Firm research, development, and commercialization in the emerging offshore marine energy sector: a mixed method study of the triple helix interactions

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Abstract

A firm's journey through the innovation process is uncertain, non-linear, and impeded by numerous unanticipated challenges. The firm frequently turns to external sources for assistance, and most firms now routinely engage in exploratory or exploitative interactions with external parties. In the developing and emerging offshore marine energy sector in Western Europe, this article explores the significance of triple helix interactions between industry, academia, and government. We use the technological level readiness (TRL) methodology to model the firm's development status and use a mixed method of both quantitative survey data and qualitative interview data. Our objective is firstly to uncover the relationship between the firm's technological development stage (i.e., research, development, and commercialization) and triple helix interactions. And second, to identify what factors induce and limit the formation of the triple helix system in the marine energy sector. University interactions are identified as being important at the early and late stages of the TRL and government interactions are important at the late stages of the TRL. A more complex web of industry-level interactions involving consultants, suppliers, competitors, and customers take place at various stages of the TRL. The interviews provide interesting depth unveiling the mechanisms of action between the helices and the factors currently preventing effective triple helix formation in the marine industry.

Keywords: Innovation; triple helix; industry, university; government.

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Introduction

One of the greatest "grand challenges" facing our society today is the climate crisis (George et al., 2016), which will necessitate significant changes in the political, sociological, and economic spheres of society (Shukla et al., 2019). According to the European Commission's (2020) report, decarbonizing the energy system will be essential to “the transition to a climate neutral economy," and offshore renewable energy (ORE) can contribute *significantly* to the achievement of this goal (Magagna & Uihlein, 2015). However, the ORE sector is still in its infancy, with many technologies still in the research and development stages (Pennock et al., 2022), and ORE devices are now supplying electricity at a cost that is too high in comparison to conventional sources (Magagna & Carlsson, 2020). As a result, there is a need to lower this cost by promoting innovation practices within the ORE sector, utilizing the sector's potential to play a significant role in the energy ecosystem, which will also help to address the grave climate issue (Vanegas-Cantarero et al., 2022).

As a firm tackles the innovation process of R&D, production, and marketing; it sources, uses, and depletes existing and new internal and external resources (Barney, 1991; Kline & Rosenberg, 2009; Roper et al., 2008; Davids and Frenken, 2018). External interactions and an *open* collaborative culture can be integral to a firm’s innovation strategy (Asakawa et al., 2010; Inauen & Schenker-Wicki, 2011). Such interactions have been recognised as key to unlocking the innovation and commercialization potential of the ORE sector (McNatt et al., 2014). The Triple Helix paradigm (Etzkowitz, 2003; Leydesdorff, 2000) which proposes a three-way axis of industry, university, and government working in unison to enhance innovation outcomes, has been used to model external interactions in innovative environments (Etzkowitz & Zhou, 2017) and to maximise knowledge development and commercial application of that knowledge (Benner and Sandström, 2000). In this paper, we attempt to answer two questions: (1) what is the relationship between the firm's technological development stage (i.e., research, development, and commercialization) and triple helix interactions? And (2) what mechanisms induce and limit the formation of the triple helix system in the marine energy sector case?

By answering these questions, we make three substantial contributions to the literature. Firstly, the mechanisms by which enterprises are better equipped to realise innovation-driven activity are informed by Ryan et al. (2018) through the adoption of a microfoundational (Barney and Felin, 2013) perspective on triple helix interactions. However, the theoretical underpinnings of how the firm navigates and exploits triple helix interactions is still under researched. We contribute to the theoretical understanding of these *mechanisms* by explicitly overlapping the triple helix paradigm (Etzkowitz, 2003) with firm level models of innovation (Kline and Rosenberg, 2009; Davids and Frenken, 2018), creating a novel apparatus to examine the dynamics of the innovation system between firm, industry, university, and government. Prior studies of the triple helix system have overly focused on academic activities inside the helix-system, which has resulted in less conceptual attention on the function and role of the firm as a crucial player instigating and limiting triple helix interactions (Ryan et al., 2018; Li et al. 2018). We address this gap in the literature by primarily focusing on triple helix dynamics from the perspective of the firm. Secondly, previous studies have emphasized the positive effects of direct interactions between universities and industry on firms' innovation performance (Lacetera, 2008; Zucker et al., 2002; Johnston & Huggins, 2017), but less focus has been placed on these relationships at the invention level (Anckaert & Peeters 2023). Further, Hannon et al., (2017) highlight that industry–university collaboration and knowledge exchange are weak in the marine energy case. This paper expands the understanding surrounding industry-university collaborations at the invention stage.

Thirdly, we make an empirical contribution by applying this framework to a unique case, involving an emerging sector consisting of many start-ups, mixed with long established incumbent firms, who are seeking to diversify their activities into new markets. More specifically, we answer calls from the literature seeking new insight on triple helix dynamics for renewable energy sectors, with Brink & Madsen (2016, p. 16) for example, calling for “further research… to reveal the long-term potential of the Triple Helix context”, while Guerra (2018: p.28) highlight that further “analysis is necessary to evaluate the position of all… institutions and their interplay within the whole governance system for ORE”.

