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TECHNO-ECONOMICS ASPECTS OF WIND ENERGY DEPLOYMENT.

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Techno-economic aspects of wind energy deployment

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Abstract

Research supporting cost reduction in wind energy technology benefits from the study of certain elements with strong impact on the formation of the cost of energy. In this context, the objective of this doctoral research is to explore some of the techno-economic aspects influencing wind energy development and deployment and to assess their impact on the technology.

The research follows two strings of work: a technology and a deployment string. The former included an analysis of time reduction in the installation of wind farms offshore and another on the technological effects of repowering wind farms onshore. The later focused on globalisation of the sector with a focus on wind farm developers and turbine manufacturers, and then more specifically on the process of internationalisation of the latter.

The research collected data from public and commercial sources, and a small amount of confidential data was used that originated from the network of contacts of the author. Varied modelling tools were applied depending on the needs of each of the four individual pieces of research. The article exploring the reduction of the installation time in offshore wind farms used Visual Basic (VB) macros in MS Excel applied to the key milestones of project installation in order to unveil to what extent time reduction had been realised during the period 2000-2017. In the article on the technological impact of repowering, Excel, VB models and statistical regression analysis with Minitab were used in turn. The article on globalisation focused on contrasting data publicly available but not normally investigated together thus unveiling trends not seen previously. Finally, the analysis of internationalisation of wind turbine manufacturers resourced to indicators that, while widely used in the literature, needed to be adapted to the wind turbine manufacture sector.

The very significant cost reductions in electricity from wind energy that have surfaced following recent auctions and tenders is justified in part by (offshore) the reduction in the time of installation and (onshore) the increased production from repowering. Regarding trade and globalisation, the research found that European wind turbine manufacturers lead globally while they are more diversified and protected against the ups and downs of the different markets. Moreover, they have been able to grow supply chains in many countries while still maintaining the bulk of the employment at home.

Resumen y conclusiones de la tesis

La necesaria investigación sobre reducción de costes de la tecnología de producción de electricidad a partir del recurso eólico debe partir de los elementos que más impactan la formación del precio de esa energía. Por ello, el objetivo de este estudio doctoral es explorar e investigar algunos de los aspectos tecno-económicos que más influyen en el desarrollo y la comercialización de la energía eólica, y evaluar su impacto en la misma tecnología.

Mi trabajo sigue dos líneas principales, una tecnológica y otra sobre la comercialización global. La primera incluye un análisis de la reducción de tiempo en la instalación de plantas eólicas en el mar, y otro sobre los efectos tecnológicos de la repotenciación de parques eólicos en tierra. La línea sobre comercialización se centra en el análisis de la globalización del sector y en particular de sus dos principales actores, los promotores de parques eólicos y los fabricantes de turbinas, para terminar explorando en profundidad cómo se internacionalizaron estos últimos.

Esta investigación se ha basado en datos públicos o proporcionados por entidades que los comercializan, y de una pequeña cantidad de datos comunicados privadamente al autor por su red de contactos en el sector. Diversos modelos han sido usados dependiendo de la necesidad de cada investigación individual. La investigación sobre tiempo de instalación en el mar se modeló con macros de Visual Basic (VB) en MS Excel aplicados a los diferentes hitos de la instalación, de esta forma descubriendo la reducción en tiempo de instalación lograda en el periodo 2000-2017. La investigación sobre el impacto tecnológico de la repotenciación de turbinas eólicas se modeló con VB, Excel y el software de análisis de regresión estadística Minitab. La investigación sobre globalización se basó en contrastar series de datos de forma innovativa, extrayendo conclusiones y descubriendo tendencias que no se habían publicado hasta entonces. Finalmente, el análisis de internacionalización de los fabricantes de turbinas utilizó indicadores ampliamente utilizados en la literatura sobre internacionalización pero que tuvieron que ser adaptados a las particularidades del sector - por ejemplo, el uso de capacidad instalada en lugar de volumen de ventas.

Las recientes subastas y licitaciones de electricidad eólica y/o renovable han revelado reducciones de costes muy significativas que se justifican en parte por la reducción en el tiempo de instalación (en el mar) y por el aumento de la producción eléctrica en el caso de la repotenciación (en tierra). Con respecto a comercio internacional y la globalización, esta investigación mostró que los fabricantes europeos de turbinas lideran el mercado global a la vez que están más diversificados y protegidos contra los vaivenes de los diferentes mercados. Es más, han sido capaces de formar cadenas de suministro en muchos países a la vez que mantenían la mayor parte del empleo en Europa.

1. Thesis description

The current document presents a PhD thesis by publication that includes the following published articles:

- *Offshore wind installation: Analysing the evidence behind improvements in installation time*. Roberto Lacal Arántegui, Dr José M. Yusta, Dr José Antonio Domínguez-Navarro. Renewable and Sustainable Energy Reviews, Volume 92, September 2018, Pages 133–145. https://doi.org/10.1016/j.rser.2018.04.044
- *Technology effects in repowering wind turbines*. Roberto Lacal Arántegui, Dr Andreas Uihlein, Dr José María Yusta. Wind Energy, Volume 23, Issue 3, March 2020, Pages 660-675. https://doi.org/10.1002/we.2450
- *Globalization in the wind energy industry - contribution and economic impact of European companies*. Roberto Lacal Arántegui. Renewable Energy, Volume 134, April 2019, pages 612-628. https://doi.org/10.1016/j.renene.2018.10.087
- *Measuring the internationalisation of the wind energy industry*. Roberto Lacal Arántegui, Dr José María Yusta. Renewable Energy, Renewable Energy 157 (2020) 593-604. https://doi.org/10.1016/j.renene.2020.05.053

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2. Introduction

2.1. Objectives

The objective of this doctoral research is to explore some techno-economic aspects influencing wind energy development and deployment and to assess their impact on the technology.

In 2009 the European Union (EU) set itself the objective of a 20 % penetration of renewable energy in final energy consumption for this year, 2020 [2]. Specifically for electricity, the EU28 generated around 13.5 % of its total electricity generation from wind energy in 2019, some 432 TWh [3]. This is only 9.25 % shorter of the foreseen 476 TWh for 2020 [4].

Wind energy is therefore expected to play an increasingly significant role in the European electricity system. It is a mature technology yet there was - and still is - an important margin for cost reduction, and more so at the time this doctoral research was defined. In this context, it is important that the key elements for cost reduction are investigated and exposed. For the engineering-oriented research community a particular focus is those reduction based on technology improvements.

The basic hypothesis of this doctoral research is that general research supporting technological cost reduction would benefit from the study of certain elements with strong impact on the formation of the cost of energy. Those elements, both technological and economic in nature, particularly affect offshore wind. Besides, the internationalisation of wind energy and its impact on the European economy are considered important aspects affecting price formation in a sector that is naturally global.

This doctoral research is therefore structured into two strings: techno-economic research on key cost-reduction issues on the one hand, and deployment-focused (i.e. globalisation of the wind sector) research on the other.

The first string of the research acknowledged from the beginning that wind energy technology is a very large engineering sector yet it is clearly divided in two subsectors: offshore and onshore. Thus, the natural decision was to tackle one important technological aspect to help reducing the cost of wind electricity that is significant in each of the sectors. The aspects chosen were the recent reduction in time (and therefore costs) of installing offshore wind farms [5] , and the technology-derived effects of repowering wind turbines on land [6].

The second string of the doctoral research, the deployment of wind energy technology, gave place to two specific aspects of research. First the globalisation of the industry was explored, with a view on the contribution of European companies [7]. The conclusions of this research led to further deepening the subject with an attempt to measuring its internationalisation, for which it was necessary the definition of specific internationalisation indices [8].

The research uses data available or that have been available and were collected from the Internet by the PhD candidate since 2009 during his work at the Joint Research Centre (JRC), as well as those collected exclusively for this doctoral research. Those data come from official publications such as official journals, administrative permits, mandatory reports to authorities (e.g. those overseeing the stock markets), energy news, press releases and reports by important players (such as developers, turbine manufacturers, installers, sector associations, consultants and research centres), or public communications in Twitter, Facebook and LinkedIn as main social media channels.

It was interesting to see how some social media channels could be so important for our research. For example, one of the milestones used in [5] was the day that a wind farm builder installed the last turbine, and this is an event that workers and managers of the installation vessel often publish in Twitter or Facebook even before any official press release is published.

2.2. Literature review

Wind energy, both onshore and offshore, is one of the key technological options for a shift to a decarbonised energy supply causing, among other benefits, a reduction in fossil fuel use and in greenhouse gas emissions[9].

It is offshore that wind energy has traditionally most been presented as an energy source with a huge unrealised potential. To date, this is because of the complexity of the technology and project management, the harsh marine environment, and the related high cost of installing wind turbines in the seas. However, this is set to change. The technological developments of the last ten years, among other factors, have led to significant cost reductions that have manifested in recent tender and auction prices.

The analysis of the evolution of offshore wind farm installation time is all but absent in the scientific literature. Schwanitz and Wierling [10] briefly discussed construction time as part of their thorough assessment of offshore wind investment, and showed that wind farm offshore construction time has increased from 2001 to 2016, but it has decreased in unit term (years/MW). One of the data issues shown by this research is the very disperse data set giving R2 = 0.05 (see Figure 4 b in [10]), when construction times are “measured as the period between the beginning of (…) offshore construction and the date of commissioning”, perhaps a relatively low level of detail. Interestingly, these authors also discuss the impact of water depth in driving installation costs.

Based on Benders’ decomposition, Ursavas [11] modelled the optimisation of the renting period of the offshore installation vessels and the scheduling of the operations for building the wind farm. This author provides interesting information on the impact of weather on installation, e.g. “*for the Borkum West project the installation of a complete top side of the wind turbine generator that MPI achieved was 25 hours yet some wind turbine generators were under construction for over 3 weeks due to weather conditions*”. This same purpose, the modelling of the optimisation of transport and installation, was the result of the research by Sarker and Ibn Faiz, concluding that “the total cost is significantly impacted by turbine size and pre-assembly method” [12].

The objective of this research is to increase scientific knowledge on offshore wind farm installation time and its evolution. This is done by exploring and analysing the installation to a high level of detail, separately focusing on foundation, turbine and whole-set1 installation. This paper quantifies the improvements for the period 2000 – 2017 in terms of days per foundation and per megawatt rating of the turbine mounted there (megawatt-equivalent or megawatt for

[1] Throughout this document the term "set" is used to reflect the set of one turbine plus all the elements that constitute its foundation, e.g. monopile/jacket, transition piece, piles fixing jackets, etc.

short). This article provides actual figures for these parameters that could be necessary for any further research on cost-reduction of the installation of offshore wind energy.

Therefore, after a period of cost increases (see Figure 4 in [13]), the cost of offshore wind energy started to descend even in a very radical way. The evidence for this, as shown in Table 1, is the successive results of tenders and auctions that different European governments used in order to foster the development of offshore wind farms. The tenders involve that the winners will receive their bid price for a number of years, with or without adjustment for inflation depending on the country regulations.

There are significant differences in the period that the bid price will be received and in other key conditions. Also, recent German and Dutch [14] bids at "market price" were awarded without any additional subsidy in addition to the wholesale electricity price.

Date announced	Country	Project name	Size (MW)	Winner	Bid (€/MWh)	Commissioning
2010/06/22	DK*	Anholt	400	Dong Energy	140.00	**2012/3**
2013/12/30†	UK	Dudgeon	402	Statoil et al.	186.10‡	**2017**
2014/04/23†	UK	Beatrice	588	SSE et al.	173.70‡	**2019**
2015/02/26†	UK	East Anglia One	714	Vattenfall/SSP	164.72	**2020**
2015/02/26†	UK	Neart na Gaoithe	448	Mainstream	157.17	*2023*
2015/02/27	DK*	Horns Rev 3	406.7	Vattenfall	103.20	**2019**
2016/07/05	NL*	Borssele 1 & 2	752	Dong Energy	72.70	**2020**
2016/09/12	DK*	Vesterhav	350	Vattenfall	63.82	*2022*
2016/11/09	DK*	Kriegers Flak	605	Vattenfall	49.90	*2021*
2016/12/12	NL*	Borssele 3 & 4	702	Shell et al.	54.50	*2021*
2017/04/13	DE*	Borkum Riffgrund West 2	240	Ørsted	Market price	*2025*
2017/04/13	DE*	He Dreiht	900	EnBW	Market price	*2025*
2017/04/13	DE*	Gode Wind 3	110	Ørsted	60.0	*2024*
2017/04/13	DE*	OWP West	240	Ørsted	Market price	*2025*
2017/09/11†	UK	Triton Knoll	860	Innogy	86	*2022*
2017/09/11†	UK	Hornsea 2	1386	Ørsted	64.1	*2022*
2017/09/11†	UK	Moray East	950	EDPR, Engie	64.1	*2022*
2018/03/19	NL*	Hollandse Kust (Zuid)	750	Vattenfall	Market price	2023

Table 1: Recent offshore wind tenders and auctions, and winning prices in EU countries. Notes: exchange rates to Euro correspond to the day the winner was announced; Dong Energy changed name to Ørsted; *offshore substation and/or HVDC transformer station, and connection to the shore are provided by the transmission system operator and thus not included in the bid price; †date of granting of contract for differences or equivalent. Sources: press releases, offshorewind.biz web site and, for (‡), WindEurope [15]. Commissioning years have been updated vs. the published article; bold means already operational

The significance of the cost reductions shown in Table 1 is even greater when compared to what the wind energy experts expected as recently as two and half years before. An expert elicitation survey of 163 of the world's foremost wind experts run during late 2015 suggested significant opportunities for 24 – 30 % reductions by 2030 [16]. Table 1 shows, for example, that reductions already reached 52 % just in the 1.8 years between the Danish Horns Rev 3 and Kriegers Flak OWF tenders.

In order to achieve these prospective cost reductions, offshore wind farm projects need to tackle all the elements that make up their cost. These elements are, in essence, depicted in Figure 1 copied here from Smart et al. [17]

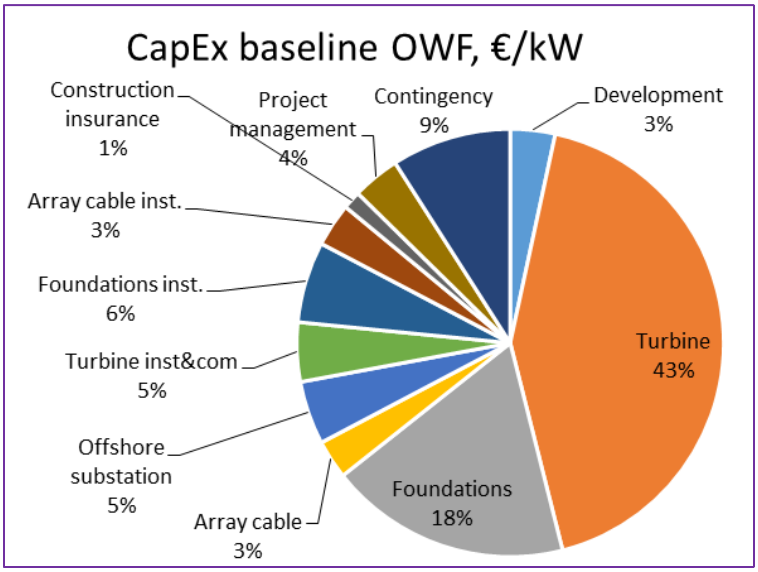

Figure 1: estimated breakdown of the capital expenditure of a baseline offshore wind farm in 2015. Source: [17]

Costs are highly project-specific. For example, cable connection to the onshore substation used to cost around one million EUR per km [18], and wind farms commissioned in the period 2015-2017 are placed between 1 and 115 km from the coast and required between 6 [19] and 210 [20] km of high-voltage export cable. For different authors wind turbine and foundation installation contributes between 10 - 12% [17] and 16 % [21] of capital expenditure (CapEx) of an offshore wind farm. The former figure corresponds to the characteristics of the ones installed in Europe during 2014/2015[2] whereas the latter was reported in 2010 with a focus on the UK.

The installation of foundations and turbines consists essentially of the following actions: (a) adaptation of the vessel for the job (an activity called mobilisation); (b) port loading of the turbines/foundations on the installation vessel[3]; (c) transport to the wind farm site; (d) installation; (e) vessel returns to port; and (f) removal of the installation equipment (called demobilisation). With turbine/foundation installation vessels able to carry a few items per trip, actions (b) to (e) above are repeated several times per wind farm [22].

Mobilisation and demobilisation are cost elements paid normally as a lump sum. Loading, transport to site, installation and return to port are activities whose effort depend on wind farm size (i.e. no. of turbines/foundations to install); distances to marshalling harbours, turbine and foundation size and type; and most crucially, weather [23].

