(0.000)		
RCN foreign collaborators	-0.006	0.001			0.003	0.005		
	(0.522)	(0.887)			(0.573)	(0.354)		
EU domestic collaborators	-0.139***	-0.142***	-0.061**	-0.73**	-0.146***	-0.149***	-0.086***	-0.089***
	(0.005)	(0.003)	(0.015)	(0.036)	(0.000)	(0.000)	(0.000)	(0.000)
RCN domestic collaborators	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000
	(0.633)	(0.882)	(0.838)	(0.951)	(0.429)	(0.855)	(0.517)	(0.897)
Collaborators in domestic markets			0.097*	0.012*			0.015***	0.014***
			(0.061)	(0.059)			(0.001)	(0.000)
Age (years)	0.002	-0.001	0.002	-0.000	0.001	-0.000	0.001	-0.000
	(0.501)	(0.373)	(0.380)	(0.451)	(0.416)	(0.298)	(0.280)	(0.394)
Size		0.027**		0.026**		0.019***		0.018***
		(0.011)		(0.016)		(0.003)		(0.005)
O&G experience		0.095***		0.096***		0.069***		0.071***
		(0.002)		(0.002)		(0.000)		(0.000)
N	2,136	2,136	2,136	2,136	2,136	2,136	2,136	2,136
R-sq	0.0501	0.0977	0.0476	0.0989	0.0258	0.0839	0.0200	0.0834

the collaborators based in countries that have developed a domestic market in offshore wind (United Kingdom, Germany, Denmark, the Netherlands, Belgium, and Sweden).

Table 4 presents the results after the introduction of the variable describing the R&D collaboration with actors based in countries with domestic markets. The results show that collaboration with partners from countries with domestic offshore wind markets[6] appears to have a significant and positive effect on Norwegian firms' participation in

[6] We consider as countries with domestic market those countries that had at least one large-scale offshore wind farm. Years in which countries built their first large-scale offshore wind farm: Denmark in 2002, UK in 2003, the Netherlands and Sweden in 2006, Germany in 2008, and Belgium in 2009. This change is taken into consideration in our panel dataset.

international offshore wind markets (confirming H4). The rest of the variables do not change in terms of significance level and coefficient sign with the addition of the new variable. The more partners a firm has in its R&D network that are based in countries where there is an offshore wind market, the greater their participation in international markets.

5. Discussion and conclusion

In this paper, we respond to a call for a better understanding of how structural couplings work by analysing how participation in different types of knowledge networks facilitates access to international markets. We built upon recent conceptualisations of GIS where different subsystems are delineated around territories or resources (Rohe, 2020). Structural couplings link these subsystems vertically (territories) and horizontally (resources). We formulated and tested a set of hypotheses on how different knowledge networks improve the conditions for structural couplings to market subsystems in GIS. More specifically, we examined the relationship between two knowledge creation modes (DUI and STI) and access to the international offshore wind market for firms based in Norway – a country with no domestic offshore wind market.

5.1. Implications for academic research

Our results show that knowledge networks function as structural couplings between territorial subsystems and the GIS. Such multiscale knowledge networks can in turn facilitate structural couplings between knowledge and market formation subsystems in the GIS. However, the extent to which knowledge networks improve market access varies depending on the type of knowledge network (DUI vs. STI) and on the geographic scale of the networks (national vs. transnational). In the following, we discuss how this varies between international PDP and R&D networks, and between different scales of R&D networks.

First, participation in international PDPs facilitates to a greater extent than participation in R&D projects, access to the global offshore wind market. Offshore wind is a technologically complex industry characterised by DUI mode of learning. In such industries, knowledge is typically created through user-producer interaction, and structural couplings that connect resources are therefore particularly important (Binz and Truffer, 2017). We find that participation in international PDPs is a key mechanism through which knowledge networks facilitate structural couplings to market resources.

We also suggest a complementary explanation for the importance of international PDPs. Participation in international PDPs provides firms the opportunity to collaborate with a wider variety of actors across the offshore wind supply chain, including actors that may operate closer to the market than what R&D partners do (Mossberg et al., 2018).