Finally, by employing a mixed-methods analysis, we make a methodological contribution to both the innovation literature in general and more specifically to the ORE sector. By doing so, the work answers the call for both quantitative and qualitative analysis in research on innovation and the triple helix (Davids & Frenken. 2018; Ryan et al., 2018; Li et al. 2018). Davids & Frenken (2018, p. 32) ask for further endeavours to systematically collect data across various product development stages to evaluate propositions statistically. At the ORE level, Hannon et al., (2017, p. 112) call for “quantitative assessment… complemented by qualitative research” into the UK’s wave and tidal energy innovation system. With its cross-country coverage, the qualitative perspective adopted in this study enables a nuanced understanding and in-depth research into "sector-specific phenomena" as well as incorporating "regional variances" all of which are aspects called for in the literature (Hernández-Trasobares & Murillo-Luna, 2020, p. 9).

The hypotheses presented are tested within an explanatory sequential mixed-methods approach, first drawing on quantitative data collection followed by qualitative analysis. This analysis method, which was once uncommon, is now used more in the literature for exploring hypotheses and propositions more extensively (Cameron, 2009; Creswell & Clark, 2017). Our quantitative study makes use of a thorough and distinctive survey that was specifically designed with the aim of testing the significance of various triple helix actors at various stages of the innovation process. At the empirical stage, we employ Technological Research Level (TRL) methodology (Mankins, 1995) as a proxy for different stages of the innovation process using 202 observations from ORE actors across Europe.

Section 2 presents the theoretical background of the paper and our conceptual framework. Section 3 discusses the quantitative and qualitative data. Section 4 presents the two methodologies employed, and Section 5 provides the results. Section 6 concludes with the key findings, limitations, and suggestions for further research.

2. Theoretical Background

2.1 How the Firm innovates.

To innovate can be an arduous path for a firm to journey. It is often not linear (Kline & Rosenberg, 2009), and product development can run into many unforeseen obstacles (Montani, Odoardi, and Battistelli 2014). Different frameworks have been adopted to explore the innovation process in the business literature such as the chain-link model (Kline & Rosenberg, 2009), the innovation value chain (Hansen & Birkinshaw, 2007; Roper et al., 2008) and the three stage model of Davids & Frenken (2018) Common to each model are the similar journey milestones taken by firms: (1) research stage; (2) product and process development stage; and (3) a commercialization stage.

The resource-based view of the firm (Wernerfelt, 1984) suggests a firm travels the uncertain innovation journey possessing a bundle of resources. Each bundle is distinct and includes resources that may be tangible, like equipment, finance, or intellectual (Maganga & Carlsson, 2020), or intangible, such as their brands reputation (Išoraitė, 2018) or intrinsic social connections (Anderson et al., 2007). To overcome unforeseen obstacles and progress through the stages of the innovation processes, firms may solely exploit knowledge "resources" that lie within the firm. However, if it lacks the requisite capabilities internally, it will be important to engage in an open innovation strategy, where actors find reciprocal benefits in information-sharing and collaboration (Lawson et al., 2009; Huizingh, 2011; Knudsen, 2007), despite any possible hazards provided by openness regarding knowledge leakage (Laursen and Salter, 2014).

The acquisition of this knowledge may vary, as the characteristics of knowledge are quite heterogenous (Davids & Frenken, 2018; Asheim, 2007). Knowledge can be classified as either (1) analytical, which is know-why based and heavily codified, or (2) synthetic, which has more implicit qualities, is know-how based, and frequently used to solve practical problems. Or, it could also be symbolic, which is typically described as highly implicit, "creative, imaginative, and interpretive" (Asheim, 2007, p. 226) and information that is typically applied to a particular cultural context (Asheim et al., 2017). Kline & Rosenberg (2009) treat knowledge as homogenous in their Chain-Linked model but Caraça et al., (2009) expand upon the Chain-Linked model by delving into the content of the knowledge resource by classifying distinct knowledge "pools" (Caraça et al., 2009, p. 864). These pools are scientific knowledge, under the umbrella of analytical and synthetic characteristics, as well as organisational and marketing knowledge, which exhibit synthetic and symbolic characteristics (entirely symbolic in the case of marketing knowledge) (Asheim 2007; Davids & Frenken 2018).

While knowledge is essential, a company also has to gain capital in order to innovate (Kline & Rosenberg, 2009). Grandinetti (2016, p. 23) notes "[o]f all the handicaps, the lack of financial capital is the one most likely to limit high growth". While a firm may initially possess some internal capital, all further finance will come externally, either via investment (from private, government or public services) or from paying customers. The latter will be unavailable at a pre-revenue stage, meaning a strong "financial system" in a country can "foster innovation", by providing the necessary financial capital (Meierrieks, 2014, p. 344). Another important, but often overlooked resource, is a supportive regulatory environment. This is critical in ORE, where a lack of appropriate supporting regulation (such as feed-in tariffs) harms the "bankability" of the tidal sector (Maganga & Carlsson, 2020, p. 30). The regulatory environment comprises part of the wider "politico-institutional environment", that can contribute enormously to successful innovation within countries (Furman et al., 2002; Varsakelis 2006). Davids & Frenken (2018) emphasise that different types of resources will be crucial for enterprises from different players due to altering demands during the research, development, and marketing stages. Many of these resources can be obtained from external sources through collaborations, including the public sector, clients, academic institutions, and government organisations (Davids & Frenken 2018) which brings us to the importance of triple helix interactions.

