Renewable and Sustainable Energy Reviews 66 (2016) 286–296

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Market strategies for offshore wind in Europe: A development and diffusion perspective

João Gorenstein Dedecca*, Rudi A. Hakvoort, J. Roland Ortt

Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628BX Delft, The Netherlands

A R T I C L E I N F O

Article history:
Received 23 March 2016
Received in revised form
20 July 2016
Accepted 3 August 2016

Keywords:
Barriers
Cooperation
Development and diffusion
Innovation
Market strategies
Offshore wind

A B S T R A C T

Offshore wind will contribute to the decarbonization of European power systems, but is currently costlier than many other generation technologies. We assess the adequacy of market strategies available to private actors developing offshore wind farms in Europe, by employing the development and diffusion pattern model. The model includes two earlier phases in addition to the large-scale deployment phase of other diffusion models: the innovation and the market adaptation phases. During its development and diffusion offshore wind moved from experimentation to a dominant design (monopile foundations and a permanent magnet generator). Simultaneously, wind farms shifted from an experimental to a commercial purpose and grew from 10 to 316 MW on average. The turbine and wind farm development markets kept a high concentration throughout all phases. Also, the wind farm life cycle and supply chain became more integrated and drew less from the onshore wind and oil & gas sectors.

This development and diffusion was shaped by the barriers of cost, project risk and complexity, capital requirements, and multi-disciplinarity. Wind farms developers combined three niche strategies to address these barriers: the subsidized, the geographic, and the demo, experiment and develop. The barriers make these niche strategies more adequate than strategies of mass-market (dominating a market) or wait-and-see (developing resources but waiting for uncertainty reduction before market entrance). Nonetheless, the barriers and market strategies changed during the development and diffusion pattern. Thus, cost and risk reductions decreased the importance of the subsidized niche, while the geographic niche becomes less important as offshore wind develops outside of Europe.

The study also identified an increase in cooperation for wind farm development, as development became more international and with more frequent alliances. Wind farm developers and development and diffusion models research must consider how contemporary forms of cooperation improve or hinder the market strategies.

Contents

1. Introduction . . . 287
 1.1. Offshore wind technology and actors . . . 287
 1.2. The cost of offshore wind power . . . 288
2. Theory and methodology . . . 289
 2.1. The development and diffusion pattern . . . 289
  2.1.1. The pattern for offshore wind . . . 290
 2.2. Methodology . . . 290
  2.2.1. Market strategies . . . 291
3. Results . . . 291
 3.1. Development and diffusion pattern and offshore wind barriers . . . 291
  3.1.1. Innovation phase . . . 292

Abbreviations: CR_2, concentration ratio for the two largest companies in the market; EPCI, Engineer-Procure-Construct-Install; LCoE, levelized cost of energy; MWh, megawatt-hour; O&G, oil & gas; O&M, operation and maintenance; PMG, permanent magnet generator

* Corresponding author.
E-mail addresses: j.dedecca@tudelft.nl, jdedecca@gmail.com (J.G. Dedecca).

http://dx.doi.org/10.1016/j.rser.2016.08.007

3.1.2. Market adaptation phase . . . 293
3.1.3. Market stabilization phase . . . 293
3.1.4. Offshore wind barriers and the development and diffusion pattern . . . 294
3.2. Market strategies . . . 294
4. Conclusions . . . 295
Acknowledgments . . . 295
References . . . 295

1. Introduction

Our paper aims to analyze different market strategies available to private actors developing offshore wind farms in Europe. These market strategies are the decisions of when and how to participate in the offshore wind farms. To achieve this goal, we apply the development and diffusion pattern model to offshore wind for the first time. The model analyzes offshore wind considering an erratic, non-continuous historical development and diffusion of the technology, separated into three different phases [1]. The results allow us to define the barriers to offshore wind power technology that affect the market strategies of private wind farm developers.

The European Union has set ambitious targets for the reduction of greenhouse gases emissions of the power sector: a 40% reduction by 2030 (compared to 1990 levels) and a complete decarbonization of the sector by 2050 [2,3]. Offshore wind is a low-carbon technology, and studies consequently predict a significant deployment which will contribute strongly to the European Union's decarbonization goals [4,5]. However, offshore wind is young when compared to onshore wind or conventional generation technologies, as it was only 25 years ago that the first offshore wind turbine in the world was installed in Sweden [6]. In 2015 wind power represented 11,4% of the total European power consumption, however offshore wind accounted for only 1,5% of this total consumption while onshore wind responded for the remaining 9,9% [7]. Nonetheless, estimates forecast that offshore wind may represent up to 15% of total power consumption by 2050 [5]. At the end of 2015 the European cumulative offshore wind installed capacity was 11 GW, or 1% of the total European net generating capacity [8,9]. But yet again, offshore capacity may range from 42 to 122 GW by 2030 – up to ten times the current figure [10]. The current modesty of offshore wind is also reflected in the annual installations: in 2015 3,4 GW of offshore wind were installed worldwide, only 5,4% of the global (onshore and offshore) wind power installations [11].

Since offshore wind is poised for important future growth, a number of recent studies target it. These use the viewpoints of technological innovation systems [12–14], technical and/or economic analysis [15–19], market structure [20,21], actor analysis [22], life cycle analysis [23], or a combination of the above, possibly also addressing regulatory issues [24–27]. However, none of them applied the development and diffusion pattern in their analysis. Our methodology has three steps: application of the development and diffusion pattern, definition of the barriers to offshore wind, and analysis of their impact on the market strategies of project developers. As the first application of the development and diffusion pattern to offshore wind, our work complements the aforementioned studies and simultaneously provides recommendations to project developers. Therefore, it is of interest to developers, companies innovating in offshore wind, and to policymakers who intend to guide this innovation. Also, we contribute to case study literature on the development and diffusion pattern.

This article is structured as follows. First, we conduct a review of offshore wind technology and of its cost. Next, the development and diffusion pattern is explained in Section 2, followed by the methodology comprising the offshore wind barriers and market strategies. Section 3 presents the results of the offshore wind pattern, barriers and market strategies. We then conclude on Section 4 on these three elements.

1.1. Offshore wind technology and actors

To understand the pattern of development and diffusion, we first briefly present the advantages and disadvantages of offshore wind, as well as the components, life cycle phases and actors of an offshore wind farm. Both onshore and offshore wind power are intermittent, meaning they are variable (changing uncontrollably in time) and uncertain (wind forecasts contain an error component). Offshore wind also competes with other economic activities such as shipping and fishing, and costs increase with water depths and distance from shore, as the near-shore potential is exploited [4]. Finally, offshore wind farms face harsher environmental conditions than onshore wind, and accessing the turbines for operation & maintenance is also more difficult. On the other hand, the offshore wind in Northern Europe has higher mean speeds and is less variable than the onshore wind, which results in higher full load hours (i.e. the equivalent time the wind turbine is generating at its full capacity) [28]. Also worth noting is that offshore wind farms currently face less socio-environmental barriers, which reduces design constraints and facilitates their implementation. Moreover, many European offshore projects can be built close to consumption centers [15,28].

Fig. 1 presents the main components of a horizontal axis offshore wind turbine. These are the rotor-nacelle assembly, the tower, the transition piece and the support structure. The rotor comprises the blades, which capture the wind mechanical energy, and the hub, which transmits it to the drive train. The drive train, located in the nacelle, is composed of gearboxes, the generator group, and the power converter, and transforms the mechanical energy to electrical energy. The gearbox and/or power converter are optional and depend on the drive train configuration. The generated power is transmitted down the turbine tower. As the name indicates, the support structure fixates the turbine on the seabed through different foundation technologies, and is usually connected to the tower by a transition piece. Other terminologies than the one used here can be found, such as in DNV [29].

It is then necessary to transmit the power generated onshore. For this, the collection system connects all turbines of a wind farm to an offshore substation. The wind turbines, the collection system and the substation constitute the offshore wind farm. The transmission system then links the offshore substation to the onshore power system (Fig. 2) [30,31]. In an offshore wind farm, items other than the turbines can account for 60% of total costs, against 30% for onshore farms. This is because the foundations and the collection and transmission systems are more expensive and complex, as is the farm installation, operation & maintenance and capital costs [21,32].