The main installation cost - turbine installation vessels- charge daily rates as shown in Table 2 of Ahn et al. [24], partly reproduced as Table 2 here. The main differences are due to vessel performance and use. For example, turbine installation vessels (TIV) have carried from 1 to 10 turbines, and a vessel carrying only two full turbine sets (tower, nacelle, hub and blades) has necessarily to be cheaper than a vessel able to

Vessel type	Daily rate (USD)
Turbine installation vessel	150,000 – 250,000
Jack-up barge	100,000 – 180,000
Crane barge	80,000 – 100,000
Cargo barge	30,000 – 50,000
Tug boat	1,000 – 5,000

Table 2: indicative costs of vessels involved in turbine installation. Source [24]

[2] The baseline data represented in this graph corresponds to a 400-MW, 100-turbine model offshore wind farm as described by IEA Wind Task 26 documentation (see Smart et al. [17]).

[3] A number of OWF projects transported foundations by floating these and using tugs instead of turbine/foundation installation vessels (the latter only did the installation)

transport ten turbine sets each trip. Nine of the largest eleven wind farm installation vessels used in Europe have been built since 2011[4].

A turbine installation vessel, MPI Resolution, installed 75 foundation and turbines at Lincs OWF (UK) starting 2011, at an average 9.5 days per set. Assuming a rate of USD 150,000/day (she was subject to a long let which can be expected to reduce daily rates), the cost of this aspect of the OWF installation was 107 M USD (plus mobilisation/ demobilisation costs), or 65.5 M GBP at the average exchange rate of 2009 Q4. The declared CapEx at the time of investment decision was 725 M GBP and thus this part of the installation is 9% of total CapEx.

Because the focus of this research was the improvement in installation times, some of the factors that complicate or delay installations were mentioned even when they were not analysed by the model. In addition to weather conditions (preventing lifts), factors include unexpected ground conditions, storm damage to the construction vessels [25], encountering unexploded ordnance [26], inexperienced project or vessel team, etc. Some types of foundations (e.g. tripiles, jackets) require longer installation time than others (e.g. monopiles), whereas different procedures for installing the turbine are subject to more strict wind conditions at hub height, and thus have fewer and shorter weather windows for installation.

Wind energy facilities, as other power generation technologies, are subject to ageing, inducing reduction of efficiency, output and availability [27]–[29]. In the case of wind turbines it was proposed that they lose up to 1.6 % of their output per each year [30]. There are many reasons for decreases in production, including fouling of blades, decreases in the efficiency of the gearbox, bearings or generator. In addition, downtime increases as the turbines get older and need more maintenance. Even lack of spare parts may become an issue at a certain age [31]. In parallel, operational costs increase with time [32].

When the asset approaches the end of its operational life, project owners have a number of options: decommissioning, repowering, life extension (partial replacement of components), or run-to-fail[5] [28], [33]. Repowering a wind farm implies dismantling the existing wind turbines and installing new turbines of a larger size with new technology [34].

Repowering wind turbines (or wind farms) brings a number of benefits. First, and most important, repowering will increase performance and electricity production of wind projects [27], [29], [32], [35], [36]. Compared to a greenfield project, financing conditions might be better for repowering projects since the wind resource is known already and planning costs will be lower [33], [37]. In some cases, parts of existing infrastructure might be usable, e.g. the wind farm substation and some of the electrical connections.

A theoretical case study for a wind farm in India showed that energy yield could increase by a factor of four [38]. Other studies have reported increase of capacity factor by 10 percentage points [33]. As a rule of thumb, a repowered wind farm has approximately half the number of turbines, double rated power and triple electricity yield [39] and therefore also uses the land available more efficiently.

[4] Source: individual vessel specifications.

[5] "run-to-fail" is leaving all turbines to run, with minimum maintenance, until maintenance costs are higher than revenues, e.g. because of the failure of a main component. Because not all turbines have major failures at the same time, the wind farm would keep running at an increasingly lower capacity until the last turbine stops working.

Repowering of wind turbines also offers advantages for the whole electricity system [27] and the society at large. In general, repowering will lead to a reduction of reactive power consumption and voltage variations [38]. Turbines have evolved to better support the grid by adding increasingly-complex features such as low-voltage ride-through. New turbines have lower rotational speeds with reduced noise emissions [40]. Bigger rotors and lower rotational speeds provide a less visually intrusive and more pleasant view than fast-rotating turbines [41], [42]. In terms of environmental effects, wind farm repowering reduces fatalities for raptors and other birds, as shown by research in California that found that repowering resulted in a reduction of fatalities by 83 % for raptors and 87 % for all birds for the same amount of energy generated [43]. Last but not least, local acceptance is also usually higher for repowering projects compared to greenfield developments [44].

A significant proportion of the installed EU wind fleet will come to the end of its lifetime between 2020 and 2030 [45]. Approximately 3.3 GW of the wind turbines installed in Europe by the end of 2017 were 20 years and older. This group, along with the approximately 18 GW of turbines between 15 and 19 years-old are the obvious candidates for repowering (Figure 2). Notwithstanding this, there are cases where younger turbines can be suited for repowering, and this would include some of the 33 GW of turbines between 10 and 14 years-old. The largest markets for repowering in Europe are Germany, Denmark, Spain, and Italy. The repowering market is also large in the United States and India with about 1.1 GW and 0.3 GW of wind turbines being 20 years and older.

Two countries that have been frontrunners in wind energy have vast experience with repowering so far: Denmark and Germany [46]. Since 2001, Denmark has supported repowering through various incentive programmes, which led to the repowering of a significant amount of the oldest wind turbines. 56 % of turbines installed before 2000 and 84 % of turbines installed before 1994 had already been repowered by end 2017. More than 3,200 turbines were dismantled in Denmark before 2018. Germany is another country where repowering has been a significant part of annual installations. About 5,470 MW (about 2,040 turbines) of wind power capacity was installed before 2018 in repowering projects. Those turbines replaced about 2,900 old turbines (2,280 MW) [47]. Table 3 shows the annual evolution of repowering in Germany.

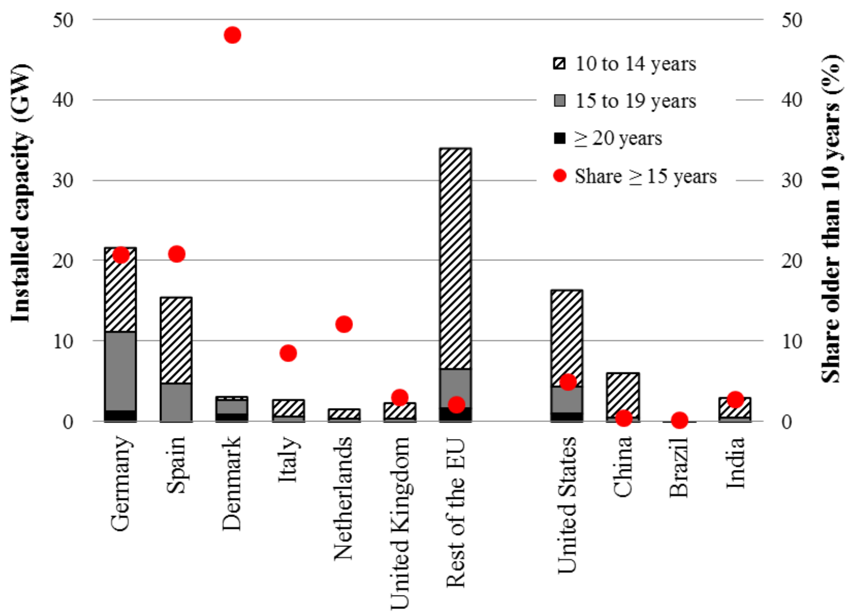

Figure 2: Age distribution of wind fleet in selected countries. Sources: [48]–[50]

Table 3: Historical account of repowering in Germany

Wind turbines	<2006	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
No. dismantled turbines	147	79	108	26	76	140	170	252	416	544	253	336	387	**2934**
No. replacement turbines	107	55	45	18	55	90	95	161	269	413	176	238	315	**2037**
MW dismantled	155	26	41	10	37	56	123	179	258	364	195	366	467	**2277**
MW replacement	190	136	103	24	136	183	238	432	766	1148	484	679	952	**5472**

Source: annual and half-year reports "Status of wind energy development in Germany" by Deutsche WindGuard on behalf of the German Wind Energy Association [47], for 2017 and previous years. Remarks: the source acknowledges that not all repowering activity has been captured in these statistics; figures prior to 2006 are obtained through subtracting from the latest cumulative figures.

Until we undertook this research, the efficiency gains and performance improvements of actual repowering projects had not been researched in a detailed manner. Some evidence was available from theoretical studies [29], [36], [51]. Some case studies had been performed on an individual wind farm basis (see, e.g. [51] for a repowering of two wind farms in Spain). The aim of this part of the PhD was therefore to fill this gap by analysing the structural and performance changes due to wind turbine repowering independent from locational changes in the wind resource, whereas taking into account the impact of hub height-related changes in the wind resource. The research presented a quantitative analysis of the characteristics of repowered and new turbines in Denmark and Germany and the corresponding impacts on turbine performance.

Globalisation[6] has involved huge benefits for humankind, from health improvements to culture diffusion and economic growth [52]. In the latter aspect, globalisation is to a large extent responsible for the economic growth of entire countries, e.g. Singapore or China [53], [54]. However, where local companies could not compete with foreign companies on a level-playing field, globalisation has caused loss of jobs and a certain impoverishment locally [55].

The most important economic effect of globalisation, after taking people out of poverty and reducing the prices for goods, is probably the increase in trade. For example, between 1970 and 2002 imports as a ratio to world gross domestic product (GDP) increased from around 12 % to above 24 % [56]. Other economic effects include foreign direct investment (FDI), e.g. where foreign companies either acquire local companies or set up local branches or production facilities, and the financing of local investment with foreign funds as seen e.g. in offshore wind farms in the North Sea [57]. On the other side, a number of negative effects have affected how people see globalisation, from changes in land use resulting in the destruction of forests to make room for cash crops [58] to the delocalisation of manufacturing to countries with lower labour costs and less-strict environmental regulations [59].

One interesting aspect of globalisation that directly affects the object of this research, is the interdependence between innovation and trade. Innovation is a competitive instrument, with producers trying to fight off rivals with the help of improved products and processes [60]. Innovation, referred to improvements in processes and products, is also a driver behind better quality and lower cost, the two key competitive elements in any established industry.

The scope of this research is less ambitious though: because it is focused on an industrial sector, wind energy, this research is centred on globalisation of this industry and within it on the contribution by European companies manufacturing turbines and developing wind farms. As part of the research, some of the economic impacts of these companies at home and abroad are analysed.

Previous research explored globalisation connected to different industrial sectors. Gourevitch et al. studied the effects on the hard disk drive (HDD) industry [61]. This industry had, at the time, worldwide revenues of $30 billion, which is of similar order of magnitude as the turbine manufacture industry at around $53 billion[7]. Although firms from the US dominated the industry in its beginnings, locally manufacturing around 80 % of the world's HDD and thus proved to be the most innovative firms, production moved to Asia by 1995. That year, while "over 80% of the world's hard disks were made by US firms, less than 5% of drives were actually assembled in the US". In terms of employment in 1995 "only 20% of the world's employees in the HDD industry worked in the United States, yet over 60% of the wage bill paid by US firms were earned in the United States."

The globalisation of the pultrusion technology industry suggests that already some time ago low labour costs stopped being the most significant element behind delocalisation of production to emerging economies. In this case, vicinity to significant markets – as the case of China – was a major reason [62]. Incidentally, the pultrusion industry is indirectly linked to wind energy in that they both use fibreglass, the main material in rotor blades [63]. Interestingly, the

6 In this research "global" is considered equivalent to "international", and refers to economic activity distributed across at least two countries.

7 Based on 54 GW installed of which 23 GW in China [111], at an average global turbine cost of 1,13M$/MW [85] with a 30% discount in China.

globalisation of the mechanical industry in Italian industrial clusters shed some additional light on the relationships client company – local suppliers that can help understanding how to promote a local supply chain [64], something that was reviewed in this research.

The analysis of globalisation of the energy field can be focused on trade of energy resources and fuels or on means of exploring, transforming and exploiting energy – the latter perhaps linked more to industrial policy than to energy policy. The globalisation of conventional energy resources (coal, natural gas, nuclear fuel, and oil and oil products) was explored by Overland (2016) who found that it is growing and accelerating [65]. Renewable energy resources are globally available per nature: solar, wind, water and biomass are present everywhere although to a different extent. Energy products from renewable energy sources (e.g. pellets from biomass) are traded [66] and thus subject to globalisation. The energy industrial sector is significantly globalised with multinational corporations operating worldwide. Further, there is evidence of the positive impact of policies in the development of the wind industry [67]. As Kuik et al. found, the competitive advantage of the European wind industry is based on the pioneering character of the related regulation, and it is long lasting [67], [68].

Many theories about the process of firm internationalisation can be found in the literature. Among the best known is the Uppsala model, which presents growth in the international activities of a company as a gradual process of expansion into new markets [69], [70]. This expansion occurs through a series of successive stages that result in an increasing degree of international operations. A second approach explains internationalisation as a process of learning or the development of company capabilities to recognize opportunities in international markets [71]. Researchers have focused on the importance of establishing relationships [70], [72]; firm growth is seen as a dynamic process, strongly dependent not only on a competitive product or service but also on the opening and strengthening of relations with players in other markets. Research has also focused on technical know-how, location [73] and international entrepreneurship [74], in which both emerging and consolidated companies can create value based on the use of their entrepreneurial skills in their internationalisation processes.

Time is a key factor of competitive advantage, as the first company entering a new country positions itself better in this market. Management of time in terms of the order, timing and speed of the process is an essential aspect of a firm's international expansion [75]. The speed of internationalisation is therefore a matter of interest in the study of business globalisation, but most studies analyse the process only until the moment the company starts to internationalise [76], [77]. However, some researchers have argued that it is necessary to consider not only the time a company takes to establish its business in the first foreign market but also the time that elapses until it consolidates its international activity [78], [79]. Furthermore, some studies have suggested that speed does not always positively influence performance [80]. Finally, firm size, firm age and other factors influence the success, measured in terms of profitability, of the international activity of a firm [81].

In the case of the wind industry, there are hardly any references that address how the international expansion processes of the companies occurred [82]. In this sector, there have been asymmetric developments in different regions, mainly depending on specific political support and the economic and industrial background. On the one hand, Europe has led technological development for 40 years, using first the local market for wind energy deployment and later expanding to other regions based on the experience gained. Innovation has been, and still is, a key factor in the growth of companies beyond their national borders. On the other hand, China has become an important player in recent years, capturing almost half of the new capacity installed annually, which has allowed the technological and business growth of local companies.

The wind industry is relatively young, since it has only reached a significant size during the last 20 years. In terms of its main indicator, cumulative installed capacity in gigawatts (GW), it has grown from less than 20 GW in 2000 to 590 GW by the end of 2018 [83]. By considering this deployment as well as the unit costs from, for example, IEA Wind [16], [84], Bloomberg New Energy Finance [85] and Joint Research Centre [86], I estimate that the approximate equivalent cumulative investment reached $50 billion by 2000 and $1370 billion by 2018.

Some research papers have confirmed that the creation of a domestic market in renewable energies has been decisive for the competitiveness and internationalisation of companies [87]–[90]. This impact of the local market is particularly true in the case of companies in Europe and the USA, whereas the large Chinese market has not been decisive for its companies to actively participate in the global industry, at least until 2018 [82].

Indicators for measuring the degree of internationalisation of firms include the transnationality index [91], the network spread index [92], the Herfindahl-Hirschman index and other indices. Those indicators have been used to measure the degree of internationalisation intensity, geographic extensity or geographic concentration of the firm's international activity, respectively [93] (cited by [94]).

However, there was little research on the internationalisation of the wind energy industry in general and of wind turbine manufacture in particular, and none of the available research papers used internationalisation indices. Yet, quantitative assessment is necessary to enable robust, unbiased research to identify the international strategies of wind companies and to increase the understanding of the historical evolution and current trends.

The objective of this part of the PhD was to select the appropriate indices for assessing the globalisation of the main wind turbine manufacturers worldwide, and to apply them. In this way, we addressed the internationalisation effectiveness of these companies that eventually resulted in the current global deployment of wind energy.

The novel contributions of this research were (a) the proposal of a set of indicators to measure the degree of internationalisation of wind turbine manufacturers, indicators which combine structural indicators with indices for measuring the speed of internationalisation, and (b) their application to data of the installed capacity by the 15 major manufacturers in 112 countries and territories over the past 40 years.

3. Published papers

The PhD thesis includes the following published articles:

- *Offshore wind installation: Analysing the evidence behind improvements in installation time*. Roberto Lacal Arántegui, Dr José M. Yusta, Dr José Antonio Domínguez-Navarro. Renewable and Sustainable Energy Reviews, Volume 92, September 2018, Pages 133–145. https://doi.org/10.1016/j.rser.2018.04.044
- *Technology effects in repowering wind turbines*. Roberto Lacal Arántegui, Dr Andreas Uihlein, Dr José María Yusta. Wind Energy, Volume 23, Issue 3, March 2020, Pages 660-675. https://doi.org/10.1002/we.2450
- *Globalization in the wind energy industry - contribution and economic impact of European companies*. Roberto Lacal Arántegui. Renewable Energy, Volume 134, April 2019, pages 612-628. https://doi.org/10.1016/j.renene.2018.10.087
- *Measuring the internationalisation of the wind energy industry*. Roberto Lacal Arántegui, Dr José María Yusta. Renewable Energy, Renewable Energy 157 (2020) 593-604. https://doi.org/10.1016/j.renene.2020.05.053

Offshore wind installation: Analysing the evidence behind improvements in installation time.