2.2 The Triple Helix Model

In a knowledge-based society, using external knowledge has become ubiquitous for even the largest innovative firms (Rigby & Zook 2002). Innovations can be assisted via *exploratory* relationships, where there is a reciprocal knowledge transfer between the parties (Borgatti & Halgin, 2011), or even outsourced entirely to a third party when appropriate (Love and Rope,r 2001). The triple helix paradigm of innovation was first developed by Etzkowitz and

Leydesdorff (1995) and describes the relationships between industry, government, and academia in the knowledge economy. They observed changing dynamics in the interactions of helix actors, where businesses were gaining access to knowledge through tentative connections with universities (Etzkowitz & Leydesdorff, 1995). Etzkowitz (1998) described how a university's function evolved and became more corporate with the rise of university technology transfer offices. Businesses began to formalise cooperative relationships with academia to actively tackle their knowledge problems in innovation.

Traditionally, Governments generally had a laissez-faire role in innovation, merely "structuring the legal environment" for knowledge-generating interactions between academia and industry (Etzkowitz, 1994). But Governments started to take a more proactive approach, adding the roles of "public entrepreneur and venture capitalist" (Etzkowitz, 2003: 293), through national laboratories (Kerry & Danson, 2016), establishing science parks (Etzkowitz and Zhou 2017), directly funding academic research (Bloch et al., 2014) and providing innovation grants to firms (Gorg & Strobl, 2007). This added a new dimension to the innovation ecosystem of firms where firms had opportunities to obtain funding (Dimos & Pugh, 2016) and engage with regulation (Blind, 2016) through government actors.

The role each actor plays within the helix is defined by Etzkowitz (2003: p. 295) as "Industry operates in the Triple Helix as the locus of production; government as the source of contractual relations that guarantee stable interactions and exchange; the university as a source of new knowledge and technology, the generative principle of knowledge-based economies." The Triple Helix presents the actors which comprise each helix as being homogenous. However, within each helix there can be significant diversity, especially in industry. Badillo et al., (2017) suggest the broad number of industry interactions that can occur with: "customers and suppliers (vertical cooperation), with firms of the same group (institutional cooperation) or with competitors (horizontal cooperation)". Each type of cooperation can bring different benefits (Bengtsson & Kock, 2014; Davids & Frenken, 2018; Ghanbari et al. 2017). In the renewable energy sector, government can play a wide diversity of roles, not only providing funding (Dimos & Pugh 2016) and setting a regulatory framework (Blind, 2016), but being a direct producer of knowledge through Research Centres, such as the CATAPULT centres in the UK (Kerry & Danson 2016), or even through its own departments (Corrigan et al., 2019). Universities play the narrowest role, creating knowledge, but particularly in the context of ORE, facilities such as tank testing are a major part universities contribute to (Draycott et al., 2019).

2.3 Hypothesis Development

From the discussion in Section 2.1 and 2.2, we can posit that firms need to interact externally to obtain the necessary resources for innovation. These exchanges will take place in the context of the Triple Helix ecosystem, where each helix has unique strengths, while some may compete to supply the same resource, such as industry and academia providing scientific knowledge to firms. Within the context of ORE, we conceptualise a three-stage model of product development (as depicted in Figure 1), analogous to Davids & Frenken's (2018) three stages of Research, Development and Marketing (commercialization). The model proposes that firms are likely to engage in different Triple Helix interactions at different stages of the innovation process depending on the type of resource being sought.

[Figure 1 about here]

2.2.1. Research Stage

At this early stage of research, the market consists of many firms (usually Small and Medium sized Enterprises (SMEs) developing their products, whereby the objective is to produce an innovative product or service (Klepper, 1996). There are many unknowns for a firm at this stage including How will the market evolve? Will competitors pull ahead? Will the idea even succeed? This uncertainty can be particularly acute in ORE, as the wider energy market is particularly volatile due to its reliance on fossil fuels, which can be severely impacted by global geopolitical events (Efimova & Serletis 2014).

SMEs must exploit relationships established outside the organisation to overcome the constraints stemming from their restricted size (Grandinetti, 2016), or as Furlan et al., (2014) outlined "[t]ruly entrepreneurial firms excel on those relational capabilities". The most important input at the research stage is basic (analytical) scientific knowledge, consequently making collaborations with knowledge creators, such as universities or private research institutes the most important external connections at this stage (Davids & Frenken 2018). It can also be beneficial to engage in *coopetition* with competitors (Ritala, 2012) posing a dilemma for firms to decide how to gain as much as possible from their relationships, while minimising potential knowledge leakage of a valuable idea (Furlan et al., 2014). However, coopetition has a greater chance of success in knowledge intensive sectors with high uncertainty (Ritala, 2012), such as ORE.

The primary role for government at this stage is to provide finance. As research is at a pre-revenue stage, external financing may be necessary, and even desirable by providing credibility to the early-stage concept (Islam et al, 2018). However, *direct* interaction with government and an ORE entrepreneur may not occur as the firm may possess *some* internal capital at the commencement of its operations. Also, costs are low in the research stage compared to later stages (Mankins, 1995), and universities may already have funding to collaborate with ORE start-ups in place via boundary spanning consortiums (Champenois and Etzkowitz 2018; SELKIE, 2022), bypassing the need for ORE start-ups to interact directly with government. We pose the following hypothesis:

> H1: Firms operating at the research stage will interact with all actors of the triple helix with a ranking of importance from (1) universities to (2) industry to (3) government

2.2.2 Development Stage

The number of peer firms naturally declines in the development stage, because of rising costs and unrealised potential (Héder, 2017). Strong connections made with key suppliers and partners at the research stage enable continued refinement of the product at the development stage. Though the development stage is not perfectly correlated with commercial readiness (ibid), attaining knowledge around imminent commercialization from other partners is vital. Universities may continue to play a significant role by providing more specialist *applied knowledge* (Asheim, 2007). For example, numerical modelling has emerged as a common service provided by universities in ORE (Blavette et al., 2014; Clarke et al., 2009).