The life cycle of an offshore wind farm has several phases as shown in Fig. 3 with the main private actors involved in each phase [23,33]. Despite the apparent linearity, the different phases influence each other. For example, the use of gearless drive trains

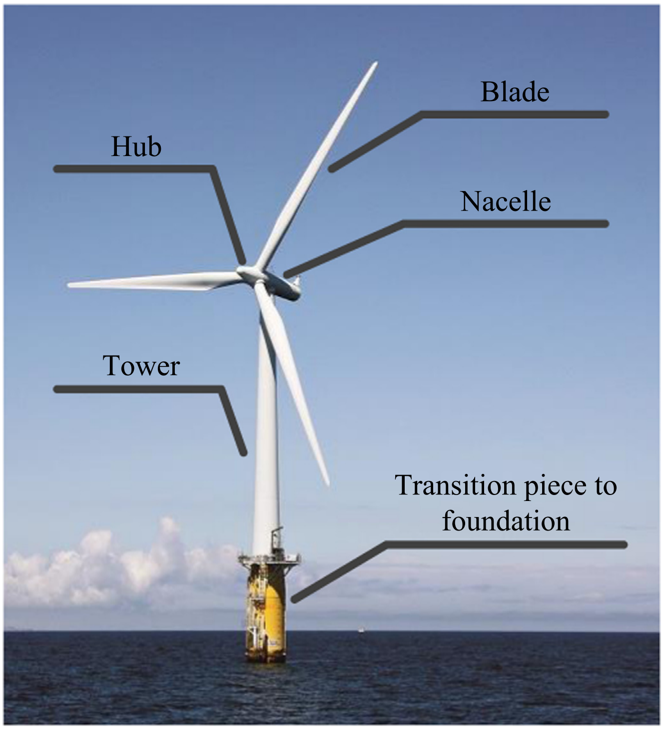

Fig. 1. An offshore wind turbine.

increases the manufacturing costs of the wind turbine, but reduces the operation & maintenance costs later on.

Project developers initiate the wind farm development, ordering the first surveys and conducting the preliminary wind farm design. Wind turbine manufacturers are responsible for the design and manufacturing of that component. Nonetheless, they can act further in the farm life cycle, and may install, operate and maintain the wind farm [34]. Then, engineering companies, contractors and manufacturers of other components are active from the wind farm design & manufacturing to the decommissioning. As such they provide services beyond the design, manufacturing and installation, e.g. dredging and surveys [33].

Beyond these private actors, governments and other public actors are crucial to offshore wind, leading the planning process for offshore wind farms and providing support mechanisms to offshore wind. The planning may involve defining the maritime spatial planning with the allowed wind farm locations and

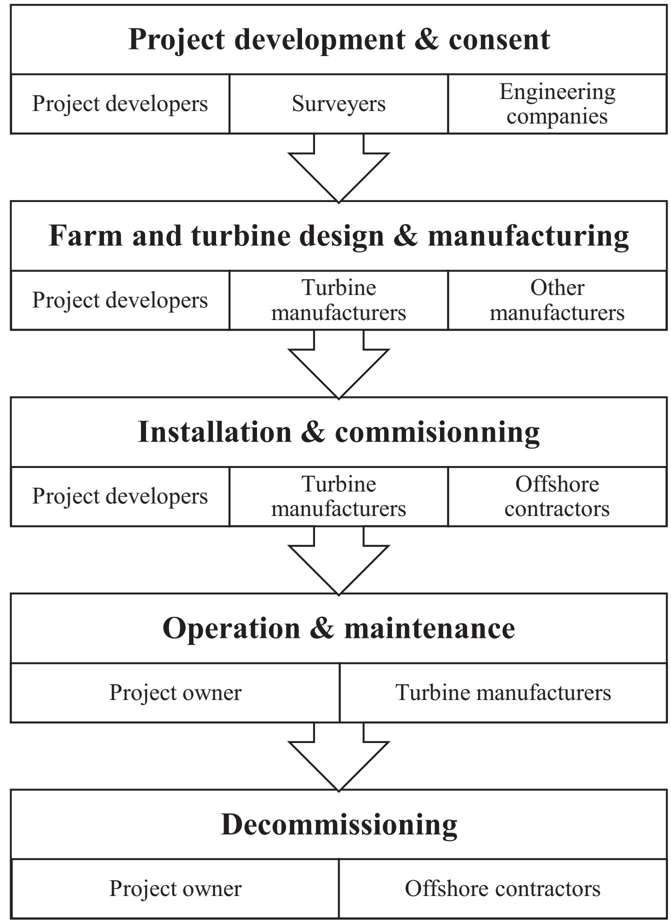

Fig. 3. Offshore wind farm life cycle and main private actors.

obtaining the environmental or other necessary permits. There is currently a convergence towards this model with governments planning and pre-permitting offshore sites, and then using competitive auctions to allocate them, supporting offshore wind with premiums paid on top of wholesale power market prices [35].

1.2. *The cost of offshore wind power*

The disadvantages of offshore wind indicated in section 1.1 currently make it more expensive than onshore wind and other

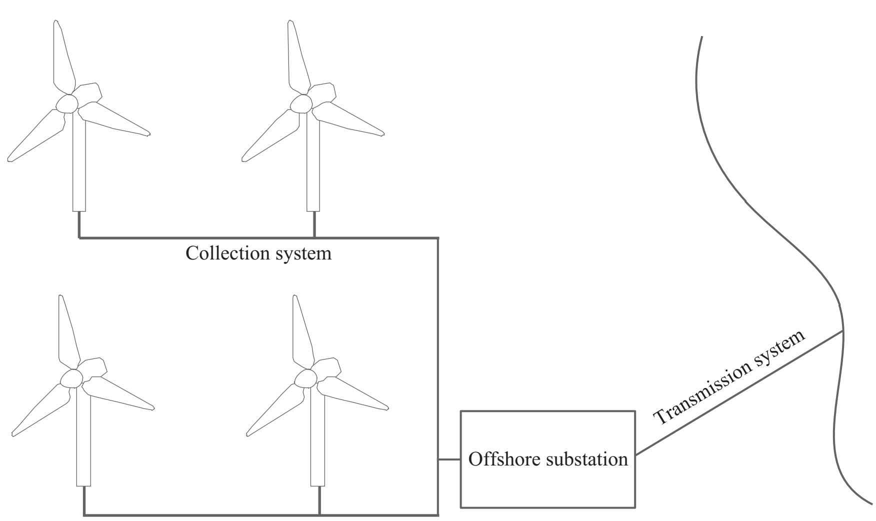

Fig. 2. Conceptual offshore wind farm.

conventional power generation technologies [20]. As seen, public actors play a central role by planning, pre-permitting and supporting wind farms, thus providing long-term signals to private actors. These private actors are on their turn the main parties responsible for achieving cost reductions for offshore wind. Therefore, the current costs of offshore wind interact with the signals provided by the public actors and the cost-reduction actions undertaken by the private actors. As such, the cost of offshore wind power is pivotal for analyzing the technology development and diffusion, and the implications for the market strategies.

The most widely used indicator to compare electricity costs is the levelized cost of energy (LCoE), which gives the present average unit cost of electricity for a certain generation technology. While it has disadvantages, such as input uncertainty and the inconsideration of system costs, the LCoE is still one of the most adequate cost indicators for comparing different generation technologies [36]. Studies analyzing the current and expected levelized costs of offshore wind include [23,24,32,37–43]. The current LCoE estimates for offshore wind fluctuates between 120 and 340 US $/MWh as Fig. 4 indicates (Table 1 presents the data). By comparison, the current range for conventional fossil fuel technologies of the LCoE studies is 38–140 US$/MWh [32,44]. For 2025 forecasts predict a cost reduction to the 90–203 US$/MWh range. The estimates illustrates how inputs and assumptions such as site location or full load hours of different technologies can cause variations in the LCoE, as reviewed by Thomson and Harrison [23].

The review of the LCoE forecasts indicates that offshore wind will remain costlier than conventional technologies up to 2030. However, the costs of offshore wind and conventional technologies do overlap in part of the LCoE range. The competitiveness of offshore wind varies with local conditions and factors such as carbon prices and the cost of capital, and hence while on average offshore wind will remain more expensive, specific projects may be competitive with conventional technologies.