Roberto Lacal Arántegui, Dr José M. Yusta, Dr José Antonio Domínguez-Navarro.

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Offshore wind installation: Analysing the evidence behind improvements in installation time

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ABSTRACT

The most important single event of the last years in wind energy technology is the reduction in the cost of producing wind electricity offshore, a reduction that can reach 75%, depending on the system boundary considered, for installations commissioned by 2024. Surprisingly, there is very little scientific literature showing how this reduction is being achieved.

The objective of this paper is to analyse the evidence behind cost reduction in one of the most significant cost elements of offshore wind farms, the installation of foundations and turbines. This cost is directly dependent on the daily rates of the installation vessels and on the days it takes to install those wind farm elements. Therefore, we collected installation data from 87 wind farms installed from 2000 to 2017, to establish the exact time for installation in each.

The results show that advances have reached 70% reduction in installation times throughout the period for the whole set, turbine plus foundation. Most of these improvements (and the corresponding impact in reducing costs) relate to the larger size of turbines installed nowadays. There is, therefore, not any leap forward in the installation process, but only incremental improvements applied to turbines that are now four times as large as in 2000.

1. Introduction

Wind energy, both onshore and offshore, is one of the key technological options for a shift to a decarbonised energy supply causing, among other benefits, a reduction in fossil fuel use and in greenhouse gas emissions [1].

It is offshore that wind energy has traditionally most been presented as an energy source with a huge unrealised potential. To date, this is because of the complexity of the technology and project management, the harsh marine environment, and the related high cost of installing wind turbines in the seas. However, this is set to change. The technological developments of the last ten years, among other factors, have led to significant cost reductions that have manifested in recent tender and auction prices.

The analysis of the evolution of offshore wind farm installation time is all but absent in the scientific literature. Schwanitz and Wierling [2] briefly discussed construction time as part of their thorough assessment of offshore wind investment, and showed that wind farm offshore construction time has increased from 2001 to 2016, but it has decreased in unit term (years/MW). One of the data issues shown by this research is the very disperse data set giving $R^2 = 0.05$ (see Fig. 4b in [2]), when construction times are "measured as the period between the beginning of (…) offshore construction and the date of commissioning", perhaps a relatively low level of detail. Interestingly, these authors also discuss the impact of water depth in driving installation costs.

Based on Benders decomposition, Ursavas [3] modelled the optimisation of the renting period of the offshore installation vessels and the scheduling of the operations for building the wind farm. This author provides interesting information on the impact of weather on installation, e.g. "for the Borkum West project the installation of a complete top side of the wind turbine generator that MPI achieved was 25 hours yet some wind turbine generators were under construction for over 3 weeks due to weather conditions". This same purpose, the modelling of the optimisation of transport and installation, was the result of the research by Sarker and Ibn Faiz, concluding that "the total cost is significantly impacted by turbine size and pre-assembly method" [4].

Abbreviations: CapEx, capital expenditure; EU, European Union; GW, gigawatt; IEA, International Energy Agency; MP, monopile; MS, megawatt; OWF, offshore wind farm; TIV, turbine installation vessel; TP, transition piece

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1364-0321/

Table 1
Recent offshore wind tenders and auctions, and winning prices in EU countries.

Date announcement	Country	Project name	Size (MW)	Winner	Bid (€/MWh)	(Expected) commissioning
2010/06/22	DK*	Anholt	400	Dong Energy	**140.00**	2012/3
2013/12/30†	UK	Dudgeon	402	Statoil et al.	**186.10‡**	2017
2014/04/23†	UK	Beatrice	588	SSE et al.	**173.70‡**	2019
2015/02/26†	UK	East Anglia One	714	Vattenfall/SSP	**164.72**	2018
2015/02/26†	UK	Neart na Gaoithe	448	Mainstream	**157.17**	2019
2015/02/27	DK*	Horns Rev 3	406.7	Vattenfall	**103.20**	2018
2016/07/05	NL*	Borssele 1 & 2	752	Dong Energy	**72.70**	2020
2016/09/12	DK*	Vesterhav	350	Vattenfall	**63.82**	2020
2016/11/09	DK*	Kriegers Flak	605	Vattenfall	**49.90**	2020
2016/12/12	NL*	Borssele 3 & 4	702	Shell et al.	**54.50**	2021
2017/04/13	DE*	Borkum Riffgrund West 2	240	Ørsted	Market price	2024
2017/04/13	DE*	He Dreiht	900	EnBW	Market price	2025
2017/04/13	DE*	Gode Wind 3	110	Ørsted	60.0	2023
2017/04/13	DE*	OWP West	240	Ørsted	Market price	2024
2017/09/11†	UK	Triton Knoll	860	Innogy	86	2022
2017/09/11†	UK	Hornsea 2	1386	Ørsted	64.1	2023
2017/09/11†	UK	Moray East	950	EDPR, Engie	64.1	2022
2018/03/19	NL*	Hollandse Kust (Zuid)	750	Vattenfall	Market price	2023

Notes: exchange rates to Euro correspond to the day the winner was announced; Dong Energy changed name to Ørsted; *offshore substation and/or HVDC transformer station, and connection to the shore are provided by the transmission system operator and thus not included in the bid price; †date of granting of contract for differences or equivalent. Sources: press releases, offshorewind.biz web site and, for (‡), WindEurope [7].

The objective of this research is to increase scientific knowledge on offshore wind farm installation time and its evolution. This is done by exploring and analysing the installation to a high level of detail, separately focusing on foundation, turbine and whole-set[1] installation. This paper quantifies the improvements for the period 2000 – 2017 in terms of days per foundation and per megawatt rating of the turbine mounted there (megawatt-equivalent or megawatt for short). This article provides actual figures for these parameters that could be necessary for any further research on cost-reduction of the installation of offshore wind energy.

Section 2 extends on specific aspects of the background e.g. giving details of costs and recent cost reductions, whereas Section 3 presents the modelling methodology used in this research and the resulting initial picture. The next three sections present and discuss the results for the three aspects under study: installation of foundations (Section 4), installation of turbines (Section 5) and installation of the set foundation + turbine (Section 6). Finally, Section 7 wraps up the results with a brief summary and conclusion.

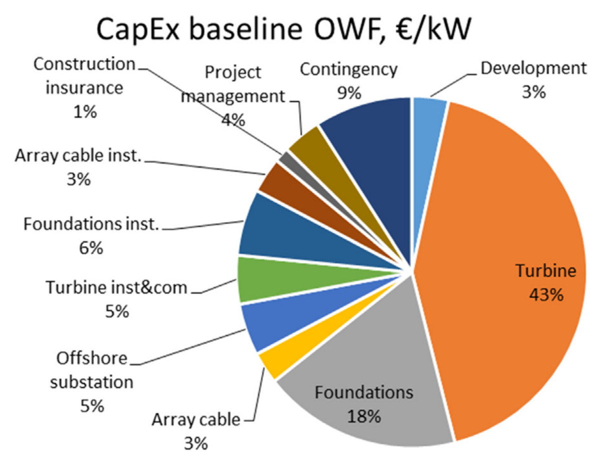


Fig. 1. Estimated breakdown of the capital expenditure of a baseline offshore wind farm in 2015. Source: [9].

2. Background

After a period of cost increases (see Fig. 4 in [5]), the cost of offshore wind energy started to descend even in a very radical way. The evidence for this, as shown in Table 1, is the successive results of tenders and auctions that different European governments used in order to foster the development of offshore wind farms. The tenders involve that the winners will receive their bid price for a number of years, with or without adjustment for inflation depending on the country regulations.

There are significant differences in the period that the bid price will be received and in other key conditions. Also, recent German and Dutch [6] bids at "market price" were awarded without any additional subsidy in addition to the wholesale electricity price.

The significance of the cost reductions shown in Table 1 is even greater when compared to what the wind energy experts expected as recent as two and half years ago. An expert elicitation survey of 163 of the world's foremost wind experts run during late 2015 suggested ***significant opportunities for 24 – 30% reductions by 2030*** [8]. Table 1 shows, for example, that reductions already reached 52% just in the 1.8 years between the Danish Horns Rev 3 and Kriegers Flak OWF tenders.

In order to achieve these prospective cost reductions, offshore wind farm projects need to tackle all the elements that make up their cost. These elements are, in essence, depicted in Fig. 1 copied here from Smart et al. [9]

Costs are highly project-specific. For example, cable connection to the onshore substation used to cost around one million EUR per km [10], and wind farms commissioned in the period 2015–2017 are placed between 1 and 115 km from the coast and required between 6 [11] and 210 [12] km of high-voltage export cable. For different authors wind turbine and foundation installation contributes between 10% and 12% [9] and 16% [13] of capital expenditure (CapEx) of an offshore wind farm. The former figure corresponds to the characteristics of the ones installed in Europe during 2014/2015[2] whereas the latter was reported in 2010 with a focus on the UK.

The installation of foundations and turbines consists essentially of the following actions: (a) adaptation of the vessel for the job (an activity called *mobilisation*); (b) port loading of the turbines/foundations

[1] Throughout this document the term "set" is used to reflect the set of one turbine plus all the elements that constitute its foundation, e.g. monopile/jacket, transition piece, piles fixing jackets, etc.

[2] The baseline data represented in this graph corresponds to a 400-MW, 100-turbine model offshore wind farm as described by IEA Wind Task 26 documentation (see Smart et al. [9]).

Table 2
Indicative costs of vessels involved in turbine installation.
Source [16]

Vessel type	Daily rate (USD)
Turbine installation vessel	150,000 – 250,000
Jack-up barge	100,000 – 180,000
Crane barge	80,000 – 100,000
Cargo barge	30,000–50,000
Tug boat	1000 – 5000

on the installation vessel[3]; (c) transport to the wind farm site; (d) installation; (e) vessel returns to port; and (f) removal of the installation equipment (called *demobilisation*). With turbine/foundation installation vessels able to carry a few items per trip, actions (b) to (e) above are repeated several times per wind farm [14].

Mobilisation and demobilisation are cost elements paid normally as a lump sum. Loading, transport to site, installation and return to port are activities whose effort depend on wind farm size (i.e. no. of turbines/foundations to install); distances to marshalling harbours, turbine and foundation size and type; and most crucially, weather [15].

The main installation cost - turbine installation vessels- charge daily rates as shown in Table 2 of Ahn et al. [16], partly reproduced as Table 2 here. The main differences are due to vessel performance and use. For example, turbine installation vessels (TIV) have carried from 1 to 10 turbines, and a vessel carrying only two full turbine sets (tower, nacelle, hub and blades) has necessarily to be cheaper than a vessel able to transport ten turbine sets each trip. Nine of the largest eleven wind farm installation vessels used in Europe have been built since 2011.[4]

A turbine installation vessel, MPI Resolution, installed 75 foundation and turbines at Lincs OWF (UK) starting 2011, at an average 9.5 days per set. Assuming a rate of USD 150,000/day (she was subject to a long let which can be expected to reduce daily rates), the cost of this aspect of the OWF installation was 107 M USD (plus mobilisation/demobilisation costs), or 65.5 M GBP at the average exchange rate of 2009 Q4. The declared CapEx at the time of investment decision was 725 M GBP and thus this part of the installation is 9% of total CapEx.

Although the focus of this study is the improvement in installation times, it is perhaps worth mentioning some of the factors that complicate or delay installations. In addition to weather conditions (preventing lifts), these include unexpected ground conditions, storm damage to the construction vessels [17], encountering unexploded ordnance [18], inexperienced project or vessel team, etc. Some types of foundations (e.g. tripiles, jackets) require longer installation time than others (e.g. monopiles), whereas different procedures for installing the turbine are subject to more strict wind conditions at hub height, and thus have fewer and shorter weather windows for installation.

3. Methodology and overall picture

3.1. Units used

The installation unit used for this analysis is "vessel-day", or the number of days that a given installation vessel spends installing a foundation, set of foundations, turbine or set of turbine items. Thus, for example, if one vessel installs all the turbines, the number of vessel-days per turbine is:

$$Vd_t = \frac{d_{ie} - d_{is}}{N_t}$$

where $\boldsymbol{Vd_t}$ is the number of vessel days per turbine installed; $\boldsymbol{d_{ie}}$ is the date turbine installation ends; $\boldsymbol{d_{is}}$ is the date turbine installation begins, and $\boldsymbol{N_t}$ is the number of turbine installed by the given vessel

In the cases when more than one vessel has been installing the given item or set of items, it is necessary to take into account the period that each vessel has been installing, and the formula is modified to:

$$Vd_t = \sum_{i=1}^{n} \frac{(d_{ie} - d_{is})}{N_t}$$

where $\boldsymbol{n}$ is the number of vessels installing any turbine items. For example, two vessels that installed the same item (e.g. turbines) during one week are counted as 14 vessel-days.

These aspects will also be analysed in terms of days per megawatt installed.

The concept of "vessels" used for this analysis includes only large installation vessels able to install the heavy items (see below), such as purpose-built TIV (e.g. Bold Tern [19], Pacific Orca [20]); self-propelled jack-ups (e.g. Sea Installer [21], Seajacks Leviathan [22]); jack-up barges which need tugs for propulsion (e.g. JB114 [23]); or heavy-lift vessels (e.g. Oleg Strashnov [24], Jumbo Javelin [25], or Svanen [26]).

Items whose installation is considered separately, when information is available, include: the complete turbine or any of its parts; monopile, transition piece, gravity foundation, jacket, tripile and anchor piles (for jackets and tripiles).

3.2. Milestones used

The equations above are based on $\boldsymbol{d_{ie}}$ and $\boldsymbol{d_{is}}$, the key date milestones:

- $\boldsymbol{d_{ie}}$ is the day the last foundation or turbine item is installed.
- $\boldsymbol{d_{is}}$ is the day the vessel leaves the operations, or marshalling, harbour towards the wind farm site for installing the first foundation or turbine component.

whereas $\boldsymbol{d_{ie}}$ is very often reported in press releases, $\boldsymbol{d_{is}}$ is often not reported and, instead, the date the first item is installed is reported. In most of these cases, the data were sought specifically and, when not available, an allowance was made of 2 days to cover for the first trip to site.

Appendix A includes the number of vessel-days resulting from calculations by using these milestones.

3.3. Data issues and assumptions

Some key data were sometimes subject to contradictions, and an attempt was made to verify these data. At times, the contradiction remained and a decision had to be taken based on the reliability of the different sources.

The data on which this research is based have been collected by the authors mostly from the following sources:

- Direct communication from companies Muhibbah, MPI, others
- Notice to Mariners sent by email or published from Tom Watson (Irish Sea), Seafish (English part of the North Sea), or developers
- Web sites of installation companies, including press releases, track records, annual financial reports and others
- Web sites of developers, wind farms, ports, consultants and other players.
- Twitter, Linkedin and Facebook, where individuals post information about specific events
- Sector web sites 4COffshore [27] and offshorewind.biz
- Generalist, but mostly local, web sites such as Daily Post (www.dailypost.co.uk)
- Official reports such as those from the UK's Offshore Wind Capital Scheme

[3] A number of OWF projects transported foundations by floating these and using tugs instead of turbine/foundation installation vessels (the latter only did the installation).
[4] Source: individual vessel specifications.

Finally, a small number of data points have been collected from AIS (Automatic Identification System), based on a beacon emitting vessel location information [28].

The research includes 89 offshore wind farms that started installation between 2000 and 2016 as shown in Appendix A. However, there are some specificities:

- Wind farms that were installed together, as a single project, were here analysed as a single data point. These include Gunfleet Sands I & II (UK); Lynn and Inner Dowsing (UK); and Gode Wind I & II (Germany).
- Wind farms that installed two different kind of foundations were split into two data points. For example, EnBW Baltic 2 installed 41 turbines on jackets and 39 on monopiles, thus they were considered 2 wind farm projects.
- Only commercial projects were considered whereas experimental/prototype wind farms were excluded. However, most of the latter are included in Appendix A for reference.
- Outliers were included in the research as far as they are commercial projects.

As a result, the number of data points varied depending on the item analysed. For example, the analysis of turbine installation included 74 data points, whereas there were 59 monopile foundation installations analysed.

A significant part of the vessel time is lost due to bad weather making working offshore unsafe, this is called "waiting-on-weather" or "weather days". There was no way those days could be identified and therefore a key methodological decision was not to take them into account in the analysis. Another reason contributed to this decision: it was considered that an effect of vessel technology improvement is to reduce weather days, and thus this effect should be captured in this research.

Time lost due to mechanical breakdown was not discounted either, unless the vessel left the site for a period longer than two weeks.

Fig. 2 shows the overall picture of wind farms –this time including most experimental ones- with turbines fully installed from 2000 to 2017, based on the year the first foundation was installed. The figure includes 57 monopile installations, 11 gravity-base foundations, 9 jackets and 4 tripod/tripile installation for a total of 81 single-entry offshore wind farms. The first floating OWF, Hywind Scotland, is not included in the graph.