Despite the potential importance of universities and industry at this juncture; the crucial partner at this stage is likely to be government, as firms attempt to traverse what is known as the *valley of death*, where costs increase dramatically for the firm as funding for basic research expires, while the risks remain too high for private investors (Murphy & Edwards, 2003). Liquidity for the firm's survival is often dependent on government funding (Murphy & Edwards, 2003). Interactions around enacting regulation may also be important, as a supportive regulatory environment (e.g. feed-in tariffs) can support green investment (Eyraud et al., 2013). Li et al.,

(2018) highlight that it is crucial for the government to be involved when a sector of the economy is still emerging, performing poorly, or facing market failure. We pose the following hypothesis:

> H2: Firms operating at the development stage will interact with all actors of the helices with a ranking of importance from (1) government to (2) industry to (3) university.

2.2.3 Commercialization Stage:

At this stage, firms will likely possess important, highly developed relationships (Withers et al., 2011). There will be less need for university interaction, as their capabilities, especially basic knowledge creation, are less relevant (Davids & Frenken, 2018). Finance now comes from firms commercial activities or the private sector, so government interactions around capital finance are also reduced, though interactions to ensure a supportive regulatory environment may remain (Magagna & Uihlein, 2015). Instead, the focus lies on interactions with suppliers (Brink & Madsen, 2016) and customers (Brink, 2017). Suppliers will provide feedback on optimising the product's production process to reduce costs, while customers can highlight issues with the operation and desirability of the product. These feedback processes are predicted by Kline and Rosenberg (2009, p. 290) in the feedback loops of the Chain-Linked model. We pose the following hypothesis:

> H3: Industry interaction is important at the commercialization stage.

3.0 Data and Methods

Our research enquiry is based upon sequential explanatory mixed-methods analysis, where our initial quantitative examination is compared against a subsequent qualitative study (Cameron, 2009; Creswell & Clark, 2007). In the first stage of our research, we draw on responses from a purpose-built survey on ORE innovation, to determine of the stage of development matters for the type of interactions with six industry categories, as well as interactions with universities and government. The second data enquiry consists of semi-structured interviews to reveal the motivations and microfoundations behind Triple Helix interactions in the ORE sector. The qualitative results allow an extension of the quantitative findings and demonstrate the underlying nuances of the Triple Helix interactions

3.1 Empirical Setting and Quantitative Dataset

The ORE sector is a suitable sector to explore the potential relationship between the innovation process of firms and the Triple Helix. It is nascent (Pennock et al., 2022), but one that holds much diversity in terms of technologies (Wiersma & Devine-Wright 2014) with firms at various development stages (Appiott et al., 2014). The sector is highly innovative (Wimmler et al., 2015), and there is large university (Lehmann et al., 2017) and government interest in the sector (Böhringer et al., 2017), indicating it is quite appropriate for a Triple Helix enquiry.

For our quantitative study, we draw upon 202 responses from a unique, purpose-built survey for actors in the ORE sector. It was purpose built as ORE firms only comprise a very small sample of existing innovation surveys (such as the Community Innovation Survey) and relying on these samples would distort the true economic activities of ORE firms. The Renewable Energy Innovation Survey (REIS hereafter) was initially conducted in 2021. The REIS asked questions about the firm’s innovation activities, knowledge sourcing activities, networks, resources, and performance for the years 2017 to 2019, and received ethical approval from a research ethics board. Firm activities were not requested for the year 2020, due to the bias that the COVID-19 pandemic would likely have induced.

The survey's sampling frame was compiled from publicly available online ORE supply chain databases (see Appendix A1 for more information on the list of databases). 1,342 firms were included in the sampling frame, which indicates a large increase in the number of firm entries into the sector over the past 5 years (Magagna et al., 2017). The firms were contacted via email, with follow-up calls as necessary. The data collection ended with a total of 227 responses, representing a response rate of 16.4%. Of the 227 responses, once cleaned of errors and omissions, 202 responses could be used for the quantitative analysis in this study.

3.2 Variables of quantitative research

3.2.1 Dependent Variables

Our dependent variables consist of the types of helix interaction that could occur. We use data from a question determining the firm's "innovation co-operation partners". We use six possible industry partners: consultants, suppliers, competitors, clients, customers and enterprises within a firm's enterprise group and Other Enterprises. One partner represents our government indicator: government. University interactions are represented by an interaction by the firm with universities or higher education institutions.

[Table 1 about here]

There are eight dependent variables representing Triple Helix actors. With enormous heterogeneity in industry actors (Badillo et al., 2017) we treat each possible industry actor with equal importance by running six different regressions representing each possible industry type.

3.2.2 Independent Variables representing the innovation process of firms

Three variables represent the technological readiness level (TRL) (i.e. innovation process) status of firms: Early Stage (TRL 1-5), Late Stage TRL (6-9) and Commercialization. The TRL was first initially created by NASA to improve communications around the development of new technologies (Mankins, 2009). The framework has been applied to other fields such as power systems, batteries, AI technologies, recycling technologies and consumer electronics (Olechowski et al., 2015; Andwari et al., 2017; Martínez-Plumed et al., 2021) and the TRL is an official policy tool of the EU (European Commission, 2011). The TRL framework provides nine levels of technological development (Table 2) ranging from "basic [scientific] principles observed" to "actual system proven in operational environment" (European Commission, 2014). The TRL framework is often applied to engineering contexts (Olechowski et al. 2020) and is consequently appropriate for application in the ORE sector (Lehmann et al., 2017).