Recently a number of supply chain actors committed to achieving significant reductions to the cost of offshore wind. In the UK the offshore wind industry pledged to an LCoE of 156 US $/MWh for projects reaching a final investment decision in 2020 [46]. In the Netherlands the commitment is for a 40% reduction in the same year relative to 2010, which translates to a target of 133 US$/MWh [40]. This caused leading private actors in offshore wind to affirm that “offshore wind will be fully competitive with new conventional power generation” by 2025 [47]. In the UK the actions with the greatest cost reduction potential are the upscaling of wind turbines rating, increasing competition within the industry for turbine manufacturing, and reducing the cost of equity [41]. These three actions account for 30% of the cost reduction potential. In the Netherlands the main cost reduction actions largely agree with the British ones, with the addition of vertical cooperation across the supply chain and reducing the cost of debt, accounting in total for 27,8% of the cost reduction potential [40]. Many other actions compose the remaining 70–72% of the identified cost reduction opportunities.

2. Theory and methodology

Studies of offshore wind innovation use different viewpoint to analyze the technology, as shown in section 1 [12–27]. For example Sovacool and Enevoldsen [25] present innovation challenges to then analyze intrafirm innovation approaches. Wieczorek et al. [13] use the technology innovation systems to study the offshore wind in four European countries. Also, in a previous article some of the authors propose to analyze innovation not only according to system functions, but also following structural dimensions [48]. Finally, Jacobsson and Karltorp [12] separate the functions of technological innovation systems among strong and weak ones. Despite these various studies, to the best knowledge of the authors the development and diffusion pattern of Ortt and Schoormans [1] has not yet been applied to offshore wind. We hence present the pattern and then the methodology to analyze offshore wind barriers and market strategies.

2.1. The development and diffusion pattern

As indicated by Tidd [49], the S-shaped diffusion curve established by the seminal work of Rogers [50] constitutes the most frequently used model for the diffusion of innovations. This S-curve indicates the total cumulative number of adopters of a given innovation over time (Fig. 5).

Subsequently, research on innovation led to alternative innovation and diffusion models and further development of the S-curve model itself. Ortt and Schoormans [1] present a model for understanding patterns of development and diffusion of breakthrough technologies in the communications sector. The authors argue that while at first sight the classical S- curve fits the diffusion pattern, the innovation and diffusion process actually includes at least two earlier phases. These are referred to as the innovation and the market adaptation phases, which combine with the subsequent market stabilization phase (the S-curve). After analyzing 50 cases of radically new high-tech products, the authors show that a similar multi-phase pattern of development and diffusion can be witnessed in several industries. The model claims that after invention it often takes several years before the crude and immature principle demonstrated at the time of invention can be introduced as a product in the market. Furthermore, often after

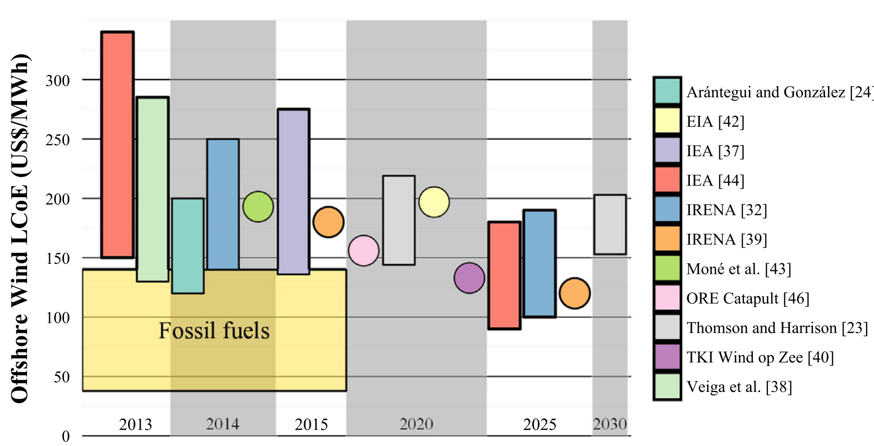

Fig. 4. Offshore wind LCoE estimates.

Table 1
LCoE studies for offshore wind.[a]

US$/MWh		Arántegui and González	Veiga et al.	Moné et al.	International Energy Agency (IEA)	TKI Wind op Zee	ORE Catapult	Energy Information Administration (EIA)	International Energy Agency (IEA)	International Renewable Energy Agency (IRENA)		Thomson and Harrison
Reference		[24]	[38]	[43]	[37]	[40]	[46]	[42]	[44]	[32]	[39]	[23]
Location		Europe	World	US	World	NL	UK	US	World	World	World	UK
Current	Year		*2014*		*2015*				*2013*	*2014*	*2015*	*2020*
	Cost	120–200	120–200	193	136 – 275				150–340	140–250	180	144 – 219
Future	Year						*2020*			*2025*		*2030*
	Cost					133	156	197	90–180	100 – 190	120	153 – 203

[a] Exchange rates are those of the International Energy Agency (IEA) [45].

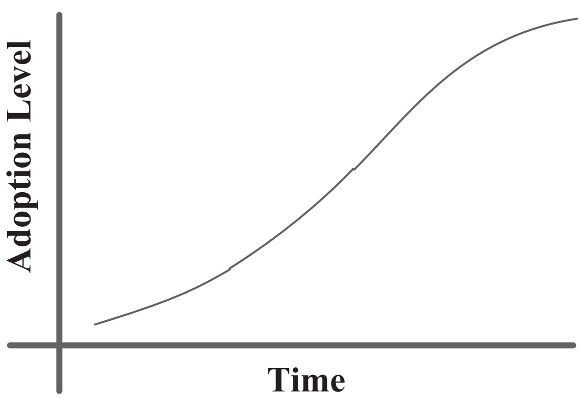

Fig. 5. The S-curve model of innovation adoption.

the introduction of the first product an erratic diffusion pattern rather than the smooth diffusion curve can be witnessed prior to the start of large-scale diffusion. This extended model must be adapted for each case, as is done in the current study. For example, the phases may vary in length, or in some cases the development and diffusion of a specific technological system is aborted because another much more promising technological system is developed that outperforms the previous one.

Fig. 6 presents an overview of the three phases. Here, the innovation phase "comprises the period from invention of a technology up to the first market introduction of a product incorporating the technology" [1]. This phase, which can last decades, is characterized by the involvement of research organizations and uncertainty on the product design, performance and markets. Although the technological principle is demonstrated in the invention, the technology might be immature, making implementation difficult and leading to postponements of development projects [51,52]. The following phase, referred to as market adaptation, starts with the market introduction of the first products based on the invention. This phase lasts a decade on average between early niche product introductions and later standard products diffusing in a mass market. It is characterized by competing product designs in different market segments and is thus a period of experimentation. In this phase infrastructures are built up, complementary products and services are created, institutions are re-arranged, and attempts are made to scale up concepts and benefit from economies of scale. To arrange this, networks of actors align around alternative concepts and complex forms of competition emerge. This leads to a non-linear development of the technology, with the appearance and disappearance of concepts and actors, promising advances and disappointing setbacks. Finally, market adaptation is followed by the market stabilization, where a dominant design emerges and a mainstream application is established. Ortt and Schoormans [1] explain that this dominant design still undergoes changes, as actors apply incremental modifications both to the product and its intended markets.

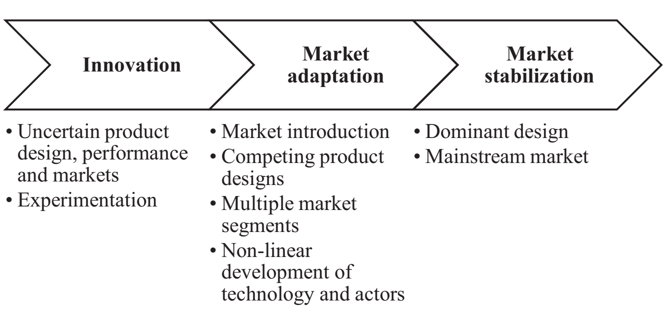

Fig. 6. Pattern of development and diffusion.