The vertical axis has been limited to 20 vessel-days in order to allow better readability. Because of this, prototypes or demonstration projects

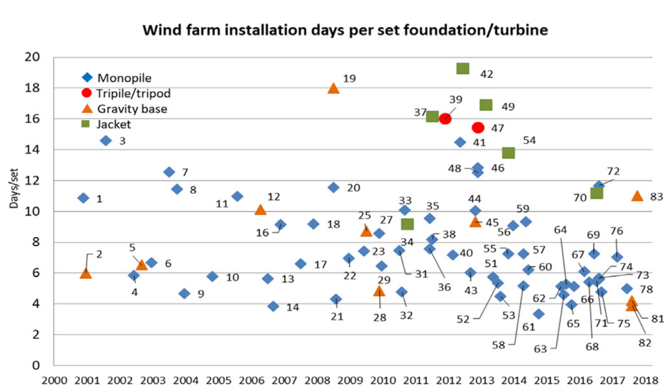


Fig. 2. Overall picture of installation (vessel-) days per each set of one turbine plus its corresponding foundation, with breakdown according to type of foundation. Source: own data. Notes: wind farms that were installed as a single entity (e.g. Lynn and Inner Dowsing) were counted as a single project; numbers correspond to wind farms in Appendix A; vertical axis has been triggered to 20 in order to allow better readability, even when this leaves out of range outliers such as Bard (tripile) or experimental projects such as Beatrice pilot (jacket), Alpha Ventus (tripod and jacket), and Nissum Bredning (steel gravity).

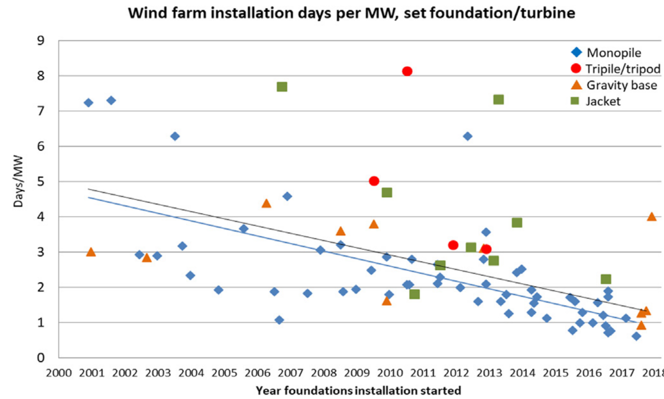


Fig. 3. Wind farm installation days per megawatt of installed capacity, for the set turbine + foundations, with breakdown according to type of foundation. Source: own data.

such as Belwind Haliade cannot be seen in the graph. OWF installed prior to the year 2000 are not considered either.

It is interesting to note that the spread of projects with installation days in Fig. 2, first increasing and lately decreasing, is broadly consistent with the evolution of installation costs [5]. The R-square value of all projects is 0.0095. However, if experimental installations are excluded, the R^2 value increases to 0.02, it reaches 0.1323 for monopile-based wind farms, and finally 0.1629 if only a range of monopile installations (for turbines between 3 and 4 MW) is considered.

Time needed for transporting foundation items (typically monopiles as in Anholt but also e.g. jackets in Alpha Ventus) when transport vessels were tugs or barges was not accounted for, even when it is acknowledged that this has an impact of reducing the use of larger installation vessels.

Some uncertainty in some of the data above is due to different, specific reasons:

- When the milestone was not specified but loosely, e.g. "mid-April". In this case the middle day of the period specified was taken, e.g. the 16th April in this case.
- When more than one vessel was used and the exact dates were not published. Different assumptions were made in this case, e.g. comparing with installation time of a vessel with similar characteristics.

Fig. 3 shows vessel-days per MW of the set of a turbine plus its foundation. Figs. 2 and 3 are comparable because the same OWFs are included with the only exception of the four OWF out of vertical range in Fig. 2.

Comparing both figures suggests that the bulk of the dots rotates in a clockwise direction, a result of the effect of increasingly larger turbines in reducing installation time per MW. In other words: installation of the foundation-turbine set has not reduced time significantly but the sets are getting larger, thus reducing the installation time per MW.

4. Foundations installation: results and discussion

4.1. Generalities about foundation installation

Offshore wind foundations in Europe is a field dominated by the simple and well-proven monopile technology. Fig. 4 shows the type of foundations per installed capacity in the EU, at the end of 2017, based on offshore wind farms already installed (in green), and in the different stages of construction or in advanced development.[5]

[5] The following situations are defined as "in development": the project won a tender or auction; a turbine purchasing agreement has been signed; or the project has consent in place and is clearly advancing towards taking a final investment decision.

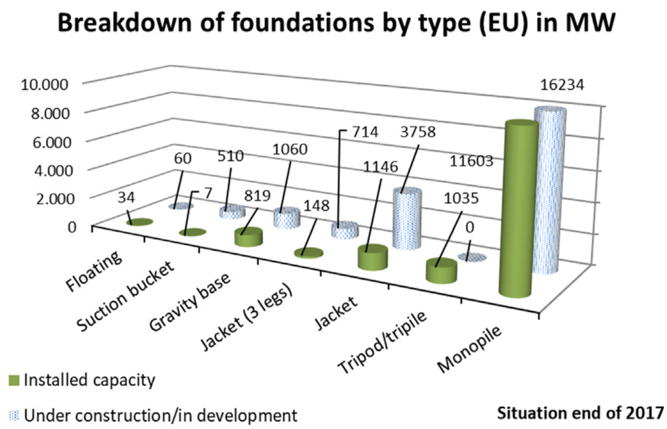


Fig. 4. Breakdown of offshore wind capacity per foundation type, for European OWF, both operational by the end of 2017 and under construction, or in development at the end of 2017 with expected commissioning by 2024. Source: own data. Remarks: 55% of the 22 GW in development have decided the foundation type; for the other 45% it was assumed that monopiles will be used for average depths below 36 m, jackets above 36 m and a few projects will use floating or gravity base foundations.

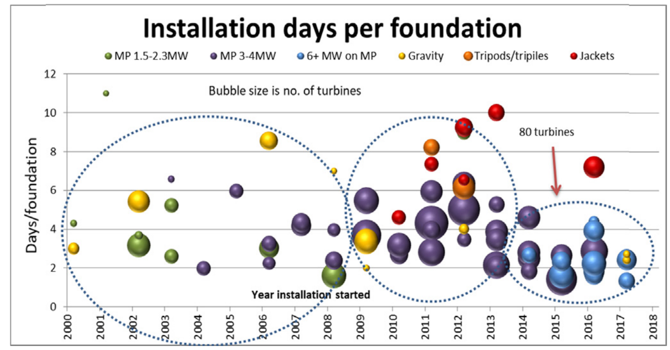


Fig. 5. Overall picture of the time taken to install one foundation (without the turbine) for each OWF that has finished foundations installation. Source: own data.

The domination of monopile foundations is not likely to be challenged in the near future, even when jacket technology is -at the moment- a preferred technology for depths between 36 and 60 m, and suction bucket systems are starting to emerge. Projections to 2024 in Fig. 4 show the decline of tripod and tripile technologies in favour of jackets and monopiles.

OWFs which are not exactly offshore were included in the Fig. 4 but not in the detailed analysis below. These include turbines in inner lakes (e.g. Vanern in Sweden), or physically connected to the coast at the shoreline (e.g. Irene Vorrink in The Netherlands).

Because some of the last OWFs already finished foundation installation there are more foundation than turbine data points, 78 and 74 respectively, excluding floating and non-commercial projects. Of the former, 59 use monopile systems (10 in the 1.5–2.3 MW range, 36 in the 3–4 MW range and 13 above 6 MW), 9 gravity, 3 tripod/tripile, and 6 use jackets.

Fig. 5 shows the overall picture of the evolution of time taken only for the installation of the foundations, in vessel-days per foundation. Three phases can be distinguished: an initial phase until 2008 featuring few installations and very high dispersion, a consolidation phase from 2009 to 2013 when projects became large (up to 175 turbines), significant variation in the type of foundation and higher overall installation time, and the pre-industrialisation from 2014 onwards which shows significant time reductions.

Figures in Table 3[6] show that the set of OWF foundations installed after 2013 took significantly less time to install than the set of foundations corresponding to 2009–2013.

Monopiles installed recently (2014–2017) required only 56% (2.39/4.24) of the installation time needed during the previous period (2009–2013). However, if measured in terms of installation time per megawatt, recent monopiles required only 38% (0.50/1.32) of the time of the previous period.

Comparing figures per megawatt in the recent period shows that the set "all foundations" takes longer to install per MW (0.54 vessel-days) than monopiles (0.50). The difference is minor only because monopile installations outnumbered non-monopile installations 23 to 4 during the period 2014–2017

Fig. 5 shows as well that whereas modern monopile-based installations are the fastest foundations to install, two gravity base projects very close to the coast also were object of very efficient installation. However, on average non-monopile projects on average take longer to install.

There is therefore a pre-eminence of monopile foundations in the OWF installed or being installed, resulting in a larger dataset. In addition, there is a trend for monopiles to cover increasingly deeper waters and larger turbines. Thus, it is appropriate to focus the remaining analysis of foundations and turbine-foundation sets on monopile-based installation.

4.2. Does installation time depend on water depth and/or distance from the coast?

Fig. 6 shows that the number of existing OWFs really far from the coast or in waters 30 m or more is small: 4 and 9 respectively, out of 59. The graphs show that most deep-water monopile installations to date took place not far from the coast, up to 45 km.

In theory at least, both deeper waters and distances farther from shore should cause longer installation times. This is because deeper waters would make installation more complex and monopiles are larger and need to be hammered deeper into the subsea; further distances involve longer navigation time for the installation vessels.

However, the data in Fig. 6 tell a very different story: installation time is in general independent from average water depth whereas it only shows a minor positive correlation with distance to shore in the case of the larger turbines. Regarding water depth, it is perhaps significant that the dispersion of installation days with water depth is very high below 25 m but it is much lower beyond this depth. Regarding distance, the two farthest-away data points of the 3–4 MW turbine series shown in Fig. 6 (right) correspond to wind farms with low installation time, 2.7 and 1.43 vessel-days per monopile respectively. The reason is perhaps that both wind farms (Sandbank and Gemini) started installation very recently (2015), when technological advances and organisational learning caused important reductions in installation time.

Conversely, Fig. 6 shows that wind farms with equal or very similar depth/distance have taken very different installation time. For example, OWFs Meerwind and Borkum Riffgrund 1, at 24 and 26 m depth, located 53 and 54 km from shore and with similar distances to the installation ports (92 and 80 km), took 6.4 and 2.5 vessel-days, respectively, to install. Interestingly, they both installed the same turbine model and had similar total capacity, and thus these factors cannot be accounted for the differences. The main difference is likely to relate to vessels and installation methods. In addition, the former started installation in 2012 whereas the latter in 2014.

[6] Table 3 does neither consider floating wind farm Hywind Scotland nor experimental projects Alpha Ventus, Gunfleet Sands III, Belwind Haliade, Nissum Bredning, Blyth Demonstration, and Beatrice pilot.

Table 3
Average installation time in vessel-days of the periods 2009–2013 and 2014–2016. Data include outliers. Source: own calculations.

Non-weighted average installation time of foundations	(Vessel-days) /foundation	(Vessel-days) /MW
Foundations started construction between 2009 and 2013 (all foundations)	5.22	1.39
Foundations started construction between 2014 and 2017 (all foundations)	2.56	0.54
Foundations started construction between 2009 and 2013 (monopiles)	4.24	1.32
Foundations started construction between 2014 and 2017 (monopiles)	2.39	0.50

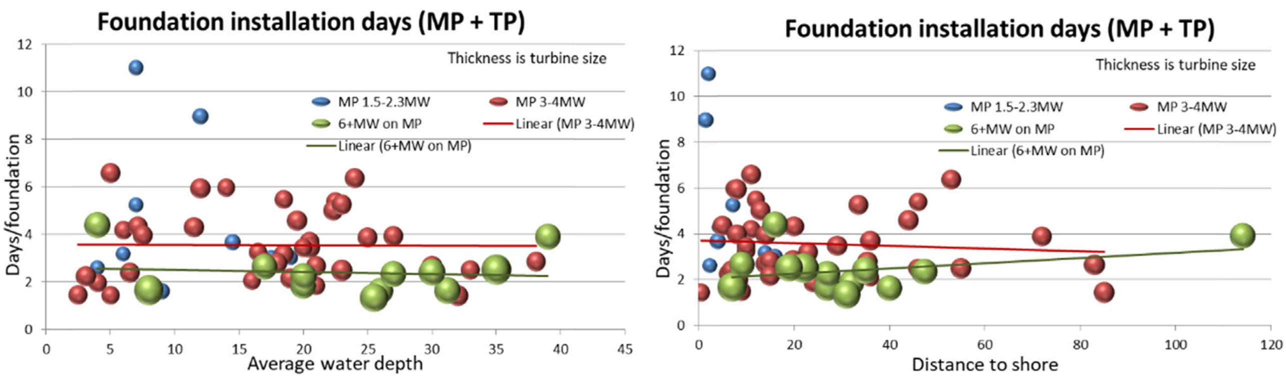
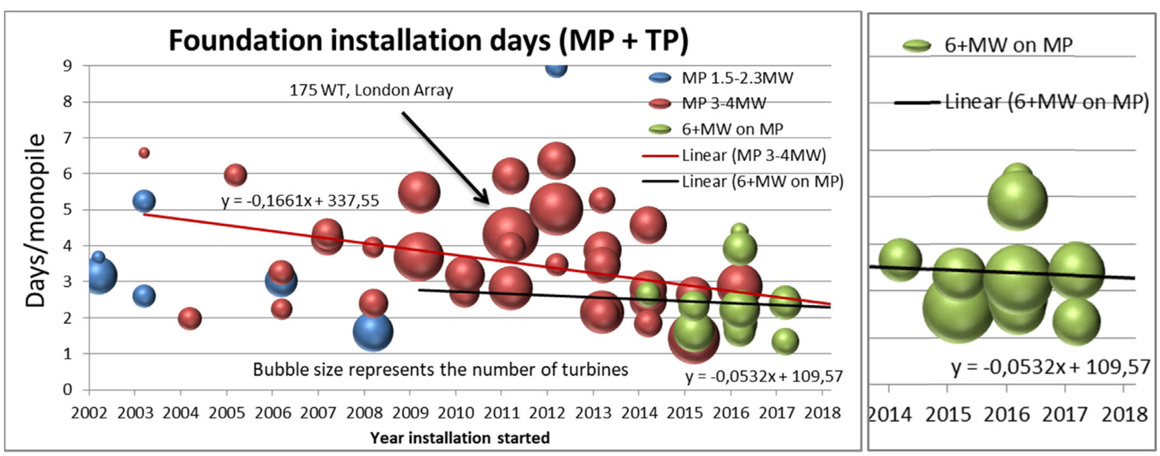


Fig. 6. Relationship between installation time and average water depth and distance to shore. Source: own data, 4COffshore.



(a) (b)

Fig. 7. (a) Evolution of foundation installation days related to wind farm size; (b) enhanced view of the 6 + MW set.

4.3. Economies of scale: relation to wind farm and turbine size

This subsection explores how monopile installation time is related to the wind farm and turbine sizes.

In Fig. 7 the number of turbines is a proxy for wind farm size. The figure shows that there are large wind farms above and below the 3–4 MW trend line. The size of the bubbles (i.e. number of turbines per OWF) does not suggest the existence of economies of scale, as larger wind farms do not take generally less time to install per foundation.

The series of installations with turbines rated 6 MW or above suggest a slightly different situation. Part (b) of Fig. 7 shows that in this group of installations the two largest wind farms (Gode Wind I & II, Race Bank) are, by different margins, more efficient than the weighted average of 2.28 days/monopile. Note that given the higher number of data points, the message conveyed by the 3–4 MW group should be considered more robust.

Given the apparent contradiction, more insight was sought by plotting installation time against the same indicator, the number of turbines, without taking into account the evolution factor (year installation started), for all monopile installations together (Fig. 8).

The data shows that the number of vessel-days reduces only slightly

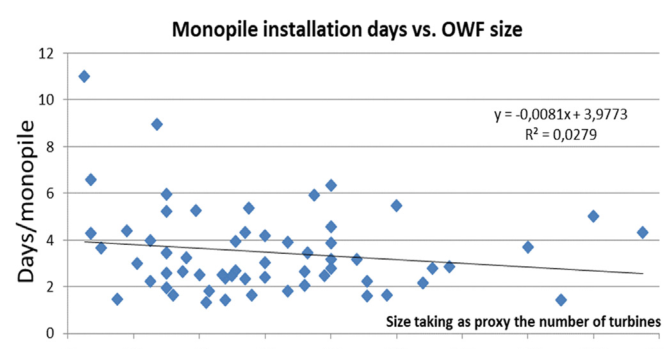


Fig. 8. Relationship between monopile installation time and wind farm size as reflected by the number of foundations.

as the wind farm increases in size. In addition, the R-square factor of 0.0279 shows a level of dispersion such that the results cannot be considered conclusive. Similar analysis but taking the wind farm capacity (in MW) as the proxy for size only improves R-square slightly to 0.0891. This aspect is therefore still not conclusive and by taking both

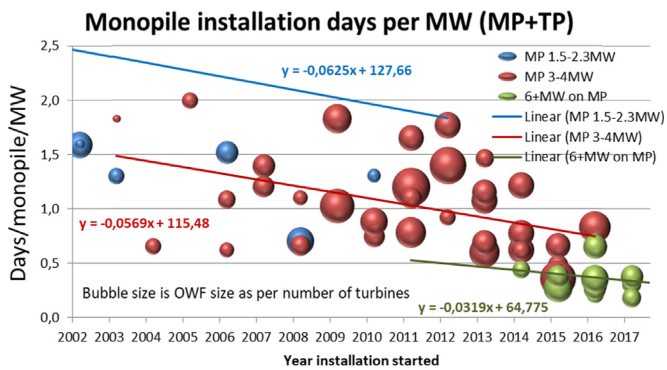


Fig. 9. Monopile installation days per MW terms.

approaches into account we can conclude that there is only a low level of economies of scale with wind farm size.