[Table 2 about here]

In REIS, firms were asked to consider their involvement in several energy sectors (e.g. wave, tidal, ocean thermal energy, salinity gradient energy, floating offshore wind and offshore wind). Firms were asked if they were involved in the specific sector Yes or No, and to indicate one of four TRL or commercial levels of involvement in each sector: Early R&D Phase (TRL 1-5), Demonstration Phase (TRL 6-9), Early Sales or Established Sales. We categorise TRL 1-5 responses to be the research stage, TRL 6-9 responses to the development stage and early sales or established sales to the commercialization stage aligning to the theoretical framework in Figure 1.

3.2.3 Control Variables

Several control variables are included to account for the heterogeneities within the sector. We control for firm size and age, as larger firms can influence firm openness (Drechsler & Natter, 2012), while older firms can potentially accumulate more knowledge and experience from previous innovation (Pellegrino & Piva, 2020; Levitt & March, 1988). The education level of employees is often treated as a proxy for human capital and is thus also included (Čadil et al., 2014). Multi-plant firms may possess unique learning advantages over single-plant firms (Dibella et al., 1996) and public funding can stimulate both upstream (with university and research institutions) and downstream (with other firms) interactions (Kang & Park 2012) We also include country dummies to account for cultural and regulatory differences across jurisdictions. 50% of respondents are based in the UK and 30% from Ireland, with the remaining 20% from Europe.

3.3 Quantitative Method

The model used in this paper is a probit model, used to determine the probability of an industry, university, or government interactions. This model is chosen due the binary nature of each dependent variable and is specified as follows:

$$TH_{ih} = \beta_0 + \beta_1 EarlyTRL_{ih} + \beta_2 LateTRL_{ih} + \beta_3\ Commercialisation_{ih} + \beta_k Z_{ih} + \varepsilon_i \qquad (1)$$

TH represents the dependent variable of firm *i*'s collaborative activity with other firms, with *h* specifying the type of interaction: consultants, suppliers, competitors, clients and customers, enterprises within a firm's enterprise group, as well as university and government interactions. *EarlyTRL* represents firm *i* activity in an ORE sector between TRL 1-5, *LateTRL* represents if firm *i* is active in an ORE sector at the TRL 6-9 and *Commercialization* represents if firm *i* is active in an ORE sector at the commercialization stage. Z_i represents the control variables which include firm age, multiplant firm, firm size, receipt of government subsidies and where the respondents firm is located. The equations were estimated using cluster standard errors by firm type as the TRL stage the firm is operating at and their potential collaborations are likely to be determined by firm type; meaning academic, consultancy, marine operations or developer firm errors are not likely to be independently distributed.

3.4 Qualitative Method

While the quantitative study reveals which Triple Helix actors are important at different innovation stages, we conducted a qualitative analysis to help us answer our second research question which is – what mechanisms induce and limit the formation of the triple helix system in the marine energy sector case? We employed semi-structured interviews to understand the perceptions of industry actors in terms of these mechanisms. Following the second stage of the REIS survey rollout, we invited interview participants to engage in the qualitative study. These participants held leadership positions within ORE organisations. Further interview participants were sourced through recommendations from interviewees after interviews, and others were sourced through their membership in the Selkie cross-border Ireland-Wales consortium network of marine energy firms and supply chain companies.

Initial contact was made by telephone, followed by an email clearly stating the study objectives. In total, we have interview data from ten firms. The interviews followed a semi-structured format (See Appendix B of supplemental documentation) and began with a discussion about the candidate's background, their experience and knowledge followed by a deep dive into their organisation's innovation activities. The remainder of the interview focused on their Triple Helix interactions, concluding with questions around finance, societal interaction, and an open-ended question about the future.

4.0 Results and Discussion

4.1 Quantitative Findings and Discussion

Table 3 displays the regression output from the model, reporting marginal effects. At the early TRL 1-5 (research stage), four external interactions are significant. The industry interactions of consultants, competitors, enterprises within their own group are positive and statistically significant here. The results on industry actors underlines the value of external knowledge sourcing at early stages of development. At this stage, it is assumed firms are keen to learn through their external interaction – consultants can aid with business planning; competitors can aid through co-opetition opportunities; and enterprises within their group can share relevant knowledge and services. University interaction is also relevant at this stage, whereby the application of basic knowledge is at its most important, including for example the provision of fundamental 'tank-testing' facilities for early scale model development. However, using seemingly unrelated estimation, a ranking of importance (i.e. comparing coefficients across interaction regressions) is not detected, indicating that industry interactions with consultants, competitors and industry grouping firms are as likely, as university interactions at this stage. Consequently, we find partial support for H1 where firms operating at the research stage are significantly likely to interact with universities and industry actors. But contrary to our expectations, firms are not significantly likely to interact with government and there is no ranking of importance across the triple helix actors at this stage.

[Table 3 about here]

Like at the early TRL stage, consultants are important at the late TRL stage. It is not difficult to rationalise why this may be the case. For instance, when businesses approach the commercialization of device(s), specialised consultants can help businesses with the complexity of the devices as well as with navigating the onerous regulatory environment. Firms in the late TRL stage again are significantly likely to interact with universities. This is understandable given that university agents can aid businesses with knowledge application beyond providing basic scientific understanding, such as by numerically modelling a device's performance in the ocean. Firms in the late TRL stage are also significantly more likely to interact with government. Costs will considerably increase as a company scales the TRL, thus government financial assistance is necessary at the development stage to cross the funding gap and avoid the valley of death (Ellwood et al., 2022). Interactions with government are also important to set in place the appropriate regulation to allow firms to test their devices in the natural environment (Ramos et al., 2021). Once more, our findings point to partial support for H2. Companies in the development stage will interact with actors from all the helices, but, as with H1, we find that there is no hierarchy of importance for interaction types at the development stage using the seemingly unrelated regression technique.