2.1.1. The pattern for offshore wind

Offshore wind went through a similar development and diffusion pattern, but with three differences. Namely, in the offshore industry support policies are necessary, the target market for offshore wind is more defined, and there is a relatively high actor concentration. First, S-curves and the pattern methodologies consider support policies as exogenous diffusion factors [53,54]. By analyzing the support of public actors to offshore wind inside the development and diffusion pattern we contribute to the need indicated by Kemp et al. [53] to consider policies in diffusion models. Second, concerning the target market and actor concentration, the investment size of offshore wind farms limits their application to large power systems, as opposed to isolated ones. Markard and Petersen [20] observe in the sector a concentration of large firms (confirmed in our study) due to increased risks and capital requirements. Thus, for offshore wind there is less uncertainty on applicable markets than for other technologies studied with the development and diffusion pattern. This concentration could compromise the applicability of the pattern if wind power were dependent only on this handful of actors, but this is not the case. In addition to academia and public actors, many firms are active in all life cycle phases, of which Fig. 3 presents only the main ones [23,33].

2.2. Methodology

The focus of this study is the offshore wind farm with bottom-founded horizontal axis offshore wind turbines, the currently dominant design for offshore wind [55]. In this way, our focus does not include the transmission system. Although relevant, transmission systems involve separate technologies with their own pattern of development and diffusion. Moreover, although innovation in offshore wind in other regions is discussed, this study has a European focus. Europe is expected to remain at the forefront of offshore wind innovation and installation in the medium term: Arántegui and González [24] forecast that until 2030 Europe will still be responsible for more than 50% of global installations.

Our methodology contains three steps: the application of the development and diffusion pattern, the identification of offshore wind barriers from this pattern, and the analysis of market strategies for the development of offshore wind farms according to our findings. The methodology iterates between those steps, for the pattern, the barriers and the market strategies are linked.

To define the development and diffusion pattern for offshore wind, we used a literature review with a semi-structured approach, with search keywords applied to Scopus and Google scholar. The search applied was (offshore wind) AND (development OR technology OR history OR technology review OR technology roadmap OR innovation). The search results were complemented with the literature already known by the authors. We analyze the following aspects for each phase of the pattern: design concept, wind farms size and purpose, life cycle and supply chain, private actors and support from public actors.

The barriers are characteristics of offshore wind that shape its pattern of development and diffusion. The literature on the pattern of development and diffusion does not apply the same characteristics for all technologies [54,56,57]. Thus, we derive specific barriers to offshore wind by analyzing the pattern and the reviewed literature, such as [25,58,59]. Finally, from the pattern and the barriers we analyze the adequacy of three market strategies for the development of offshore wind farms: mass-markets, wait-and-see and niches.

2.2.1. Market strategies

Given a technology and barriers affecting its innovation, companies may adopt a number of market strategies. Ortt et al. [60] present three main categories of such strategies during the developments and diffusion of breakthrough technologies: mass-market, wait-and-see and niche strategies. Mass-market strategies develop products for fast introduction into large markets (companies adopting mass-market strategies rely on network or scale effects to build up a large market share). Companies adopting wait-and-see strategies do not immediately introduce products. They develop and maintain the resources to introduce them, but wait until the market conditions improve and introduction becomes possible. This strategy reduces product and market uncertainties because it waits for new information and more favorable conditions.

Finally, niche strategies develop specific product designs for designated small markets. Ortt et al. [54] indicate they can be adopted to circumvent or remove existing barriers to product development, manufacturing or large-scale diffusion. The authors review a number of factors that determine the market situation, thereby shaping the adequacy of the possible niche strategies of Table 2. Moreover, niches can be accumulated in order to increase the market and further circumvent existing barriers [61].

3. Results

3.1. Development and diffusion pattern and offshore wind barriers

Fig. 7 provides an overview of the development and diffusion pattern for offshore wind. Three characteristics mark the phases of the pattern of development and diffusion: the design concept, the project size and the project purpose. In summary, the innovation phase comprises the first research on the adaptation of onshore turbines to the offshore environment and the first turbine installations in shallow water. The development of large offshore wind farms with a commercial purpose marks the beginning of the market adaptation phase. Then, very large commercial wind farms using the dominant design of monopile foundations with permanent magnet generators (PMG) characterize the market stabilization phase.

Those are the defining characteristics of offshore wind according to the development and diffusion pattern model. Beyond these characteristics, our analysis indicated that the farm life cycle and supply chain distanced itself from the onshore wind and oil & gas sectors which were pivotal in the early phases of the technology, eventually developing dedicated resources such as manufacturing facilities and installation vessels. Nonetheless, there are still important interactions with these sectors. Also, the turbine and farm development markets were concentrated throughout the pattern. Thus the turbine market had a CR_2 concentration ratio (i.e. the total market shares of the 2 biggest companies) of 70–99%. Beyond being less concentrated (CR_2 of 54–64%), farm development shifted in the pattern from separate national markets to a European one, with increased cooperation. Finally, the support of public actors remained throughout the period of analysis, but with an increasing exposure of wind farms to power markets and the use of competitive mechanisms for site allocation.

In this section we present the development and diffusion pattern for offshore wind for each phase in detail, with a brief history and the aspects indicated in Table 3. With the pattern we observe the barriers that shaped the offshore wind development and diffusion, namely:

- Comparative high cost: Offshore wind costs were higher than onshore wind and conventional generation technologies, and investment costs have shown even an increase up to 2015 [25,58].
- Capital requirements: Due to high costs and the size of wind farms, offshore wind requires high capital investments. In 2015 ten wind farms reached final investment decision, with an average investment cost of US$ 1,48B (€ 1,33B) [7].
- Project risk: The development of an offshore wind farm involves higher risks than onshore, due to factors such as uncertain soil conditions, harsh weather and site-specific turbine performance [25,58].

Table 2
Niche strategies of Ortt et al. [54].

Niche Strategy	Description
Dedicated system or stand-alone	Isolated use of the product due to inexistent or insufficient environment (e.g. necessary infrastructure)
Demo, experiment and develop	Controlled product introduction to manage and improve limited performance
Educate	Education of actors such as suppliers and customers to overcome actor barriers
Explore multiple markets	Product introduction in multiple simultaneous applications
Geographic	Product introduction where barriers are lower (e.g. more favorable regulation or supply chain characteristics)
Hybridization or adaptor	Combination with complementary products and services, possibly through development of an adaptor
Lead-user	Product development for and in cooperation with early adopters
Redesign	Design simplification to overcome performance, cost, supply chain or institutional barriers
Subsidized	Subsidization of market due to social or group-wide product benefits
Top niche	Differentiated product dedicated to high-end market segment users

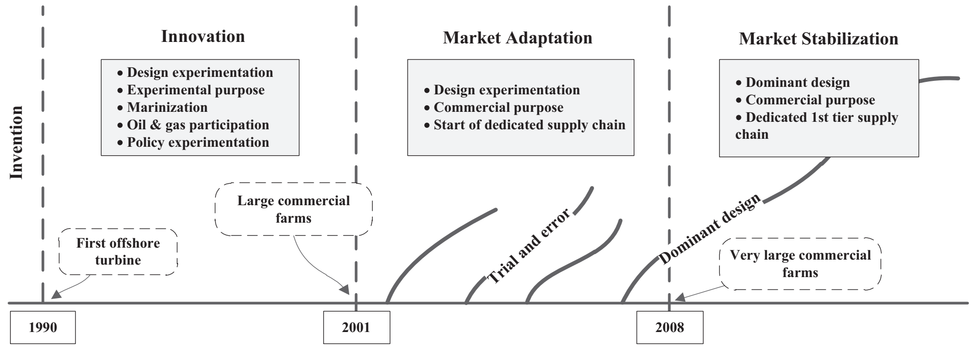

Fig. 7. Development and diffusion pattern for offshore wind.

- Multi-disciplinarity: Throughout the life cycle of a wind farm multiple knowledge fields are involved, such as mechanical, electrical, physics, software and civil engineering. These fields need to be integrated together with additional competences such as project management, meteorology and health, environment and safety [59].
- Project complexity: The supply chain, life cycle phases and components of an offshore wind farm are more numerous and integrated than onshore farms. This results in projects of high complexity that require not only the integration of multiple knowledge fields (i.e. the multi-disciplinarity barrier) but also of the supply chain and of life cycle phases [58,59].

3.1.1. *Innovation phase*

Tavner [62] presents a brief history of onshore wind technology since the late 19th century. After advances and setbacks, the simple Danish turbine design concept became dominant in the eighties, when large onshore wind farms were developed in California, then Europe, and afterwards in other regions. For offshore wind Sun et al. [16] describe the 1980s as a research stage, which provided the foundation for the subsequent development of offshore wind. This characterizes the 1980s as the invention (pre-innovation) phase of the pattern of development and diffusion.