4.4. Reduction in foundation installation time per megawatt-equivalent

The picture changes significantly if the focus of the analysis is the megawatt-equivalent of monopile installation, as shown in Fig. 9. This unit is better placed to connect with the eventual reduction in the cost of energy.

In effect, the fact that turbine technology has improved and larger turbines are being installed in each foundation is claimed to have had the biggest impact in the reduction of installation days per megawatt. From 1991 up to 2004 essentially only turbines below 2.5 MW were installed on monopiles, whereas after 2006 only turbines in the 3–4 MW range were installed (Fig. 9), with two exceptions. In 2016 for the first time, most wind farms that started installation were designed for turbines larger than 4 MW – in fact as much as 8 MW.

Improvements in foundation installation times per megawatt has thus clearly outpaced improvements per foundation. The reduction in installation time per monopiles from 2000 to 2017 was 58%, as taken from two samples: the non-weighted average of the seven wind farms built between 2000 and 2003 (5.22 days per foundation), and the corresponding one for four wind farms that started to install in 2017 and already finished (2.19 days). Data show that the corresponding figures ***per MW*** of the turbine installed were 2.47 days in 2000–2003 and 0.30 days in 2017, ***an 87% reduction***. One wind farm, Belgian Rentel project, even managed to install monopiles at 0.18 days/MW.

Fig. 9 very vividly proves the large impact that the newer, large turbines have had in reducing installation time per megawatt. Comparing the trend lines for the groups of turbines shows the significant reduction first from the 1.5–2.3 MW to 3–4 MW and recently to the 6 + MW technologies.

4.5. Discussion

Monopile technology dominates the market for offshore wind foundations fixed to the sea floor. Monopiles take, on average, less time to install than any other type of foundation, and more so when measured in terms of days per MW equivalent.

There is no correlation of installation days with water depth nor with distance to shore, but there is a clear trend towards shorter installation time overall. Other variables have a stronger influence, the most important of which could probably be the capabilities of the vessels used and the distance to the construction port instead of the direct distance to the shore.

On average, significant time reductions began to happen after 2013, with monopiles being installed in only 38% of the time (per MW equivalent) as in the period 2009–2013. This was coincidental with entry into service of new, large vessels (140– 160 m long) Pacific Orca, Pacific Osprey, Vidar, Aeolus, Scylla…

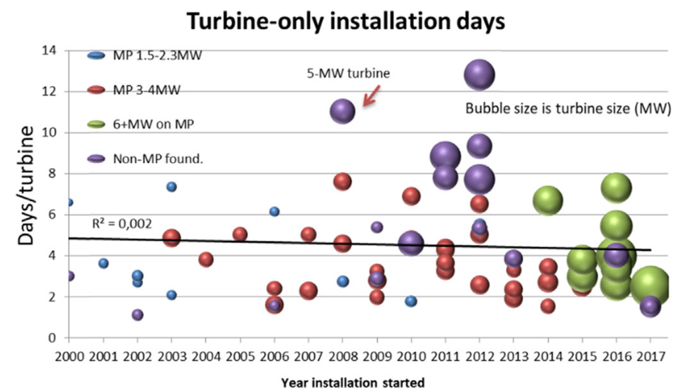


Fig. 10. Evolution of the turbine-only installation days and turbine size for monopile-based installations with turbines between 1.5 and 2.3 MW (blue) between 3 and 4 MW (red), and larger than 6 MW (green), as well as non-monopile-based installations of any turbine rating (purple). Source: own database. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

There is a certain correlation between wind farm size and installation time but this correlation has not evolved with technology or process learning.

The reduction in the time of installation per MW between two samples (2000–2003 and 2017) reached 87%, from 2.47 down to 0.30 days/MW.

5. Turbine installation: results and discussion

Turbine installation is generally independent of the kind of foundation used, and thus this analysis of turbine installation includes turbines on all kinds of foundations.

Has the installation of turbines obtained the same efficiency gains as in the case of the monopile foundations?

Fig. 10 shows that the data have a high level of dispersion, and suggests that turbine installation is nowadays ***only marginally*** more efficient per turbine. This graph shows the turbine installation rate for European OWFs[7] from 2000. The trend line shows only a very slight sign of a reduction in installation time. Therefore, when considered from the point of view of installing only the turbine, the improvement is marginal. Still, it should be noted that turbines have been increasing in size, and this increase makes installation time longer because:

(a) Methods and procedures to install that were learnt and already well managed are not necessarily valid with the larger turbines, and
(b) Larger cranes are needed which may render old vessels unusable.

The size of the bubbles, which represents the size of the wind turbines, hints a more positive view: the installation time per megawatt has been reduced radically, as shown in the following paragraphs and figures.

Fig. 11 plots the time needed to install turbines in megawatts terms for the whole set of turbines and only for turbines installed on monopiles. The vertical axis has been trimmed in order to better show the important points. This leaves out of the picture three wind farms installed in 2000, 2003 and 2006, plus BARD.

The weighted average turbine installation rate **increased** from 2.92 days/turbine in the 9 wind farm built in the period 2000–2003 to 3.39 days for the 12 projects started in 2016–2017 and already finished. However, the installation rate per megawatt of the same set of wind

[7] One OWF is actually not shown in the graph, BARD Offshore 1, at 26.6 days/turbine. It started installing in 2010 and finished three years later with up to four vessels installing turbines. The developer went bankrupt.

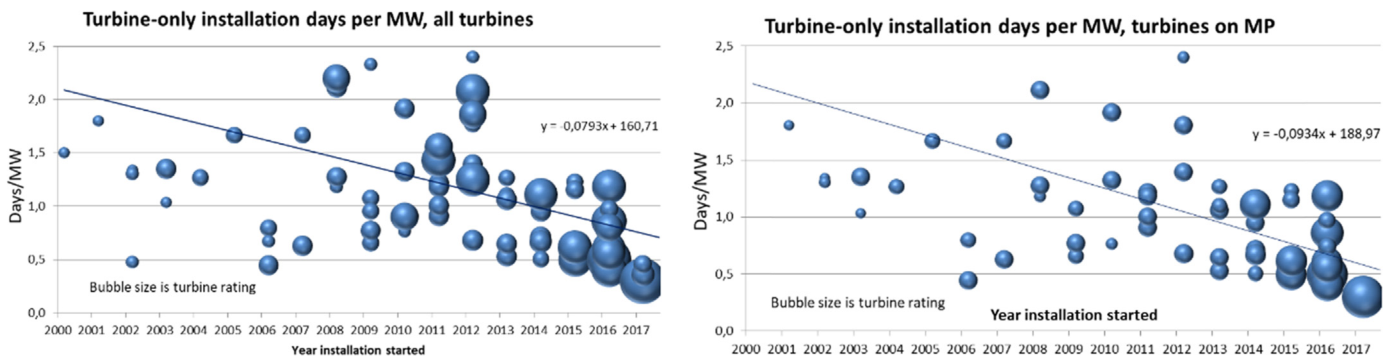


Fig. 11. Turbine-only installation days per MW under two scenarios: all turbines (left) and only turbines on monopiles (right). The installation year corresponds to the start of installation.

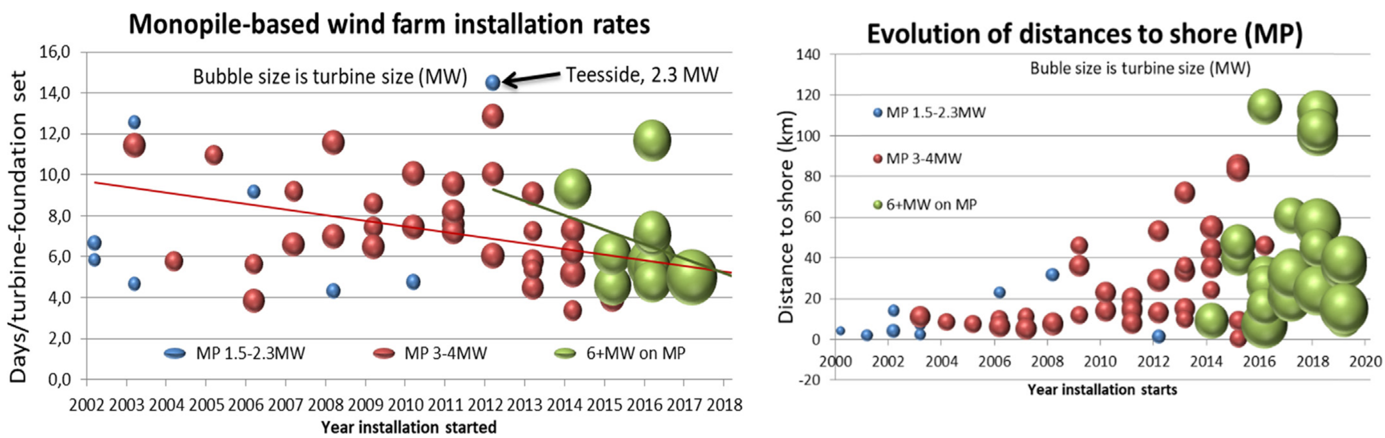


Fig. 12. Monopile-based, full-set installation times and distances to shore.

farms **decreased** from 1.38 to 0.62 days/MW, a 55% reduction.

There are interesting differences between both graphs in Fig. 11. For example, there are no large turbines installed on monopiles prior to 2014; also, the reduction in installation time is steepest in the case of monopile-mounted turbines. However, those two points are more connected that a first look might suggest: because the data shown correspond installation time ***per MW***, the new installation of large turbines (up to 8 MW) on monopiles from 2014 onwards makes the reduction trend per MW steeper for monopiles.

Note that prior to 2014 only two turbines larger than 3.6 MW had been installed on monopiles, at the Gunfleet Sands Demonstration project, and this project is not included in our analysis because of its experimental character.

Both graphs also suggest that from 2013 the dispersion of turbine installation times has been greatly reduced.

In summary, turbine installation times have increased per unit and have significantly decreased per megawatt.

As in the case of monopiles, the availability of larger vessels able to carry more turbines has helped improving installation times per megawatt: the highest number of megawatts carried by a vessel was 9.2 in the period 2000–2003 (4 turbines rated 2.3 MW each) whereas Scylla carried six 6-MW turbines during the installation of Veja Mate OWF.

6. Whole set installation: results and discussion

6.1. Installation rate (vessel-days/set), monopile-based

The graphs show the evolution of the installation time for the whole set turbine plus foundation. Fig. 12 shows that the trend towards a reduction in the installation time of OWF using the smaller turbines (1.5–2.3 MW rated capacities) was broken by the eventful Teesside installation (started in 2012 and needing 14 vessel-days/set). However, the decreasing trend shown by mid-size turbines (3–4 MW rated capacities) is clear and it is based on enough data points to consider it a robust trend. The largest turbine set shows a similar decreasing trend but note that data are less robust because of the lower number of data points.

Interestingly, this reduction in installation times occurs despite the increase in distances to shore.

Focusing on the medium-range turbine group (3–4 MW), whereas Fig. 7 shows that the installation of monopiles has indeed seen a time improvement, Fig. 10 shows that the installation time of turbines on monopiles has not progressed at the same pace.

When observed over the trend line in Fig. 12, the installation of the whole set is reduced from 9 days in 2003 to 6.25 days in 2015 for medium machines (3–4 MW) on monopiles.

6.2. Installation time per megawatt of installed capacity

The picture is very different and the rate of reduction more clear in the case of installation times per MW of turbine (or wind farm) capacity.

Fig. 13 shows that the installation time of OWFs based on monopiles has improved on a per megawatt basis, both for the smaller and for the larger turbines.

The results shown there strongly support the hypothesis that wind farm installation per megawatt is becoming less time-demanding. This conclusion is further reinforced when analysing all wind farms based on monopiles put together, irrespective of turbine rating (Fig. 14).

This figure shows how installation times have decreased per MW for all commercial wind farms using monopiles. The weighted average of the seven wind farms built between 2000 and 2003 was 3.67 days per MW, whereas the average of the nine wind farms that started to install in 2016 and 2017 and have already finished turbine installation was

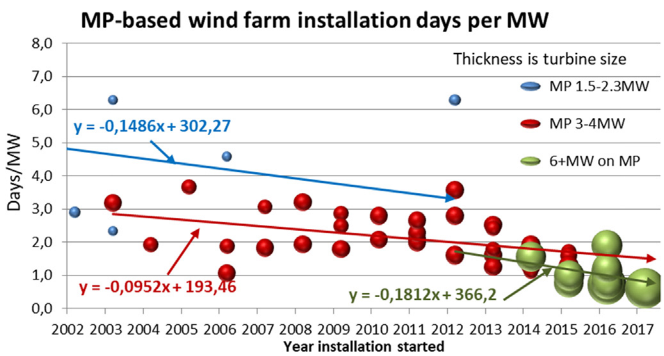


Fig. 13. Evolution installation rates per MW of installed capacity in wind farms with monopile foundations.

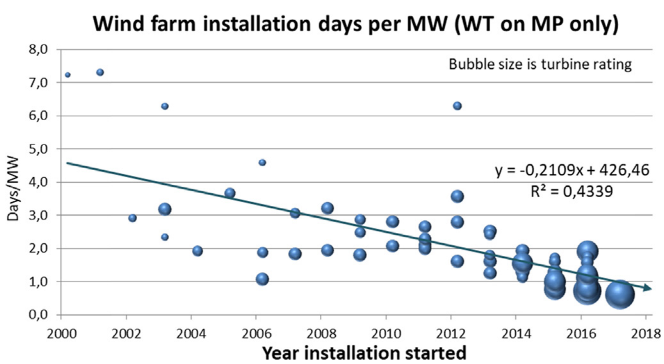


Fig. 14. Evolution of the installation rate for turbines mounted on monopiles, all turbine ratings in a single data series.

Table 4
Average figures for the beginning and the end of the period under study, set foundation plus turbine, and corresponding reduction.

	Simple average		Weighted average	
	Per turbine	Per MW	Per turbine	Per MW
Sets in 7 MP-based wind farms starting construction 2000–2003	9.52	4.59	7.58	3.67
Sets in 9 MP-based wind farms starting construction 2016–2017	6.44	1.17	5.93	1.06
Reduction	32%	75%	22%	71%

1.06 days, ***a 71% reduction***. The wind farm that achieved the lowest installation time, the Walney 3 project, managed to install each set at an average 0.60 days/MW.

The whole impact of larger turbines can only be seen by comparing figures per set and per megawatt (see Table 4).

In conclusion, the installation time of the foundation and the turbine of an offshore wind farm on monopiles has reduced by 22% on a per-turbine basis but a much more impressive 71% on a per-megawatt basis. The latter is a very significant drop that is responsible for an important part of the reduction in the cost of energy from these offshore wind farms.

7. Conclusions

This research presents for the first time the quantification in temporal terms of the learning-by-doing and technological improvements in installation of turbines and foundations of offshore wind farms.

This study shows that turbine plus foundation installation time has decreased from 7.6 days in 2000–2003 to 5.9 days in 2016–2017 for monopile-based projects. Interestingly, this reduction in installation times occurs despite the increase in distances to shore.

The reduction in installation times is stronger when the effect of larger turbines is taken into account. Installation times for all wind farms with monopile foundations were reduced from just below 4 days per MW in 2000–2003 to 1.06 days per MW in 2016–2017, a 71% reduction.

This reduction is mostly caused by improvements in the installation of the foundations. Foundation installation times per megawatt has improved by 87%, significantly more than turbine installation per MW (55%). However, the biggest effect was achieved by the increase in the size of individual turbines (to 8.25 MW at Walney 3) and the corresponding increase in foundations size and reduction in the number of foundations and turbines for the same given wind farm capacity.

This research found that the effect of economies of scale, measured based on wind farm size, was not significant in reducing the installation time for either foundations or turbines.

A limitation of this study is that the effect of waiting-on-weather days has not been discounted, as discussed in subsection 3.3, and we strongly recommend follow-up work that discounts this effect if possible. A second limitation is that some of the dates corresponding to the oldest wind farms lack the accuracy of data available for the newest projects.