At commercialization stage, the volume of significant interactions is at its lowest. Customers become important, as well as interactions with enterprises in the same industry and other enterprises. These are not surprising results as good relationships with other enterprises enable cost reductions through economies of scale (Badorf et al., 2019) and feedback from clients and customers naturally become important for even ORE developers as they now generate (at least a portion of) their financial resources through selling the products they have developed (West & Bogers, 2014). At this stage, university and government interactions were not hypothesised as important and our results support this contention. Interactions may still occur with these helices, but the inputs they provide such as scientific knowledge and (public) funding respectively are no longer as essential to the firm as before and so the intensity of interactions and their significance drops. In all, the results provide support for H3 as the interactions with industry actors are important at the commercialization stage.

4.2 Qualitative Findings and Discussion

In-depth explanatory insights (Creswell & Clark, 2007) are added to the quantitative results by the qualitative follow-up study, which analyses ten interviews from the ORE technology developer perspective. Four detailed cases studies are presented in the supplemental documentation for interested readers (Appendix D) and Appendix E presents a summary table of interviews with a short synopsis of key interactions, purpose, challenges, and quotes for each firm. Table 4 outlines a summary of emerging themes from the developer interviews.

[Table 4 about here]

ORE developers stated that they interact with other industry actors to obtain diversified and tacit knowledge, but that engagement is challenged by information asymmetry problems. For example, other non-developer companies might not be aware of the difficulties involved in creating components for the ORE sector, or at the same time ORE developers might not be aware of the actual capabilities possessed by other companies to assist them in achieving their goals. The size of the company an actor worked with can also have an impact with larger companies described as being less flexible, when contrasted with SME developers which were described as ‘nimbler’.

Working with academia provided a far more standard set of benefits and interactions, and engagement with universities was abundant among innovating actors. The primary advantage of interactions with higher education institutes is the access to critical knowledge that does not lie within the company, such as knowledge gleaned through tank-testing and numerical modelling. University interactions were also useful for firms seeking to source interns and students who could work on behalf of the company. However, there was also a far more standard set of barriers and challenges from working with universities. Many firms referred to the academic term timelines that universities work around as rigid, with universities benefitting from less pressure, which is in stark contrast to how industry needs to operate. Another problem noted with university interactions is the inherent conflict between the differing objectives of industry and academia, with academics focused on getting grants and publishing papers, whereas industry actors are looking to identify engineering solutions as quickly as possible.

This led to some actors noting the need for quite strict oversight of their academic interactions to ensure that university actors stayed on task.

Industry actors highlighted the necessity of government for providing finance, particularly as industry actors highlighted problems around obtaining private funding due to the risky, high-cost stage the sector is at. Regulatory matters and bureaucracy proved to be an issue with government interactions. One industry interviewee described the bureaucracy as “hard, complicated, and difficult to overcome”. The speed at which things were completed in government was also a common observation with industry noting lack of deadlines, long durations in getting replies with repetitive questioning. The final common issue was industry actors were dispirited by a lack of support for and understanding of wave and tidal energy amongst government actors.

5. Conclusion and Implications

In this paper, we provide a nuanced understanding of the role of triple helix interactions for firms at different stages of development within the ORE sector. Also, we identify the mechanisms that induce and limit the development of a triple helix system in the marine energy case. We do this by using a mixed method approach, by first, exploiting quantitative data from 202 marine energy firms and second, by taking a deep dive into the triple helix dynamics, from the industry perspective, using data from ten industry interviews.

5.1 Theoretical Implications

By fusing firm level models of innovation with the triple helix paradigm, we fill a gap in the theoretical literature concerning how firms navigate and take advantage of triple helix interactions. We further respond to the calls for more research from Brink & Madsen (2016)

(2016) and Guerra (2018) into the long-term potential of the Triple Helix context in renewable energy systems and in doing so we also answer the call for both quantitative and qualitative analysis on firm level innovation activities (Davids & Frenken, 2018; Ryan et al., 2018). When employing a firm level theoretical lens, we discover significant triple helix interactions in the ORE sector. We identify interactions with universities as being important at the early research and late development stages of the innovation process, while interactions with government are important only at the late development stage of the innovation process. Industry-level interactions involving consultants, suppliers, competitors, and customers take place at various stages of the innovation process, and into full commercialization. However, our analysis reveals that a hierarchy of actor importance does not currently exist at any stage of the innovation process in ORE and there are also several challenges in the proper functioning of the ORE triple helix system as revealed by the qualitative analysis.