The first offshore wind turbine would be installed on Nogersund in Sweden in 1990, with a small rating of 200 kW [6]. Then, the first offshore wind farm was installed in Vindeby (Denmark) in 1991, with 11 turbines totaling 4,95 MW in capacity [63]. Following this, all new offshore wind farms of the 1990s were installed in Europe. The region had good offshore wind resources, shallow North Seas and climate and energy policies driving renewable energy sources, while onshore wind faced spatial and noise restrictions [6,64,65].

Concerning the design concept, in the innovation phase of the pattern (1990–2001) multiple foundation, support structure and drive train design concepts were tried and abandoned. This trial and error with a lack of a dominant design concept is a central characteristic of innovation phases in the pattern of development and diffusion. As to the wind farm purpose, Sun et al. [16] see the 1990s as “an experimental testing stage”, and indeed farms built in the innovation phase had a significant learning aspect. This is exemplified by environmental, social and technical studies at the Nogersund turbine and the Vindeby and Lely wind farms [6,66]. Hence, wind farms in the innovation phase had more of an experimental purpose than a commercial one. Finally, farms commissioned up to 2001 had on average only 10 turbines and an installed capacity of 10 MW, with the 20 turbines of the 40 MW Middelgrunden (DK) farm making it by far the largest [63].

The first offshore farms were small, experimental and had no dominant design concept, which characterizes the innovation phase for offshore wind. In this phase we observe two more characteristics concerning the life cycle and supply chain aspect: a strong marinization of onshore turbines, and a significant contribution of the oil & gas sector [67]. First, all projects in the innovation phase were implemented in shallow water, some even being called semi-offshore [65,68]. These shallow-water turbines were marinized versions of onshore designs, with adaptations for corrosion protection, de-humidification and lifting capabilities [16,69]. The smaller challenges posed by the depth allowed the use of onshore designs, with the experimentation of support structure concepts. Second, the expertise of the oil & gas sector contributed to designing and experimenting with these support structures, such as jackets and monopiles [63].

Next, we can analyze the private and public actors. The concentration of turbine manufacturers was high, but the number of projects was low (only Vestas installed more than one wind farm in the period). If we discount the Middelgrund farm (which accounts for half of the capacity installed in the phase and marks the transition to the market adaptation), Nordtank led the market

Table 3
Development and diffusion pattern aspects.

	Innovation	Market Adaptation	Market Stabilization
Period	1990–2001	2002–2008	2009-present
Design concepts	Experimentation	Experimentation	Dominant (monopile foundation with PMG) and incremental innovation
Wind farm size (average)	Small (10 MW)	Large (68 MW)	Very large (316 MW)
Wind farm purpose	Experimental	Commercial	Commercial
Life cycle and supply chain	Marinization Strong oil & gas participation	Reduced marinization Start of dedicated supply chain	Integrated design Dedicated 1st tier supply chain
Private actors: Turbine manufacturers (CR_2)	Highly concentrated (70%) but market still in formation	Highly concentrated (99%)	Highly concentrated (75%)
Private actors: Developers (CR_2)	Concentrated (64%) but market still in formation	Concentrated (54%) with internationalization to UK	Concentrated (58%) with alliances
Public actors support	Experimentation	Experimentation with shift to commercial purposes	Bottom-up convergence to fostering competition

with a 28% share, stemming from a single project. This was not yet a fully formed market with established project developers, although in the second half of the innovation phase Nuon in the Netherlands and DONG in Denmark would take a more prominent role, indicating the transition to the market adaptation [63,70].

As for public actors, there was a lack of knowledge about how to effectively support offshore wind during the first phase of the pattern. Indeed, policies for offshore wind and renewable energy sources in the 1990s were novel, diverse and could at times be counterproductive [63,65]. As an example, Gaudiosi [65] indicates that “up to now applications have been considered not economic by government decision makers even due to limitations introduced by the “Electricity Feed Law” affecting particularly the offshore sector”. And indeed the first German offshore wind farm (Alpha Ventus) would be installed only ten years later [71]. Also, noteworthy is that leading countries or actors in offshore wind could change throughout the phases, as is observed in development and diffusion pattern studies. For example, although Sweden established the world's first wind turbine and one of its first wind farms, offshore wind would not be important locally, despite the role of Swedish private actors in other countries [70].

3.1.2. Market adaptation phase

A major watershed in offshore wind power was the commissioning of the Horns Rev I wind farm in 2002. With its 160 MW of total capacity and 80 wind turbines, it was the first farm with a capacity higher than 100 MW [62]. It is described by Zaaijer and Henderson [72] as “a representation of the new era”, and was followed in 2003 by the Rødsand farm with 73 turbines. Tavner [62] and Madariaga [26] present lists of the European offshore wind farms installed or under construction at that time.

The milestone of the market adaptation phase (2002–2008) was the implementation of large wind farms with a commercial purpose, although a dominant design concept yet had yet to emerge. Hence as in the innovation phase, actors experimented with a number of drive train and foundation concepts [73,74]. An example is the single suction-bucket foundation at the Frederikshavn wind farm in Denmark. After presenting a dislocation during a breaking test, it would take over a decade before the concept regained the attention of researchers, despite its advantages [55,75]. The adaptation phase was also marked by setbacks and abandonment (permanent or temporary) of supply chain and design concepts. Hence, the European Wind Energy Association (now WindEurope) [34] observes the use of “a single major construction contract under an EPCI (Engineer-Procure-Construct-Install) arrangement”, with high competition between contractors. However, due to subsequent losses on these arrangements the industry ceased with the EPCI practice, returning to them only in the mid-2010s [34].

The market adaptation phase saw a growth in the number and size of projects. In the market adaptation phase 19 wind farms with an average size of 68 MW were commissioned, against eight wind farms averaging 10 MW in the previous phase. Concerning the project purpose, it shifted from experimental to commercial. Hence, while the 2001 round 1 tender in the UK aimed for “demonstration scale” projects, round 2 already aimed at commercial projects [76]. Similarly, Denmark would foster competitive processes to develop offshore wind in the market adaptation phase [77].

The contributions of onshore wind and the oil & gas sectors to offshore wind decreased during the market adaptation. There is thus technological development dedicated to the offshore market, with lower marinization. In this way, the European Wind Energy Association [78] indicates a shift to “developing dedicated offshore turbines from a dedicated supply chain”. Also, turbine installation vessels in the previous innovation phase came from the oil & gas sector. However, starting in 2002 companies such as Mammoet van Oord and Mayflower Energy commissioned the first vessels built for offshore wind specifically [79].

The analysis of the private actors of the adaptation phase indicates a concentration, as Tavner [62] shows. Indeed, although Zaaijer and Henderson [72] list as much as eight offshore turbine manufacturers, Vestas and Siemens had virtually the whole market in the adaptation phase [62]. The developer landscape was more varied than for turbine manufacturers, but still concentrated – the Danish developers DONG and Elsam accounted for 54% of the offshore wind installations in the market adaptation [70]. An important trait is the internationalization of the developers, mainly to the United Kingdom. DONG, Elsam and E.ON were all active in the UK. As a contrast, only the 4 MW Blyth farm had international lead developers in the innovation phase [70].

Public actors kept supporting offshore wind in the market adaptation phase, and policies remained diverse and concentrated at a national level, as the main cases of the UK and Denmark show. Wind farms in the UK where developed through competitive tenders, starting with the 2001 Round 1 [77]. Denmark on its turn started with state-owned companies developing offshore wind farms on the government's initiative, switching to parallel competitive tenders and an “open-door” system which depended on the initiative of developers [77].

3.1.3. Market stabilization phase

The market stabilization phase began in 2009 with an increase in the total offshore wind capacity installations – in 2009 576,9 MW would be installed (53% more than in the previous year), followed by 882,7 MW in 2010 [80]. The appearance of very large commercial wind farms with several hundred megawatts and a dominant design marks the passage from the adaptation to the stabilization phase. The average annual capacity installed in 2009–2015 is 1362 MW/year, against 201 MW/year for the adaptation phase. Similarly, the average wind farm would have 316 MW, against 68 MW previously [80]. As in the adaptation phase, these large scale projects had a commercial purpose, with individual farms above 100 MW appearing in the UK, Germany, Denmark, Belgium and the Netherlands [81].