We suggest that this research could be a starting point for thorough quantification of key technological and non-technological elements behind the impressive offshore wind cost reductions of late. These include, e.g. other installation elements, mainly cable installation, or the impact of evolving financing rates and financing structures. The resulting research could be put together to fully understand how a technology that is subject to the strong force of nature has been able to manage and dominate it.

Appendix A

See Table A1.

Acknowledgements

This research constitutes a contribution by the Joint Research Centre to the work of the IEA Wind Technology Collaboration Program Task 26 (Cost of Wind Energy), and benefits from input from previous work carried out by the main author for the Joint Research Centre of the European Commission [29].

The authors would also like to thank the provider of industry intelligence 4COffshore and in particular Mr Robert Brookes for their clarification of events in specific cases.

Table A1
Main wind farm features and installation days.

No	Wind farm project	No. of WT	WT power (MW)	WF capacity (MW)	Type of foundation	Year start installation	Days/ foundation	Days/ turbine	Days/ set
1	Utgrunden	7	1.5	10.5	Monopile	2000	4.29	6.57	10.86
2	Middelgrunden	20	2	40	Gravity base	2000	3.00	3.00	6.00
3	Yttre Stengrund	5	2	10	Monopile	2001	11.00	3.60	14.60
4	Horns Rev 1	80	2	160	Monopile	2002	3.18	2.68	5.85
5	Rodsand 1	72	2.3	165.6	Gravity base	2002	5.42	1.10	6.52
6	Samso	10	2.3	23	Monopile	2002	3.67	3.00	6.67
7	North Hoyle	30	2	60	Monopile	2003	5.23	7.33	12.57
8	Arklow Bank I	7	3.6	25.2	Monopile	2003	6.57	4.86	11.43
9	Scroby Sands	30	2	60	Monopile	2003	2.60	2.07	4.67
10	Kentish Flats	30	3	90	Monopile	2004	1.97	3.80	5.77
11	Barrow	30	3	90	Monopile	2005	5.97	5.00	10.97
12	Lillgrund	48	2.3	110.4	Gravity base	2006	8.56	1.54	10.10
13	OWEZ	36	3	108	Monopile	2006	3.25	2.39	5.64
14	Burbo Bank	25	3.6	90	Monopile	2006	2.24	1.60	3.84
15	Beatrice pilot	2	5	10	Jacket	2006	8.50	30.00	38.50
16	Prinses Amalia	60	2	120	Monopile	2006	3.03	6.13	9.17
17	Lynn & Inner Dowsing	54	3.6	194.4	Monopile	2007	4.33	2.26	6.59
18	Robin Rigg	60	3	180	Monopile	2007	4.18	5.00	9.18
19	Thornton Bank I	6	5	30	Gravity base	2008	7.00	11.00	18.00
20	Rhyl Flats	25	3.6	90	Monopile	2008	3.96	7.60	11.56
21	Horns Rev 2	91	2.3	209.3	Monopile	2008	1.61	2.71	4.32
22	Gunfleet Sands I & II	48	3.6	172.8	Monopile	2008	2.39	4.58	6.97
23	Thanet	100	3	300	Monopile	2009	5.47	1.97	7.44
24	Rodsand II	90	2.3	207	Gravity base	2009	3.37	5.36	8.73
25	Alpha Ventus (T)	6	5	30	Tripod	2009	7.50	17.67	25.17
26	Alpha Ventus (J)	6	5	30	Jacket	2009	14.83	8.67	23.50
27	Sprogo	7	3	21	Gravity base	2009	2.00	2.86	4.86
28	Belwind	55	3	165	Monopile	2009	5.38	3.22	8.59
29	Greater Gabbard	140	3.6	504	Monopile	2009	3.69	2.78	6.47
30	Walney I	51	3.6	183.6	Monopile	2010	2.69	4.76	7.45
31	BARD Offshore I	80	5	400	Tripile	2010	14.09	26.63	40.71
32	EnBW Baltic 1	21	2.3	48.3	Monopile	2010	3.00	1.76	4.76
33	Sheringham Shoal	88	3.6	316.8	Monopile	2010	3.18	6.89	10.06
34	Ormonde	30	5.075	152.25	Jacket	2010	4.61	4.57	9.18
35	London Array	175	3.6	630	Monopile	2011	4.31	3.26	7.57
36	Lincs	75	3.6	270	Monopile	2011	5.93	3.61	9.55
37	Thornton Bank II	30	6.15	184.5	Jacket	2011	7.36	8.80	16.16
38	Walney II	51	3.6	183.6	Monopile	2011	3.94	4.25	8.20
39	Trianel Borkum 1	40	5	200	Tripod	2011	8.23	7.80	16.03
40	Anholt	111	3.6	399.6	Monopile	2011	2.81	4.37	7.18
41	Teesside	27	2.3	62.1	Monopile	2012	8.96	5.52	14.48
42	Thornton Bank III	18	6.15	110.7	Jacket	2012	6.52	12.78	19.30
43	Borkum Riffgat	30	3.775	113.25	Monopile	2012	2.97	2.83	5.80
44	Gwynt y Mor	160	3.6	576	Monopile	2012	5.02	5.02	10.04
45	Karehamn	16	3	48	Gravity base	2012	4.00	5.31	9.31
46	Meerwind	80	3.6	288	Monopile	2012	6.36	6.49	12.85
47	Global Tech I	80	5	400	Tripod	2012	6.14	9.30	15.44
48	Gunfleet Sands III	2	6	12	Monopile	2012	6.00	6.50	12.50
49	Nordsee Ost	48	6.15	295.2	Jacket	2012	9.24	7.69	16.93
50	Belwind Haliade prot.	1	6	6	Jacket	2013	0.00	44.00	44.00
51	Dan Tysk	80	3.6	288	Monopile	2013	3.86	1.90	5.76
52	Northwind	72	3	216	Monopile	2013	2.07	3.29	5.36
53	West of Duddon Sands	108	3.6	388.8	Monopile	2013	2.16	2.32	4.48
54	EnBW Baltic II (J)	41	3.6	147.6	Jacket (3 legs)	2013	10.00	3.81	13.81
55	Humber Gateway	73	3	219	Monopile	2013	3.45	3.79	7.25
56	EnBW Baltic II (MP)	39	3.6	140.4	Monopile	2013	5.26	3.81	9.07
57	Amrumbank West	80	3.775	302	Monopile	2014	4.58	2.69	7.26
58	Borkum Riffgrund 1	78	4	312	Monopile	2014	2.48	2.68	5.16
59	Westermost Rough	35	6	210	Monopile	2014	2.66	6.66	9.31
60	Butendiek	80	3.6	288	Monopile	2014	2.79	3.41	6.20
61	Luchterduinen	43	3	129	Monopile	2014	1.84	1.51	3.35
62	Westermeerwind	48	3	144	Monopile	2015	1.44	3.69	5.13
63	Gode Wind I & II	97	6	582	Monopile	2015	1.63	2.97	4.60
64	Kentish Flats Extension	15	3.3	49.5	Monopile	2015	1.47	3.80	5.27
65	Gemini	150	4	600	Monopile	2015	1.43	2.52	3.95
66	Sandbank	72	4	288	Monopile	2015	2.64	2.50	5.14
67	Nordsee One	54	6.15	332.1	Monopile	2015	2.33	3.76	6.09
68	Rampion	116	3.45	400.2	Monopile	2016	2.86	2.55	5.41
69	Veja Mate	67	6	402	Monopile	2016	3.91	3.34	7.25
70	Dudgeon	67	6	402	Monopile	2016	1.84	3.63	5.46
71	Wikinger	70	5	350	Jacket	2016	7.04	3.99	11.03
72	Nordergrunde	18	6.15	110.7	Monopile	2016	4.39	7.28	11.67
73	Nobelwind	50	3.3	165	Monopile	2016	2.49	3.20	5.69
74	Burbo Bank Extension	32	8	256	Monopile	2016	1.66	3.96	5.62

(*continued on next page*)

Table A1 (*continued*)

No	Wind farm project	No. of WT	WT power (MW)	WF capacity (MW)	Type of foundation	Year start installation	Days/ foundation	Days/ turbine	Days/ set
75	Race Bank	91	6.3	573.3	MP	2016	2.23	2.55	4.78
76	Galloper	56	6.3	352.8	MP	2016	1.64	5.41	7.05
77	Walney 3	40	8.25	330	MP	2017	2.51	2.48	4.98
78	Walney 4	47	7	329	MP	2017	2.51		
79	Ajos	8	3.3	26.4	Gravity	2017	2.70	1.50	4.20
80	Tahkoluoto	10	4.2	42	Gravity	2017	2.40	1.50	3.90
81	Blyth Demonstration	5	8.3	41.5	Gravity	2017	8.00	3.00	11.00
82	Hywind Scotland	5	6	30	Spar floater	2017		1.87	1.87
83	Rentel	42	7.35	308.7	MP	2017	1.33		
84	Arkona	60	6.417	385	MP	2017	2.40		
85	Nissum Bredning	4	7	28	Gravity	2017	14.75	13.25	28.00
86	Aberdeen (EOWDC)	11	8.4	93.2	SBJ	2018			

Notes:

– Experimental wind farms or prototype installations are coloured red and underlined.
– Wind farms installed as part of a single project (Gunfleet Sands I&II, Lynn & Inner Dowsing, and Gode Wind I&II) are counted as a single project. Wind farms installing more than one type of foundation (Alpha Ventus and EnBW Baltic II) are treated as two different projects.
– The table does not reflect which wind farms used tugs for floating the monopiles to site (with the consequent time savings) or barges to move other elements (e.g. jackets) to site.

Appendix B

See Table B1.

Table B1
Wind farm installation dates and vessels.

No.	Name	Foundation installation Start	End	Vessels	Turbine installation Start	End	Vessels
1	Utgrunden I	01.09.00	30.09.00	Wind	16.09.00	31.10.00	Wind
2	Middelgrunden	01.10.00	30.11.00	Eide Barge 5	01.11.00	31.12.00	MEB-JB1
3	Yttre Stengrund	01.05.01	25.06.01	Excalibur	15.06.01	15.07.01	MEB-JB1
4	Horns Rev 1	30.03.02	03.08.02	Buzzard, Wind	07.05.02	21.08.02	Sea Energy, Sea Power
5	Rodsand 1	01.06.02	01.07.03	Eide Barge 5	09.05.03	27.07.03	Sea Energy
6	Samso	04.10.02	05.11.02	Vagant	10.12.02	03.01.03	Vagant
7	North Hoyle	07.04.03	15.08.03	Excalibur, The Wind	03.08.03	15.03.04	MEB-JB1, Excalibur, Resolution
8	Arklow Bank I	16.07.03	31.08.03	Sea Jack	01.09.03	05.10.03	Sea Jack
9	Scroby Sands	20.10.03	06.01.04	Sea Jack	25.03.04	01.06.04	Sea Energy, Excalibur
10	Kentish Flats	22.08.04	19.10.04	Resolution	01.05.05	22.08.05	Sea Energy
11	Barrow	15.05.05	15.11.05	Resolution	01.12.05	30.04.06	Resolution
12	Lillgrund	11.01.06	26.02.07	Eide Barge 5	03.08.07	16.10.07	Sea Power
13	OWEZ	03.04.06	28.07.06	Svanen	02.06.06	26.08.06	Sea Energy
14	Burbo Bank	05.06.06	30.07.06	Sea Jack	20.05.07	29.06.07	Sea Jack
15	Beatrice Pilot	15.07.06	31.07.06	Rambiz	01.07.07	31.07.07	Rambiz
16	Prinses Amalia / Q7	22.09.06	26.03.07	Sea Jack	16.05.07	16.11.07	Sea Jack, Sea Energy
17	Lynn & Inner Dowsing	15.04.07	05.12.07	Resolution	15.03.08	15.07.08	Resolution
18	Robin Rigg	15.09.07	09.01.09	Resolution	04.11.08	31.08.09	Sea Worker, Sea Energy
19	Thornton Bank I	26.04.08	06.06.08	Rambiz	16.07.08	20.09.08	Buzzard
20	Rhyl Flats	29.04.08	05.08.08	Svanen	03.04.09	10.10.09	Lisa A
21	Horns Rev 2	13.05.08	07.10.08	Sea Jack	15.03.09	14.11.09	Sea Power
22	Gunfleet Sands I & II	14.10.08	31.12.08	Svanen, Excalibur	24.03.09	31.01.10	Sea Worker, KS Titan
23	Thanet	15.03.09	31.03.10	Sea Jacks, Resolution	09.12.09	24.06.10	Resolution
24	Rodsand II	01.04.09	01.02.10	Eide Barge 5	20.03.09	15.07.10	Sea Power
25	Alpha Ventus	17.04.09	01.06.09	Odin, JB114	02.06.09	16.09.09	Taklift 4,
26	Alpha Ventus	01.09.09	07.09.09	Buzzard, JB115, Thialf	25.09.09	16.11.09	Thialf, Buzzad
27	Sprogo	01.09.09	15.09.09		16.10.09	05.11.09	Sea Energy
28	Belwind	02.09.09	16.02.10	Svanen, JB114	26.03.10	16.09.10	JB114, JB115
29	Greater Gabbard	08.10.09	08.09.10	Stanislav Yudin, Javelin, Leviathan,	09.05.10	21.03.12	Leviathan, Sea Jack, Kraken,
30	Walney 1	02.04.10	17.08.10	Goliath, Vagant	10.07.10	24.01.11	Kraken, Sea Worker
31	BARD Offshore I	07.04.10	08.05.13	Wind Lift I,	02.12.10	01.08.13	Brave Tern; Thor; JB115; JB117
32	EnBW Baltic 1	05.05.10	10.07.10	Sea Worker	27.07.10	02.09.10	Sea Power
33	Sheringham Shoal	25.06.10	21.08.11	Svanen, Oleg Strashnov	08.06.11	10.07.12	Endeavour; Leviathan
34	Ormonde	22.07.10	24.10.10	Buzzard, Rambiz	17.03.11	01.08.11	Sea Jack
35	London Array	01.03.11	19.10.12	Sea Worker, Adventure, Svanen, Sea Jack	27.01.12	29.12.12	Discovery, Sea Worker, Sea Jack
36	Lincs	29.03.11	15.06.12	Resolution, JB114	04.07.12	31.03.13	Resolution
37	Thornton Bank II	06.04.11	28.09.11	Buzzard, Rambiz	18.03.12	27.07.12	Neptune, Vagant
38	Walney 2	07.04.11	06.08.11	Svanen, Goliath	15.05.11	26.09.11	Leviathan, Kraken
39	Trianel Windpark Borkum 1 (40)	01.09.11	24.04.13	Goliath, Oleg Strashnov, Stanislav Yudin	24.07.13	01.06.14	Adventure

(*continued on next page*)

Table B1 (*continued*)