Second, we find that R&D project participation, which we use as an indicator for STI learning, per se does not affect the access to international markets in our particular case. Although the lesser relative importance of STI is expected, given the DUI dominance in offshore wind, we do observe positive effects of engaging in STI collaboration under certain conditions. While participation in national R&D networks has a negative effect on market access, increased R&D collaboration with international partners enhances the Norwegian firms' access to the international market. This means that horizontal structural couplings between knowledge creation and market access depend on the presence of vertical structural couplings connecting national and international knowledge networks. We also see that firms' market access benefits from R&D collaborations with actors located in countries with domestic offshore wind markets. This means that structural couplings to the knowledge creation subsystem in countries with domestic markets are particularly important. These insights contribute to disentangle the relation between vertical and horizontal couplings in GIS, when only partial resource formation occurs on the national scale.

Even though our analysis is based on a single case study, the results have broader relevance. Offshore wind is an industry characterised by interactive learning between users and producers, DUI mode of innovation, and context-specific demand (Rohe, 2020). Resource formation occurs in different subsystems, and the functioning of the GIS depends on structural couplings between these subsystems (Binz and Truffer, 2017). We have argued that participation in international PDPs can facilitate the creation of structural couplings in such industries. This is likely to apply to other industries that share the same characteristics. Based on the recent GIS literature, other industries that share some of the relevant characteristics include concentrated solar and geothermal energy (Malhotra and Schmidt, 2020). Moreover, we have shown that knowledge networks based around STI mode of innovation in some circumstances can facilitate the creation of structural couplings. Thus, we suggest that in other complex energy related industries characterised by context dependent demand and STI mode of innovation, such as carbon capture and storage and nuclear (Binz and Truffer, 2017), participation in international R&D networks can facilitate structural couplings with market formation subsystems. Beyond the energy sector, these findings could be relevant for other complex sectors and technologies such as waste recycling and management, hyperloop train-systems, water treatment and purification, and sustainable solutions in the agricultural sector.

5.2. Implications for policy

Our findings are relevant for countries with strong knowledge creation linked to industries where there is limited or no national market formation. More specifically, countries that have system strengths linked to certain resources (in our case knowledge) within a territorial subsystem, can strategically leverage these and, at least partly, circumvent challenges posed by domestic system weaknesses (in our case lack of domestic market formation) through the creation of structural couplings to the GIS. Our results have implications for how such a policy strategy should be designed. Policy should stimulate domestic firms' participation in international PDPs. Moreover, national R&D funding programs should be restructured to incentivise more collaborations with international actors, and especially collaboration with actors located in countries with a domestic market. Such incentives for strategic cross-border collaboration deviate from traditional R&D policy approaches with a predominant orientation towards national or regional scales.

5.3. Limitations and directions for future research

An interesting continuation of our research would be to compare how different knowledge networks facilitate market access in other territorial subsystems across multiple industries with different characteristics. For instance, comparative analyses could explore whether the important role of PDPs for market access is something specific to complex, DUI based industries or if this is a more generic mechanism across different industries. Such a study should then include STI based industries with higher degrees of market standardization.

Another continuation would be to further unpack how collaborator characteristics matter for the creation of the structural couplings that we observe in our study. We identify an aggregate effect of participation in different knowledge networks on international market access, and that collaboration in PDPs matters most. Future studies could investigate whether there are particular types of collaborators that are more useful than others to team up with. Our findings suggest that this would be particularly relevant to explore in the context of PDPs, considering how PDPs can include a large variety of actors with different roles (Mossberg et al., 2018). For R&D projects we have shown that the location of collaborators matter. However, also here other characteristics of collaborators should be further explored.

Finally, future studies could extend our research in at least two directions. We have explored the role of structural couplings between the knowledge and market subsystems in global innovation systems. A first opportunity could be to investigate this relationship through a qualitative case-based approach. This line of inquiry would give detailed insights into the specific mechanisms that our results have indicated. A second opportunity would be to strengthen the conceptualisation of structural couplings by investigating how couplings link other system resources such as financial resources or legitimation. Such an approach could potentially apply similar methods as this study, but would require different data sets and involve different types of actors.

CRediT authorship contribution statement

Maria Tsouri: Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Jens Hanson:** Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Håkon Endresen Normann:** Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, 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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