Also differently from previous phases, a turbine design concept became dominant in the stabilization phase. Arántegui [55] indicates turbines with monopile foundations and permanent magnet generators became the norm. Monopile foundations are cheaper than the main alternative (jacket foundations), while PMGs have “increased reliability, higher partial-load efficiency, and more flexibility of integration with compact gearboxes or power electronics” [74].

The development & design of turbines and wind farms progressively considered all life cycle phases and the supply chain. Thus, current guidance for research calls not only for a joint consideration of the rotor-nacelle, tower, support structures and foundation components, but also of the manufacturing, installation, O&M and decommissioning of the wind farms [82,83]. The supply chain continued to distinguish itself from the oil & gas sector, with integrated solutions, and dedicated resources such as manufacturing facilities and installation vessels. Thus, the gradual return of EPCI contract offerings indicated by the European Wind Energy Association [34] points to a holistic approach in search of further cost reductions in the stabilization phase. Also, 1st tier suppliers (i.e. providing the main direct components of a wind farm) developed dedicated manufacturing facilities for offshore wind [34]. E.g., turbine manufacturers invested in manufacturing plants producing exclusively offshore wind turbines, while previously plants produced both onshore and offshore turbines. However, the 2nd and 3rd tier suppliers (i.e. tending the 1st tier suppliers) remained dedicated to the wind industry (supplying both the onshore and offshore sectors). Finally, bigger purpose-built vessels are and will be more common in offshore wind to install future turbines and extra-large monopole foundations [24,83].

Private actors in the stabilization phase remained concentrated. Between 2009 and 2015 S and Senvion (Repower) had 75% of the turbine market, a high concentration ratio but still lower than in the market adaptation phase. The developer concentration slightly increased, to a 58% market share in 2009–2015 for the two main developers, DONG and RWE. A further important trend in the stabilization phase is the greater complexity in project cooperation. Indeed, from 2009 on, projects are usually alliances between two and increasingly even more developers [70,80,84].

In the market stabilization phase public actors still develop offshore wind at the national level, although there is a bottom-up convergence towards more exposure of offshore wind farms to power markets and more competition in the assignment of sites [35]. As indicated, in the stabilization phase the UK, Germany, Belgium, Denmark, and the Netherlands all established very large offshore wind farms with capacities above 100 MW [81].

3.1.4. Offshore wind barriers and the development and diffusion pattern

Section 3.1 indicates that the barriers which shaped the development and diffusion pattern of offshore wind were the comparative high cost, capital requirements, project risk, multi-disciplinarity and project complexity. Here we analyze how these barriers affected the aspects of Table 2: the *design concepts*, the wind farm *size* and *purpose*, the *life cycle and supply chain*, the *private actors,* and the *support from public actors.*

Various *design concepts* were tried in the innovation and market adaptation phases to address the cost barrier. However, the risk and complexity of offshore wind projects led to difficulties and to the abandonment of concepts such as the suction-bucket [75]. Slowly the sector moved to a proven concept - the monopile-founded turbine with PMG - to address the cost and risk barriers. However, as a design becomes dominant in the stabilization phase, a product still undergoes changes according to the development and diffusion pattern model [1]. The risk and multi-disciplinarity barriers indicate that the technology will evolve incrementally in the future. Hence alternative foundation concepts (and even floating foundations) may slowly increase their participation in offshore wind in the future. Efforts are also geared to drive-train improvements such as in AC/DC converters and superconductivity, reducing the installation & commissioning costs, and scaling up wind turbines [17,24,40,46,55].

Wind farms continuously increased in *size* during the development and diffusion pattern and shifted from an experimentation to a commercial *purpose*. Nonetheless, the cost and risk barriers made the technology dependent on governmental support throughout the phases. Moreover, the scaling of wind farms to attain economies of scale intends to address the cost barrier, but increases the capital requirements and the project complexity, and thus also increases the entry barriers.

As the pattern progressed the offshore *wind life cycle and supply chain* became more integrated but also more self-contained, drawing less resources and knowledge from the onshore wind and oil & gas sectors. 1st tier suppliers developed dedicated resources to offshore wind as risks decreased and the market grew.

The barriers strongly shaped the *private actors* and their cooperation. Even though the observed private actors' concentration decreased somewhat in the market stabilization phase, the capital requirements, multi-disciplinarity and complexity of offshore wind were and remain significant entry barriers to new actors. We have demonstrated that the development and diffusion pattern was also marked by a move of project developers to other European countries, for the entry barriers provide opportunities for incumbent private actors to internationalize. Furthermore, an increased cooperation in project development was observed in the stabilization phase. This allows to allocate risks in the project and to combine different resources from cooperating actors to address the capital requirements, multi-disciplinarity and complexity barriers.

In the development and diffusion pattern of offshore wind the high cost and project risk meant that both experimental and commercial wind farms were dependent on *governmental support*. This support remains a constant of the offshore wind sector, and the pattern was marked by experimentation and a bottom-up convergence of the support towards more competitive, commercially-oriented mechanisms.

3.2. Market strategies

Section 3.1.4 analyzed the effect of the offshore wind barriers on the pattern of development and diffusion. We now analyze how the same barriers affect the current and future adequacy of the mass-market, wait-and-see and niche strategies for the development of offshore wind farms.

Starting with the mass-market, the barriers of project complexity, capital requirements and multi-disciplinarity led to a market concentration, as demonstrated. Despite causing concentration, these barriers also impede a mass-market strategy where a single developer dominates the market. This would overexpose the developer to governmental support and project risks (such as schedule overruns), and require capital beyond its capabilities. Actors cooperating in project development are able to allocate these risks and combine different capabilities and resources. So the barriers limit the number of project developers, but also impedes the dominance of a single one. Hence, actors in the onshore wind and oil & gas sectors will still participate in offshore wind development, as in the cooperation of Shell, the offshore contractor Van Oord and the energy company Eneco in the first 2016 Dutch tender [85].

The wait-and-see strategy is also inadequate, unless the late entrant can cooperate in a project, bringing its own capabilities and resources but also utilizing those of incumbents. This is because the project complexity and multi-disciplinarity are entry barriers for late entrants in offshore wind, a fact reinforced by Steen and Hansen [67], to whom much of the offshore wind knowledge cannot be codified. Thus, a late entrance in the market without cooperating with incumbent companies is infeasible.

Given the inadequacy of the mass-market and wait-and-see strategies, it is not surprising that project developers followed niche strategies. Namely, they used the subsidized, the geographic and to a lesser extent the demo, experiment and develop niches. In the subsidized niche they depended on different support mechanisms during the innovation and adaptation phases, which continued in the stabilization phase to create very large wind farms. The exclusivity to Northern Europe characterizes the geographic niche, where water depths are lower, synergies exist with the North Sea oil & gas sector and onshore wind faces public opposition. The demo, experiment and develop niche was used in the experimental farms of the innovation phase and some few projects later on, such as Alpha Ventus and Frederikshavn [71]. However, the reduced number of experimental projects in later phases and the recently modified Leeghwater project in the Netherlands [86] exemplify the difficulties and narrower application of the demo, demonstrate and develop niche. Thus, to face the offshore wind barriers project developers not only used niche strategies, but actually accumulated them. They simultaneously leveraged governmental support, did so in a specific region (Northern Europe), and experimented in order to address the barriers.

With the development and diffusion of offshore wind the importance of these accumulated niches changes. First, the geographic niche may lose importance as offshore wind finally starts developing and diffusing in Asia and America. By the end of 2016 the installed capacity outside of Europe was 1073 MW, the majority located in China [8]. Rodrigues et al. [4] presents the offshore potential, projects in development and targets of China, Japan and the United States. Second, the analysis also showed a reduction of the subsidized niche importance, as public actors moved to an increased exposure of wind farms to power markets and competitive mechanisms for project allocation, although support is still required. The demo, experiment and develop niche will continue to be relevant so that industry can achieve its cost reduction commitments, but as seen it is the one niche strategy which has faced most difficulties.

In addition to niches, barriers also changed throughout the development and diffusion pattern. Actors were able to reduce the cost and risk barriers of offshore wind by employing a dominant design and scaling up commercial wind farms, and are now implementing further incremental innovations to further address the offshore wind barriers. However, while cost and risk decreased, the size increases that accompanied the market adaptation and stabilization phases increased capital requirements and the project complexity. Therefore, as for niches, the development and diffusion of offshore wind affected the barriers unequally.