No.	Name	Foundation Start	installation End	Vessels	Turbine Start	installation End	Vessels
40	Anholt	30.12.11	27.07.12	Svanen, Javelin	31.08.12	19.05.13	Sea Power, Sea Worker, Sea Installer, Sea Jack
41	Teesside	06.02.12	01.12.12	Sea Jacks, JB114	06.01.13	02.06.13	Adventure
42	Thornton Bank III	02.03.12	29.05.12	Buzzard, Rambiz	11.03.13	03.07.13	Goliath, Vagant
43	Borkum Riffgat	10.06.12	07.09.12	Oleg Strashnov	25.04.13	18.07.13	Bold Tern
44	Gwynt y Mor	05.08.12	23.04.14	Stanislav Yudin, Friedrich Ernestine	29.04.13	28.06.14	Sea Jack, Sea Worker
45	Karehamn	29.08.12	01.11.12	Rambiz	01.05.13	25.07.13	Discovery
46	Meerwind	03.09.12	29.06.13	Zaratan, Leviathan, Oleg Strashnov	17.07.13	03.04.14	Zaratan, Leviathan
47	Global Tech I	09.09.12	01.01.14	Innovation, Stanislav Yudin	22.08.13	29.08.14	Thor, Brave Tern, Vidar, HGO Innovation
48	Gunfleet Sands III	17.09.12	29.09.12	Ballast Nedam	03.01.13	16.01.13	Sea Installer
49	Nordsee Ost	16.12.12	14.03.14	Victoria Mathias	19.05.14	27.12.14	Victoria Mathias, Friedrich Ernestine
50	Belwind Haliade Prototype	02.01.13		Pacific Osprey	07.10.13	17.11.13	Bold Tern
51	Dan Tysk	07.02.13	13.12.13	Seafox 5	28.03.14	27.08.14	Pacific Osprey
52	Northwind	11.04.13	09.09.13	Neptune	20.07.13	29.03.14	Resolution, Neptune
53	West of Duddon Sands	16.05.13	26.10.13	Pacific Orca, Sea Installer	25.09.13	03.06.14	Sea Installer
54	EnBW Baltic II	16.08.13	26.01.15	Goliath, Taklift 4	11.08.14	11.06.15	Vidar
55	Humber Gateway	19.08.13	05.01.15	Resolution, Discovery	20.07.14	23.04.15	Resolution
56	EnBW Baltic II	01.10.13	07.11.14	Svanen			Vidar
57	Amrumbank West	05.01.14	24.08.15	Svanen, Discovery	05.02.15	08.09.15	Adventure
58	Borkum Riffgrund 1	19.01.14	29.07.14	Pacific Orca	25.10.14	22.05.15	Sea Installer
59	Westermost Rough	22.02.14	26.05.14	Innovation	06.08.14	27.03.15	Sea Challenger
60	Butendiek	29.03.14	18.09.14	Svanen, Javelin	12.09.14	12.06.15	Bold Tern
61	Luchterduinen	30.07.14	17.10.14	Aeolus	06.04.15	10.06.15	Aeolus
62	Westermeerwind	15.03.15	23.05.15	Crane on a barge,	06.09.15	01.03.16	De Schelde
63	Gode Wind I & II	11.04.15	16.09.15	Innovation	05.08.15	19.05.16	Sea Challenger
64	Kentish Flats Extension	01.05.15	23.05.15	Neptune	14.06.15	10.08.15	Neptune
65	Gemini	01.07.15	17.10.15	Aeolus, Pacific Osprey	12.02.16	23.08.16	Aeolus, Pacific Osprey
66	Sandbank	06.08.15	12.02.16	Pacific Orca	25.07.16	21.01.17	Adventure
67	Nordsee One	13.12.15	17.04.16	Innovation	03.03.17	22.09.17	Victoria Matthias
68	Rampion	25.01.16	08.11.16	Pacific Orca, Discovery	07.03.17	20.09.17	Discovery, Adventure
69	Veja Mate	31.03.16	26.10.16	Scylla, Zaratan	07.01.17	30.05.17	Bold Tern, Scylla
70	Dudgeon	02.04.16	03.08.16	Olev Strashnov	05.01.17	05.09.17	Sea Installer
71	Wikinger	20.04.16	02.01.17	Giant 7, Taklift 4	16.01.17	22.10.17	Brave Tern
72	Nordergrunde	03.05.16	21.07.16	Victoria Matthias	12.08.16	21.12.16	Victoria Matthias
73	Nobelwind	18.05.16	22.09.16	Vole au Vent	25.10.16	03.04.17	Vole au vent
74	Burbo Bank Extension	29.05.16	21.07.16	Svanen	06.09.16	14.12.16	Sea Installer
75	Race Bank	28.06.16	22.01.17	Innovation, Neptune	30.04.17	18.12.17	Sea Challenger
76	Galloper	26.12.16	28.03.17	Innovation	14.05.17	22.12.17	Pacific Orca, Bold Tern
77	Walney 3	30.03.17	15.08.17	Aeolus, Svanen	03.08.17	10.11.17	Scylla
78	Walney 4	30.03.17	15.08.17	Aeolus, Svanen	28.12.17		Scylla
79	Ajos	15.05.17	11.06.17	Vole au Vent	18.06.17	03.07.17	Vole au Vent
80	Pori Tahkoluoto	19.05.17	12.06.17	Vole au Vent	18.06.17	03.07.17	Vole au Vent
81	Blyth Demonstration	11.07.17	20.08.17	Tugs	13.09.17	28.09.17	Vole au Vent
82	Hywind Scotland	19.07.17			19.07.17	16.08.17	Tugs
83	Rentel	20.07.17	14.09.17	Innovation			Apollo
84	Arkona	22.08.17	13.01.18	Fairplayer, Svanen			Sea Challenger
85	Nissum Bredning	20.09.17	17.12.17	Crane, Matador 3	13.11.17	05.01.18	Crane on a barge
86	Aberdeen (EOWDC)	23.03.18		Asian Hercules III	06.04.18		Pacific Orca

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Technology effects in repowering wind turbines

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RESEARCH ARTICLE

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Technology effects in repowering wind turbines

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Abstract

This research investigates, analyses, and quantifies the technological effects of wind turbine repowering (ie, where old turbines are removed and new turbines are installed at the same or a very close location, including the enhanced performance in energy production). In these cases, it is assumed that both old and new turbines are subject to the same wind regime, other than because of technological elements, such as hub height, and thus it is possible to isolate the effects of new technology from the effect of changing local wind conditions. This research is based on the analysis of empirical data on repowering turbines in Denmark and Germany, and on historical production data available for the Danish component of the data set. Technological innovations are expected to enable new wind turbines to capture more energy at the repowering site, mostly through larger rotors and higher hub heights, and this is what this study has analysed. The results show that new turbines in repowering projects are twice as high, have three times the rotor diameter, nine times the swept area, six times the nominal power, and nine times as much electricity as the old turbines. However, the most significant improvement is probably the increase of capacity factor of 7.1% on a per-turbine basis, or 9.7% on a per-production basis.

KEYWORDS

dismantling, innovation, repowering, technological progress, wind energy

1 | INTRODUCTION

Wind energy facilities, as other power generation technologies, are subject to ageing, inducing reduction of efficiency, output, and availability.[1] In the case of wind turbines, it has been suggested that they lose up to 1.6% of their output per each year.[2] There are many reasons for reductions in production, including fouling of blades and decreased efficiency of the gearbox, bearings, or generator. In addition, downtime increases as the turbines get older and need more maintenance. Even the lack of spare parts may become an issue at a certain age.[3] In parallel, operational costs increase over time.[4]

When the asset approaches the end of its operational life, project owners have a number of options: decommissioning, refurbishment (or partial repowering), repowering, life extension, or run to fail. Given that an excellent description of the former three options can be found in Topham et al,[5] we will not expand on this here. Run to fail involves leaving all turbines working, with minimum maintenance, until maintenance costs are higher than revenues.[6]

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Repowering a wind farm implies dismantling the existing wind turbines and installing new turbines of a larger size with new technology[7] at or near the positions of the old turbines. Although repowering can apply (but has not been done so to date) to offshore wind farms, in this research, we focus on the experience of repowering onshore wind facilities.

The structure of this paper is as follows: Section 2 introduces the background to repowering wind turbines. Section 1 presents the methodology, model, and main data issues; Section 2 represents the results of our research, the technology effects of repowering in Germany and Denmark on the most significant technical characteristics of the turbines, and the impact of repowering on energy production for Danish wind turbines. Finally, some conclusions are drawn in Section 3.

Throughout the paper, the following definitions will apply:

- *Repowering*: the process of replacing existing wind turbines with new turbines, which either have a larger nameplate capacity or more efficiency, resulting in a net increase of power generation (according to del Rio et al[8]).
- *Dismantled*: refers to any turbine that has been decommissioned; *removed* refers to turbines that were decommissioned and dismantled in the context of a repowering project; and *new* refers to the replacing of turbines.
- *Repowering year*: the year the new turbine was commissioned.

2 | BACKGROUND—REPOWERING WIND TURBINES

Repowering wind turbines (or wind farms) brings a number of benefits. First, and most important, repowering will increase performance and electricity production of wind projects, as demonstrated under different circumstances by previous studies.[1,4,8-11] This increase in performance is partly because the sites with the best wind conditions were often used in the 1980s or 1990s.[12] Compared with a greenfield project, financing conditions tend to be better for repowering projects because the wind resource is known already and planning costs will be lower.[6,13,14] In some cases, parts of existing infrastructure might be usable,[15] eg, the wind farm substation and some of the electrical connections. Repowering will have a positive effect in reaching climate change commitments at a national level, as modelled by Jung et al in the German case, Serri et al in the Italian case, and by Ramírez et al in the Spanish case.[11,16,17]

A theoretical case study for a wind farm in India has shown that energy yield could increase by a factor of four.[18] Other studies have reported an increase in capacity factor by 10 percentage points.[14] Interestingly, research based on actual wind farm repowering cases found that while maintaining the same rated power, electricity production was doubled.[19]

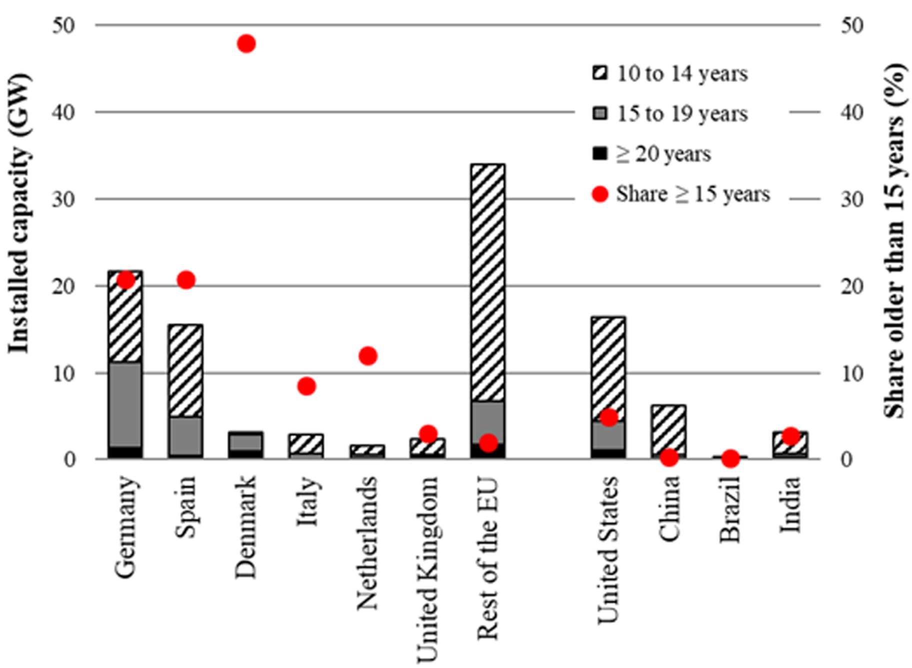

FIGURE 1 Age distribution of wind fleet in selected countries. Sources: Global Wind Statistics,[29] Wind in Power 2017,[30] and JRC Wind Energy Database[31] [Colour figure can be viewed at wileyonlinelibrary.com]

Repowering of wind turbines also offers advantages for the whole electricity system[8] and the society at large. In general, repowering will lead to a reduction of reactive power consumption and voltage variations.[18] Turbines have evolved to better support the grid by adding increasingly complex features, such as low-voltage ride-through. Further, new turbines have lower rotational speeds with reduced noise emissions.[20] Bigger rotors and slower rotational speeds provide a less visually intrusive and more pleasant view than fast-rotating turbines.[21]

In terms of environmental effects, wind farm repowering has a number of benefits. Fatalities for raptors and other birds are reduced, as shown by a research in California, which found that repowering resulted in a reduction of fatalities by 83% for raptors and 87% for all birds for the same amount of energy generated.[22] In Mediterranean mountain ecosystems, repowering was found to reduce the relative mortality of skylark males as compared with new turbine installation.[23] Repowering impact on global warming has also been investigated, and researchers found that the impact of removing the old and installing the new turbines (and other works) is "clearly offset by the benefits of increasing the generation of electrical power from renewable sources."[24] The visual effect was investigated based on a real case, and it was found that the repowering wind farm project achieved a 37% power increase with no additional visual effects.[25] Last but not least, local acceptance is also usually higher for repowering projects compared with greenfield developments.[26,27]

A significant portion of the installed European Union (EU) wind fleet will come to the end of its lifetime between 2020 and 2030.[28] Approximately, 3.3 GW of the wind turbines installed in the EU by the end of 2017 were 20 years and older. This group, along with the approximately 18 GW of turbines between 15 and 19 years old are the obvious candidates for repowering (Figure 1). Notwithstanding this, there are cases where younger turbines can be suited for repowering, and this would include some of the 33 GW of turbines between 10 and 14 years old. The largest markets for repowering in the EU are Germany, Denmark, Spain, and Italy. The repowering market is also large in the United States and India, with about 1.1 and 0.3 GW of wind turbines being 20 years and older.

Two countries that have been frontrunners in wind energy have accumulated significant experience with repowering so far: Denmark and Germany.[32] Since 2001, Denmark has supported repowering through various incentive programmes, which led to the repowering of a significant amount of the oldest wind turbines. Fifty-six percent of turbines installed before 2000 and 84% of turbines installed before 1994 had already been removed by the end of 2017. More than 3200 turbines were dismantled in Denmark before 2018.

In Germany, about 5470 MW (approximately 2040 turbines) of wind power capacity has been installed before 2018 in repowering projects. Those turbines replaced about 2900 old turbines (2280 MW).[33] Table 1 shows the annual evolution of repowering in Germany.

So far, the technological effects, efficiency gains, and performance improvements of actual repowering projects have not been researched in a detailed manner. Some evidence is available from theoretical studies.[1,10,34] Some case studies have been performed on an individual wind farm basis (see, eg, Castro-Santos et al[34] and Villena-Ruiz et al[20] for actual repowering wind farms in Spain), then the focus has been economic or techno-economic, rather than technological. Also, at a national level, the focus of the assessment or modelling of repowering has been from an economic (eg, de Simón-Martín et al,[27]) or techno-economic (eg, Serri et al.,[17]) perspective.

The objective of this research is therefore to fill this gap by analysing the technological and performance (in terms of energy production) changes due to wind turbine repowering independent from locational changes in wind resource. In addition, unlike previous research, this research focuses on a large number of cases in which different analytical tools have been applied.

3 | METHODOLOGY AND DATA USED

3.1 | Methodology

There are two main methodological elements in this research. First, technology trends were uncovered through graphical representation. Second, regression analysis was performed to show how variations in performance are linked to the key technology trends.

TABLE 1 Historical account of repowering in Germany

Wind Turbines	<2006	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Removed turbines	147	79	108	26	76	140	170	252	416	544	253	336	387	2934
New turbines	107	55	45	18	55	90	95	161	269	413	176	238	315	2037
Removed MW	155	26	41	10	37	56	123	179	258	364	195	366	467	2277
New MW	190	136	103	24	136	183	238	432	766	1148	484	679	952	5472

Note. Source: Annual and half-year reports "Status of wind energy development in Germany" by Deutsche WindGuard on behalf of the German Wind Energy Association,[33] for 2017 and previous years. Remarks: the source acknowledges that not all repowering activity has been captured in these statistics; figures prior to 2006 are obtained through subtracting from the latest cumulative figures.

The data sample consists of sets of two wind turbines, one removed and a second one newly installed in the vicinity (see the next paragraphs) around the same period. Data include the technical characteristics of both turbines and the corresponding energy produced during a reasonably long period of time.

Microsoft Excel and Visual Basic for Applications were used as the main modelling tools before applying regression analysis to the results. A Visual Basic for Applications macro selected pairs of removed/newly installed turbines under the following conditions:

- maximum distance between them was 1500 m;
- new installation occurred between 30 days before and 500 days after dismantling the old turbine.

The maximum distance of 1500 m was decided after Monforti and González-Aparicio found that "*uncertainty in the wind farm locations of the order of a few kilometres is not expected to visibly decrease the quality of the wind power assessment at national level.*"[35] Figure 7 in that article shows that a separation of 1500 m hardly affects the simulated wind conditions.

The period of 30 days before and 500 days after dismantling the old turbine was chosen to follow the reasonable project management process while not letting excessive time impact the available technology at the time of repowering. A much longer time period might involve completely disconnecting the old and new turbines (thus not a repowering project).

3.2 | Data sources and data availability

For Denmark, the publicly available Danish master data register for wind turbines (*Stamdataregister for vindkraftanlæg*) provided by the Danish Energy Agency was used.[36] The register contains data on geographical coordinates, turbine model, rated power, hub size, rotor diameter, date of commissioning and decommissioning, and annual energy production for most wind turbines. However, some wind farms do report global production data; in such cases, the register presents the average production per turbine. On the negative side, this database lacks wind farm names; therefore, it is not possible to unequivocally associate old and new wind farms and even turbines.

In Germany, a publicly available register of all notifications (eg, commissioning and decommissioning) of renewable energy installations since August 2014 is available from the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway.[37] For wind energy, the register contains the geographical coordinates, turbine model, rated power, hub size, rotor diameter, and date of commissioning and decommissioning per wind turbine. The register also specifies that if a new wind turbine was commissioned as part of a repowering project. Wind turbines that have been commissioned before August 2014 are not included in the sample. Also, operators are not obliged to report dismantling of old turbines, thus we cannot assume that the set of decommissioned turbines is complete. Energy production data were provided by the Federal Network Agency to the JRC under a confidentiality agreement and cover the years 2012 to 2016 only. Unfortunately, given the limited period, these data did not enable energy production analysis as in the Danish case.