5.2 *University-Business-Policy Implications*

There are lessons for all actors to promote an enhanced triple helix system in ORE. First, our qualitative analysis reveals that the industry suffers from many information asymmetry problems making interacting with other industry actors cumbersome and uncertain for ORE developers. Overcoming these bottlenecks will involve continued development and deepening of networking relations and improved coordination systems. Here, boundary spanners are likely to play a critical role in acting as platforms and anchors of coordination, between the helices in the regional renewable energy innovation system (Champenois and Etzkowitz 2018). Second, universities play a critical and important role in knowledge generation, but contrary to original posits of the university as a flexible and capacious organisation (Etzkowitz, 2000, 2001); industry interviewees criticised rigid university semesters and academic incentives that prioritise publication over making an industry impact. They highlighted these issues as barriers inhibiting more fruitful industry-university collaborations. This again points to information asymmetries which could impede investment in the sector, as there are significant gaps between what the innovator knows and what an external actor can gauge. For some time, there has been broad agreement across many political jurisdictions that funding commitments and a secure policy and planning environment is required to drive technological investment and commercialization in the sector (O'Keeffe & Haggett 2012; Wieczorek et al., 2013; Qiu & Jones 2013). Yet, our analysis indicates that industry actors continue to experience uncertainty in these domains which will likely inhibit investor confidence in the short and long run.

5.3 Limitations and Future Research

Future research should expand examining technological development in ORE by using a Quadruple Helix model. Early indications from our quantitative and qualitative data suggest that the public and media have a significant role to play in its innovation. Due to the sample size, the ORE sector was studied as a whole, rather than per ORE type in this work (i.e., offshore wind versus tidal). To discover the dynamics of the triple helix, in various ORE types, future studies could seek to conduct specific ORE type research. This would allow for more precise policy guidance for various ORE sources.

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Figure 1: ORE Knowledge Ecosystem

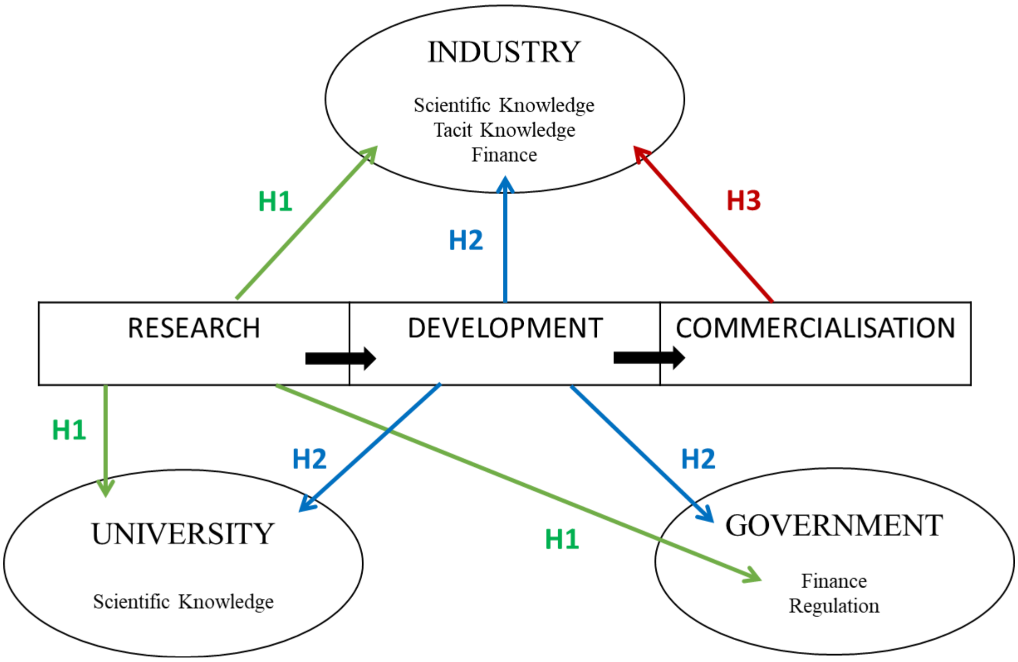

Table 1: Definitions of the Main Variables

Variable Name	Definition	Mean	SD
Dependent Variables			
Consultants	This variable is a binary variable coded 1 if a respondent has indicated they have interactions with consultants, commercial labs, or private research institutions, and 0 otherwise.	41.58	49.41
Suppliers	This variable is a binary variable coded 1 if a respondent has indicated they have interactions with Suppliers of equipment, materials, components, or software, and 0 otherwise.	40.09	49.13
Competitors	This variable is a binary variable coded 1 if a respondent has indicated they have interactions with Enterprises that are competitors, and 0 otherwise.	21.78	41.37
Other Enterprises	This variable is a binary variable coded 1 if a respondent has indicated they have interactions with other enterprises, and 0 otherwise.	24.25	42.97
Enterprises within group	This variable is a binary variable coded 1 if a respondent has indicated they have interactions with enterprises within their enterprise group, and 0 otherwise.	23.76	42.66
Customers	This variable is a binary variable coded 1 if a respondent has indicated they have interactions with clients or customers from the private sector, and 0 otherwise.	39.10	48.92
University Interaction	This variable is a binary variable coded 1 if a respondent has indicated they have interactions with university partners, and 0 otherwise.	47.52	50.06
Government Interaction	This variable is a binary variable coded 1 if a respondent has indicated they have interactions with government partners, and 0 otherwise.	29.21	45.58
Independent Variables			
Early Stage (TRL1-5)	Representing the Research Stage, this variable is a binary variable coded 1 if a respondent has indicated they are involved at TRL stage 1 to 5 in an ORE Sector, and 0 otherwise.	35.14	47.86
Late Stage (TRL 6-9)	Representing the Development Stage, this variable is a binary variable coded 1 if a respondent has indicated they are involved at TRL stage 6 to 9 in an ORE Sector, and 0 otherwise.	29.7	45.8
Commercialization	Representing the Commercialization Stage, this variable is a binary variable coded 1 if a respondent has indicated they are involved at either early sales or established Sales in an ORE Sector and 0 otherwise.	28.21	45.11
Public Funding	A binary variable which takes the value of 1 where an organisation has received public financial support for acquiring knowledge or innovation activities from one of or a combination of local government, regional government, national government, European level government during the years 2017-2019, 0 otherwise.	46.53	50.00
Multi-Plant	A binary variable coded 1 if a respondent has indicated they have operations in more than one premises, 0 otherwise	44.05	49.76
Firm Age	The natural log of the Firm's Age, a continuous variable which is calculated by subtracting the year the firm was established from the final year in which the data was collected (2022).	2.34	1.93
3rd Level %	The percentage of the organisation's employees who have obtained a third level qualification (i.e., University, College, HEI).	68.31	34.34
Employees 2019	The natural log of the number of employees reported in 2019.	2.34	1.93
UK	This variable is a binary variable coded 1 if the company is based in the United Kingdom, 0 otherwise	50.49	50.12
Ireland	This variable is a binary variable coded 1 if the company is based in the Republic of Ireland, 0 otherwise	30.19	46.02
Europe	This variable is a binary variable coded 1 if the company is based outside the UK or the Republic of Ireland, 0 otherwise	19.30	39.56
Asset Owner/Operator	This variable is a binary variable coded 1 if the company is classed as an Asset Owner/Operator, 0 otherwise	7.62	26.59
Project Developer	This variable is a binary variable coded 1 if the company is classed as a Project Developer, 0 otherwise	10.0	30.07
Technology Supplier	This variable is a binary variable coded 1 if the company is classed as a Technology Supplier, 0 otherwise	36.19	48.16