4. Conclusions

The development and diffusion pattern was applied to offshore wind for the first time, characterizing the innovation, market adaptation and market stabilization phases. Wind farms grew from an average size of 10 MW to 368 MW, and shifted from an experimental to a commercial purpose through the pattern, while simultaneously a dominant design concept for wind turbines emerged. The innovation phase lasted around 11 years and the market adaptation phase 8 years, while the market stabilization is still ongoing. This timeline agrees with other applications of the development and diffusion pattern, but offshore wind remains a unique case for three reasons. First, although the barriers of cost and project risk decreased by the stabilization phase, government support still remains relevant (and so the subsidized niche strategy is still employed). Second, although offshore wind is starting to develop and diffuse in other regions, northern Europe is still a significant geographic niche. Third, the market for offshore wind was always well-defined, contrary to the standard development and diffusion pattern model.

The persistence and even increase of some offshore wind barriers has resulted in the inadequacy of the market strategies of mass-markets and wait-and-see. Throughout the application of the development and diffusion pattern one issue stands out: the cooperation of different actors in the offshore wind supply chain. As seen, this supply chain became more self-contained and the private actor concentration remained high throughout the period (CR_2 concentration ratios of 54–64% for farm developers and 70–99% for turbine manufacturers). Despite this self-containment and concentration, an increase in integrated cooperation structures can be observed from the innovation to the market stabilization phases. First, wind farm development became more international and alliances more common. Second, current innovation studies call for the integrated design of wind turbines, wind farms and the supply chain. Nonetheless, onshore wind and oil & gas companies remain active in offshore wind. Wind farm developers must consider how contemporary forms of cooperation improve or hinder their market strategies.

Research on the development and diffusion pattern model does not address the important issue of cooperation. Thus, the effect of cooperation on market strategies constitutes a significant area for investigation, possibly by differentiating the strategies of incumbent and entrant companies. Another relevant area for future research is the impact of the different phases of the pattern on actor concentration and on the different strategies. Finally, offshore wind is at earlier stages in other regions such as Asia and America. The application of the development and diffusion pattern at a global level could indicate at which phase the technology is at each location, possibly leading to different barriers and market strategies.

Acknowledgments

João Gorenstein Dedecca has been awarded an Erasmus Mundus Joint Doctorate Fellowship in Sustainable Energy Technologies and Strategies (SETS) hosted by the Universidad Pontificia Comillas, Spain; the Royal Institute of Technology, Sweden; and the Delft University of Technology, The Netherlands. The authors would like to express their gratitude towards all partner institutions within the programme as well as the European Commission for their support.

The authors would also like to thank all who proof-read or commented this work. Especially, we would like to thank Taylor Stone, all members from the Policy Analysis peer group, the Young Energy Economists and Engineers Seminar (YEEES) reviewers Adela Conchado Rodríguez and Nikolaus Ederer, and the anonymous reviewers of the Renewable & Sustainable Energy Reviews.

References

[1] Ortt JR, Schoormans JPL. The pattern of development and diffusion of breakthrough communication technologies. Eur J Inn. Manag 2004;7:292–302. http://dx.doi.org/10.1108/14601060410565047.
[2] European Commission. Energy roadmap 2050. 2011.
[3] European Commission. A policy framework for climate and energy in the period from 2020 to 2030; 2014.
[4] Rodrigues S, Restrepo C, Kontos E, Teixeira Pinto R, Bauer P. Trends of offshore wind projects. Renew Sustain Energy Rev 2015;49:1114–35. http://dx.doi.org/10.1016/j.rser.2015.04.092.
[5] ECF European Climate Foundation. Roadmap 2050: a practical guide to a prosperous, low-carbon Europe; 2010.
[6] Barthelmie RJ. A brief review of offshore wind energy activity in the 1990's. Wind Eng 1998;22:265–73.
[7] EWEA European Wind Energy Association. Wind in power –2015 European statistics; 2016.
[8] GWEC Global Wind Energy Council. Global wind report - annual market update 2015; 2016.
[9] ENTSO-E European Network of Transmission System Operators for Electricity. Statistical factsheet 2015; 2016.
[10] ENTSO-E European Network of Transmission System Operators for Electricity. Scenario Outlook & Adequacy Forecast (SO&AF) 2014–2030; 2014.
[11] GWEC Global Wind Energy Council. Global wind report - annual market update 2014; 2015.
[12] Jacobsson S, Karltorp K. Mechanisms blocking the dynamics of the European offshore wind energy innovation system – challenges for policy intervention. Energy Policy 2013;63:1182–95. http://dx.doi.org/10.1016/j.enpol.2013.08.077.
[13] Wieczorek AJ, Negro SO, Harmsen R, Heimeriks GJ, Luo L, Hekkert MP. A review of the European offshore wind innovation system. Renew Sustain Energy Rev 2013;26:294–306. http://dx.doi.org/10.1016/j.rser.2013.05.045.
[14] Luo L, Lacal-Arantegui R, Wieczorek AJ, Negro SO, Harmsen R, Heimeriks GJ, et al. A systemic assessment of the european offshore wind innovation - insights from the Netherlands, Denmark, Germany and the United Kingdom. JRC - Inst Energy Transp 2012.
[15] Kaldellis JK, Kapsali M. Shifting towards offshore wind energy—recent activity and future development. Energy Policy 2013;53:136–48. http://dx.doi.org/10.1016/j.enpol.2012.10.032.
[16] Sun X, Huang D, Wu G. The current state of offshore wind energy technology development. Energy 2012;41:298–312. http://dx.doi.org/10.1016/j.energy.2012.02.054.
[17] Islam MR, Guo Y, Zhu J. A review of offshore wind turbine nacelle: technical challenges, and research and developmental trends. Renew Sustain Energy Rev 2014;33:161–76. http://dx.doi.org/10.1016/j.rser.2014.01.085.

[18] Perveen R, Kishor N, Mohanty SR. Off-shore wind farm development: Present status and challenges. Renew Sustain Energy Rev 2014;29:780–92. http://dx.doi.org/10.1016/j.rser.2013.08.108.
[19] Dismukes DE, Upton Jr. GB. Economies of scale, learning effects and offshore wind development costs. Renew Energy 2015;83:61–6. http://dx.doi.org/10.1016/j.renene.2015.04.002.
[20] Markard J, Petersen R. The offshore trend: Structural changes in the wind power sector. Energy Policy 2009;37:3545–56. http://dx.doi.org/10.1016/j.enpol.2009.04.015.
[21] Wüstemeyer C, Madlener R, Bunn DW. A stakeholder analysis of divergent supply-chain trends for the European onshore and offshore wind installations. Energy Policy 2015;80:36–44. http://dx.doi.org/10.1016/j.enpol.2015.01.017.
[22] Hansen GH, Steen M. Offshore oil and gas firms' involvement in offshore wind: Technological frames and undercurrents. Environ Innov Soc Transit 2015;17:1–14. http://dx.doi.org/10.1016/j.eist.2015.05.001.
[23] Thomson C, Harrison GP. Life cycle costs and carbon emissions of offshore wind power; 2015.
[24] Arántegui RL, González JS. 2014 JRC wind status report - technology, market and economic aspects of wind energy in Europe. Petten: Joint Research Centre, Institute for Energy and Transport; 2015.
[25] Sovacool BK, Enevoldsen P. One style to build them all: corporate culture and innovation in the offshore wind industry. Energy Policy 2015;86:402–15. http://dx.doi.org/10.1016/j.enpol.2015.07.015.
[26] Madariaga A, de Alegría IM, Martín JL, Eguía P, Ceballos S. Current facts about offshore wind farms. Renew Sustain Energy Rev 2012;16:3105–16. http://dx.doi.org/10.1016/j.rser.2012.02.022.
[27] Brown C, Poudineh R, Foley B. Achieving a cost-competitive offshore wind power industry: what is the most effective policy framework? Oxford Institute for Energy Studies; 2015.
[28] EEA European Environmental Agency. Europe's onshore and offshore wind energy potential; 2009.
[29] DNV GL. DNV-OS-J101 - Design of offshore wind turbine structures; 2014.
[30] Lumbreras S, Ramos A. Offshore wind farm electrical design: a review. Wind Energy 2013;16:459–73. http://dx.doi.org/10.1002/we.1498.
[31] Yaramasu V, Wu B, Sen PC, Kouro S, Narimani M. High-power wind energy conversion systems: State-of-the-art and emerging technologies. Proc IEEE 2015;103:740–88. http://dx.doi.org/10.1109/JPROC.2014.2378692.
[32] IRENA International Renewable Energy Agency. Renewable power generation costs in 2014; 2015.
[33] BVG Associates. A guide to an offshore wind farm; 2010.
[34] EWEA European Wind Energy Association. Wind our sails - the coming Europe's offshore wind energy industry. 2011.
[35] Fitch-Roy O. An offshore wind union? Diversity and convergence in European offshore wind governance; 2015.
[36] IEA International Energy Agency. Projected costs of generating electricity 2010; 2010.
[37] IEA International Energy Agency. Projected costs of generating electricity 2015; 2015.
[38] Veiga MM, Álvarez PF, Moraleda MF-M, Kleinsorge A. RE-COST - Study on cost and business comparisons of renewable vs. non-renewable technologies. Final Report; 2013.
[39] IRENA International Renewable Energy Agency. The power to change: solar and wind cost reduction potential to 2025; 2016.
[40] TKI Wind op Zee. Cost reduction options for offshore wind in the Netherlands FID 2010–2020; 2015.
[41] DNV GL. Cost reduction monitoring framework - summary report - offshore renewable energy catapult; 2015.
[42] EIA Energy Information Administration. Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2015; 2015.
[43] Moné C, Stehly T, Maples B, Settle E. 2014 Cost of wind energy review NREL; 2015.
[44] IEA International Energy Agency. Energy technology perspectives 2014 - harnessing electricity's potential; 2014.
[45] IEA International Energy Agency. World energy outlook 2014; 2014. http://dx.doi.org/10.1787/weo-2013-en.
[46] ORE Catapult. Cost reduction monitoring framework 2015; 2016.
[47] Adwen, EDP Renewables, Eneco Energie, E.ON Climate & Renewables, GE Renewable Energy, Iberdrola Renewables, et al. European offshore wind industry joint declaration on cost reduction; 2016.
[48] Wieczorek AJ, Hekkert MP. Systemic instruments for systemic innovation problems: a framework for policy makers and innovation scholars. Sci Public Policy 2012;39:74–87. http://dx.doi.org/10.1093/scipol/scr008.
[49] Tidd J. From models to the management of diffusion. Gaining momentum: managing the diffusion of innovations; 2010.
[50] Rogers EM. Diffusion of innovations. New York: Free Press of Glencoe; 1962.
[51] Markham SK. Moving technologies from lab to market. Res Technol Manag 2002;45:31–42. http://dx.doi.org/10.1080/08956308.2002.11671531.
[52] Markham SK, Ward SJ, Aiman-Smith L, Kingon AI. The valley of death as context for role theory in product innovation. J Prod Innov Manag 2010;27:402–17. http://dx.doi.org/10.1111/j.1540–5885.2010.00724.x.
[53] Kemp R, Volpi M. The diffusion of clean technologies: a review with suggestions for future diffusion analysis. J Clean Prod 2008;16:S14–21. http://dx.doi.org/10.1016/j.jclepro.2007.10.019.
[54] Ortt JR, Langley DJ, Pals N. Ten niche strategies to commercialize new high-tech products; 2013.
[55] Arántegui RL. 2013 JRC wind status report - technology, market and economic aspects of wind energy in Europe. Petten: Joint Research Centre, Institute for Energy and Transport; 2014.
[56] Ortt R. Market creation for radically new technologies: a literature review on the role of market niches. Engineering, Technology and Innovation (ICE). In: 2012 18th International ICE Conference on 2012:(1–16). http://dx.doi.org/10.1109/ICE.2012.6297642http://dx.doi.org/10.1109/ICE.2012.6297642.
[57] van der Duin PA, Ortt JR, Aarts WTM. Contextual innovation management using a stage-gate platform: the case of philips shaving and beauty. J Prod Innov Manag 2014;31:489–500. http://dx.doi.org/10.1111/jpim.12109.
[58] Schwanitz VJ, Wierling A. Offshore wind investments – realism about cost developments is necessary. Energy 2016;106:170–81. http://dx.doi.org/10.1016/j.energy.2016.03.046.
[59] Jacobsson S, Karltorp K. Formation of competences to realize the potential of offshore wind power in the European Union. Energy Policy 2012;44:374–84. http://dx.doi.org/10.1016/j.enpol.2012.01.069.
[60] Ortt JR, Zegveld M, Shah CM. Strategies to commercialise breakthrough technologies; 2007.
[61] Raven R. Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: an assessment of differences and pitfalls. Energy Policy 2007;35:2390–400. http://dx.doi.org/10.1016/j.enpol.2006.09.003.
[62] Tavner P. Offshore wind turbines - reliability, availability and maintenance. The Institution of Engineering and Technology; 2012.
[63] GH Garrad Hassan Partners. Tractebel Energy Engineering, Risø National Laboratory, Kvaerner Oil & Gas, EMU Energi & Miljoe Undersoegelser Offshore Wind Energy - Ready to Power a Sustainable Europe; 2001.
[64] Ackermann T, Söder L. Wind energy technology and current status: a review. Renew Sustain Energy Rev 2000;4:315–74. http://dx.doi.org/10.1016/S1364-0321(00)00004-6.
[65] Gaudiosi G. Offshore wind energy prospects. Renew Energy 1999;16:828–34. http://dx.doi.org/10.1016/S0960-1481(98)00267-5.
[66] BWEA British Wind Energy Association. Prospects for offshore. Wind Energy 2000.
[67] Steen M, Same Sea Hansen GH. Different ponds: cross-sectorial knowledge Spillovers in the North Sea. Eur Plan Stud 2013;22:2030–49. http://dx.doi.org/10.1080/09654313.2013.814622.
[68] Barthelmie R, Pryor S. A review of the economics of offshore wind farms. Wind Eng 2001;25:203–13. http://dx.doi.org/10.1260/0309524011496024.
[69] Jamieson P. Innovation in wind turbine design. Chichester: Wiley; 2011.
[70] LORC. LORC list of offshore wind farms; 2016. ⟨http://www.lorc.dk/offshore-wind-farms-map/list⟩.
[71] Research at Alpha Ventus. Research at alpha ventus (RAVE); 2015. ⟨http://rave.iwes.fraunhofer.de/rave/pages/welcome⟩ (accessed May 19.05.15).
[72] Zaaijer MB, Henderson AR. Review of current activities in offshore wind energy; 2004. p. 101–108.
[73] Kaldellis JK, Zafirakis D, Kondili E, Papapostolou C. Trends, prospects and R&D directions of the global wind energy sector. vol. 3; 2012. p. 1403–1411.
[74] Arántegui RL, Corsatea T, Suomalainen K. 2012 JRC wind status report - technology, market and economic aspects of wind energy in Europe. Joint Research Centre, Institute for Energy and Transport,; 2013.
[75] Westwood A. Refocus marine renewable energy report: global markets, forecasts and analysis 2005–2009; 2005.
[76] GL Garrad Hassan. A guide to UK offshore wind operatons and maintenance; 2013.
[77] Deloitte GL Garrad Hassan. Analysis on the furthering of competition in relation to the establishment of large offshore wind farms in Denmark. Background report 1: analysis of framework conditions in key EU countries; 2011.
[78] EWEA European Wind Energy Association. Oceans of opportunity - Harnessing Europe's largest domestic energy resource; 2009.
[79] GH Garrad Hassan and Partners. Sea wind Europe; 2004.
[80] EWEA European Wind Energy Association. The European offshore wind industry - key trends and statistics 2015; 2016.
[81] González JS, Lacal-Arántegui R. A review of regulatory framework for wind energy in European Union countries: current state and expected developments. Renew Sustain Energy Rev 2016;56:588–602. http://dx.doi.org/10.1016/j.rser.2015.11.091.
[82] DNV GL. Offshore wind - a manifesto for cost reduction; 2014.
[83] TPWind European Wind Energy Technology Platform. Strategic research agenda/market deployment strategy (SRA/MDS); 2014.
[84] EWEA European Wind Energy Association. The European offshore wind industry - key trends and statistics 2014; 2015.
[85] T Sterling, T. Escritt Shell participates in bid for Dutch offshore wind farm. Reuters; 2016.
[86] Offshore WIND. Leeghwater offshore wind project cancelled; 2015.