Service or consultancy	This variable is a binary variable coded 1 if the company is classed as a Asset Service or Consultancy, 0 otherwise	43.81	49.73
Other	This variable is a binary variable coded 1 if the company is classed as an Other type firm, 0 otherwise	2.38	15.28

Table 2: The EU's Horizon 2020 Nine Technological Readiness Levels

TRL	Definition
1	Basic principles observed and reported
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

Source: European Commission (2014)

Table 3: Regression Results

VARIABLES	(1) Consultants	(2) Suppliers	(3) Competitors	(4) Other enterprises	(5) Enterprises within group	(6) Private customers	(7) Universities	(8) Government
Early Stage TRL/research	0.147***	0.024	0.078**	0.046	0.064***	-0.066	0.160**	0.063
	(0.040)	(0.023)	(0.039)	(0.065)	(0.014)	(0.052)	(0.066)	(0.048)
Late Stage TRL/development	0.101**	0.161*	0.000	0.053*	-0.015	0.0425	0.153**	0.149**
	(0.040)	(0.086)	(0.088)	(0.031)	(0.044)	(0.065)	(0.076)	(0.060)
Commercialization Stage	0.091	0.132	0.069	0.142***	0.182**	0.353***	0.068	0.027
	(0.071)	(0.086)	(0.146)	(0.039)	(0.073)	(0.101)	(0.056)	(0.068)
Log of Firm Size	0.006	0.031	0.025***	-0.000	0.007	0.002	0.010	0.036***
	(0.025)	(0.025)	(0.008)	(0.008)	(0.009)	(0.017)	(0.019)	(0.011)
Log of Firm Age	-0.025	0.023	-0.011	0.021	0.012	0.006	-0.041	-0.062**
	(0.028)	(0.031)	(0.021)	(0.036)	(0.014)	(0.031)	(0.031)	(0.027)
Education (% Third Level)	0.002***	0.001*	0.001*	0.000	-0.002*	0.002***	0.000	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Multiplant Firm	0.159**	0.052	0.084**	0.000	0.190**	0.147	0.265***	0.099
	(0.072)	(0.049)	(0.033)	(0.067)	(0.089)	(0.092)	(0.082)	(0.072)
Receipt of Public Funding	0.267***	0.173***	0.118**	0.0620	0.081**	0.135**	0.358***	0.196***
	(0.041)	(0.066)	(0.050)	(0.048)	(0.036)	(0.053)	(0.046)	(0.049)
Ireland	-0.139**	-0.192**	-0.104**	-0.175*	0.018	0.036	-0.048	-0.102
	(0.058)	(0.096)	(0.046)	(0.092)	(0.055)	(0.142)	(0.101)	(0.085)
United Kingdom	-0.043	-0.103**	0.003	-0.023	0.071**	0.216**	0.031	-0.039
	(0.090)	(0.049)	(0.083)	(0.083)	(0.034)	(0.105)	(0.068)	(0.108)
Observations	202	202	202	202	202	202	202	202
R-Squared	0.1544	0.1119	0.0910	0.0808	0.1247	0.1420	0.2096	0.1441
Prob>Chi2	0.000	0.000	0.0369	0.0536	0.002	0.000	0.000	0.000

Notes: Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Reference Categories: Europe
Model controls for intragroup firm type clustering by categories in summary table

Table 4: Summary of emerging themes from qualitative data

Actor/Issue	**Industry about industry**	**Industry about University**	**Industry about Government**
Why do firms interact with triple helix actors?	Industry interaction is crucial to obtain diversified and tacit knowledge	Critical knowledge provided to solve industry needs	Government is critical for providing finance and regulatory guidance and support
Challenges in the sector	Information asymmetry is a key problem between industry actors	Misaligned timelines between university and industry actors	There is a lack of belief in viability of certain ORE sectors
	Firm size impacts flexibility in responding to firm needs	Differing objectives between university and industry	Bureaucracy is a key issue in some national contexts