For Denmark, data about repowering projects from as early as 2000 were available, whereas for Germany, the sample only includes repowering projects from the last 4 years. The data available varies according to the specific parameter analysed because of the different levels of

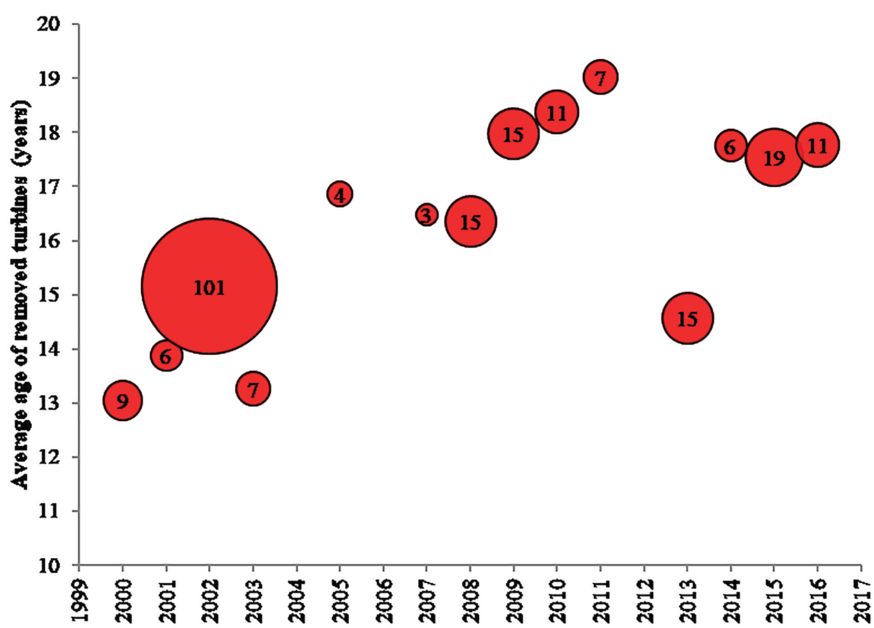

FIGURE 2 Evolution of the age of Danish removed turbines in this analysis. Size of bubble indicates number of wind turbines [Colour figure can be viewed at wileyonlinelibrary.com]

completeness in the data fields. However, there are two broad categories of parameters: technological or structural elements relate to the turbine characteristics (eg, hub height, rotor diameter, and specific power) and energy production resulting from the interaction of structural elements with the wind; in other words, turbine data vs production data.

Any data point containing valid data in structural fields was used for the respective analysis. However, the analysis related to energy production was restricted to those cases where at least three full years of data were available in order to accommodate the variability of the wind resource.

For Denmark, the data sample that could be used for the subsequent analyses included 232 pairs of turbines for the technical parameters, which is just 6% of all dismantled turbines. Data on energy production was available for 200 pairs (5.5% of all dismantled turbines). The data sample for Germany with complete information about the technical parameters contained 442 pairs of turbines and data on energy production was not used. The appendices contain detailed information about data issues and the data improvements performed.

4 | RESULTS

In Denmark, three "waves" of repowering can be identified from the data: 2000 to 2003 (123 data points), 2008 to 2011 (48 data points), and 2013 to 2016 (51 data points). The first wave is broadly consistent with the first incentive programme for repowering—April 2001 to December 2003.[38] The second wave comes roughly at the end and after the second incentive programme (2005-2009). The third wave does not correspond to any incentive programme. The overall pattern of dismantled turbines is consistent with these waves, with a total of 1569, 727 and 467 turbines were dismantled during those periods. In particular, the number of data points is low in 2005, 2007, and 2012, whereas no repowering project was captured by the model in 2004 and 2005.

The age of the turbines in Denmark when removed varies over time. The first wave average was just below 15 years, the second wave was 18 years, and the third wave was 17 years (Figure 2). German turbines in the sample are 15.9 years old, on average.

For Germany, data about repowering projects and production data were only available for 2014 onward. Thus, in the remaining of this section we will focus mainly on results for Denmark and will compare them with German data (whenever data were available).

4.1 | Technological changes

4.1.1 | Power rating

The average power rating of removed turbines increases slightly during all waves in Denmark (Figure 3). This average rating was 133 kW during the first wave, 284 kW during the second wave, and 712 kW during the third wave for removed turbines. The corresponding figures for the new turbines were 1131, 2299, and 3116 kW, respectively. The figure shows the widening gap between removed and new turbines, from approximately 1000 kW during the first wave, 2000 kW during the second wave, and 2400 kW during the third wave. The sharp increase after 2006 to 2007 has to be highlighted.

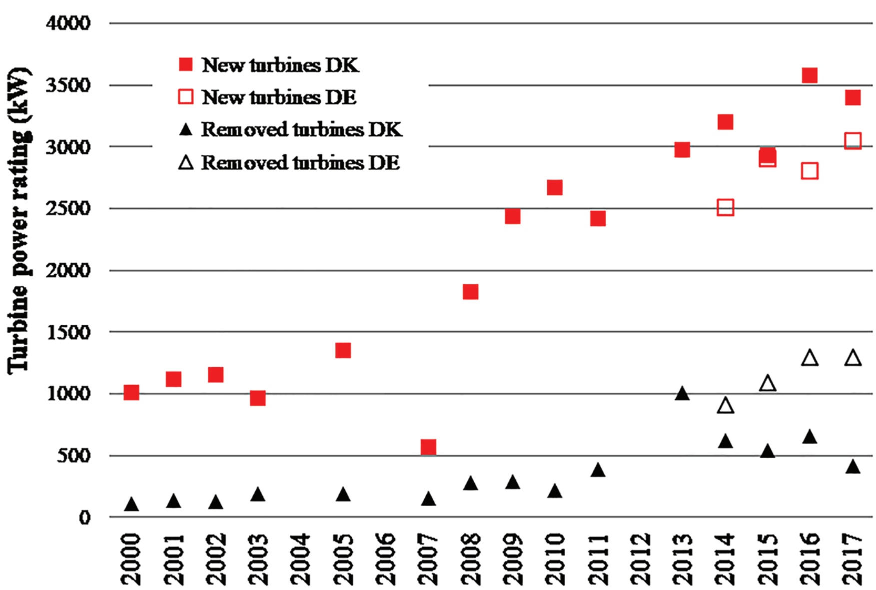

FIGURE 3 Evolution of the average power rating of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

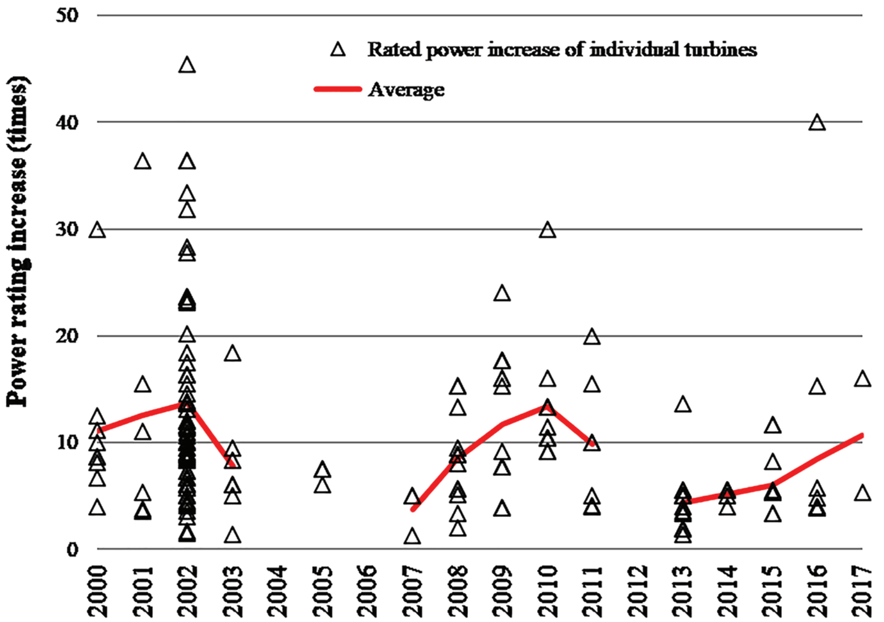

FIGURE 4 Power rating increase (times) between new and removed turbines in Denmark [Colour figure can be viewed at wileyonlinelibrary.com]

In Germany, the average power rating of removed wind turbines was between 900 and 1300 kW, while the new turbines showed more similar ratings to Denmark (for 2014 onwards), which was a capacity of between 2500 and 3050 kW on average.

The average (or mean) of power rating increases in Denmark was 11.6 times throughout the period, but the median was 8.8 times. This suggests a high number of cases where the power rating increases (times) were low, as was the case during the second part of the period, from 2008 (Figure 4). For the average power rating of new turbines (1833 kW) versus the average of old turbines (302 kW), the increase is sixfold.

New turbines in Denmark were significantly more powerful than removed turbines during the first repowering wave, when they averaged 11 to 12 times the rated power of removed turbines. Later waves saw reduced differences and in the latest wave new turbines were only 5 to 6 times as powerful as decommissioned turbines. This trend from larger to smaller differences between new and old turbines has been observed as well in Germany, where the average increase was 3.7-fold in 2014 and 3.0-fold in 2017.

Statistical analysis suggests that in 2000 to 2002, projects were more homogeneous in Denmark, with 50% of the projects increasing power by between 600 and 1300 kW each year. In 2002, the year when most cases were found (101), there were more radical outliers, with a 300- to 2651-kW difference between the new and the old turbines.

It is interesting to note that German and Danish removed turbines have very significant differences in all three key technological elements: power rating, rotor diameter, and hub height. Figures 3, 5, and 6 show that from 2014 to 2017, these elements in German and Danish removed cases start to diverge: whereas power rating, rotor diameter, and hub height of Danish turbines decreases or remains constant, in the case of German machines those parameters always increase: turbines with larger power, taller towers, and larger rotors are increasingly being removed.

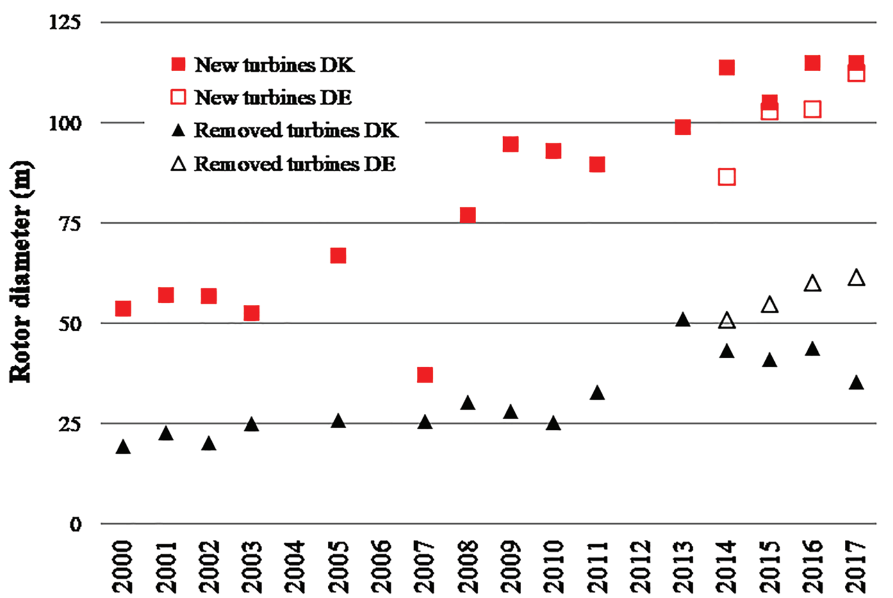

FIGURE 5 Evolution of the average rotor diameter of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

4.1.2 | Rotor diameter

The rotor is perhaps the element of the turbine that has a more direct relationship (through its swept area) to the energy produced. In Denmark, the rotor diameter of turbines, both for the decommissioned and new sets, was on average more homogeneous than in the case of turbine power rating. Old turbines had an average 21-m diameter during the early period (wave 1), 29 m during wave 2, and 45 m during wave 3; the corresponding figures for the turbine that replaced them are 56, 88, and 106 m, respectively (Figure 5). In Germany, average rotor diameter of removed wind turbines was between 51 and 62 m between 2014 and 2017 (slightly higher compared with Denmark), whereas the new turbines showed a rotor diameter between 87 and 113 m (on average).

Thus, on average, rotor diameters increased by around 30 m in 2000 and by 70 m in 2017 in Denmark. The most extreme case was where a Vestas model (V164-8 MW) was installed 470 m from where a 26-year-old Vestas V25-200 was dismantled 2 months earlier, causing a 139 m rotor increase and an increase of 43 times the swept area.

The relative increase of rotor diameter has been, on average, very stable: new turbines had a rotor three times as large as old turbines (in metres), equivalent to a 9-time increase in swept area. Given the direct relationship of swept area to energy produced, it could be concluded that the increase in rotor diameter is the single most important structural element impacting an increase in energy production.

4.1.3 | Hub height

The hub height is the last structural element analysed here that is strongly affected by repowering, and there are two reasons for this: first, larger rotors naturally require larger towers; second, at higher altitudes, winds are stronger and steadier, conditions that warrant more energy extracted and lower structural loads than turbulent winds.

The average annual hub height of turbines, both decommissioned and new, continued to increase through the periods (Figure 6). Old turbines in Denmark had an average of 26 m hub height during wave 1, 32 m during wave 2, and 45 m during wave 3; the corresponding figures for new turbines are 52, 76, and 86 m, respectively. A comparison with rotor diameter shows that hub heights for new turbines have not increased as significantly as rotor diameters.

The average annual hub heights of removed turbines in Germany were between 60 and 70 m, notably taller than the corresponding Danish data for the same years, 2014 to 2017, whereas the new turbines had hub heights between 97 and 120 m.

The average hub height increase was about 22 m in 2000 to 2003 and about 40 to 60 m in 2015 to 2017. Relative increase in hub height has been, on average, very stable at two times the old turbine hub height.

4.1.4 | Specific power

Perhaps the most interesting result from repowering is the evolution of specific power, the ratio of power rating to swept area. This is because the profile value, which measures how valuable a wind turbine generation profile is to the electricity system, increases in line with a reduction in specific power.[39] All other elements being equal, a reduction in specific power results in higher capacity factor.

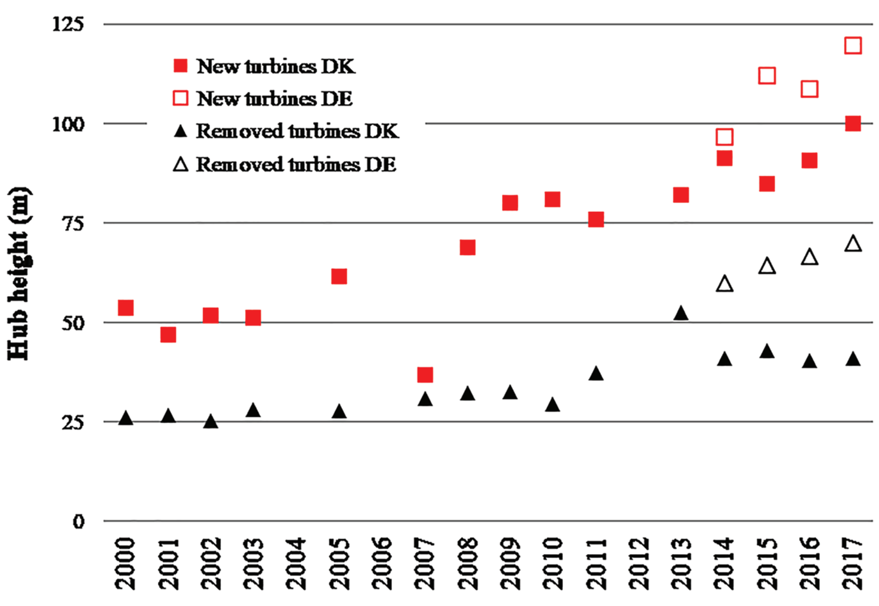

FIGURE 6 Evolution of the average hub height of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

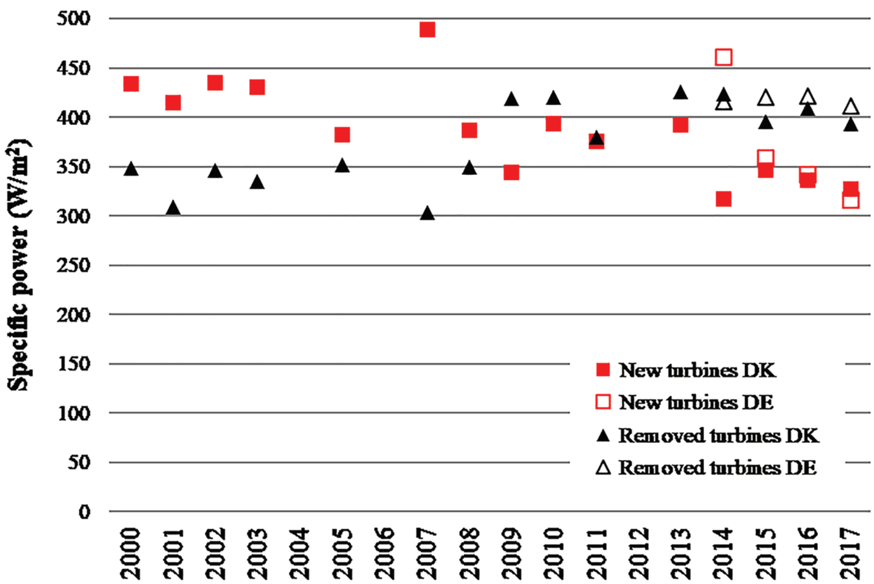

FIGURE 7 Evolution of the average specific power of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

At the beginning and throughout the first wave, new turbines had significantly higher specific power than the old turbines they replaced; 434 vs 344 W/m^2 in Denmark (Figure 7). This increase can be considered counterintuitive as it would reduce profile value. The reason can be traced back to the support mechanism in Denmark, which, by making remuneration based on a total amount of full load hours (22 000),[40] indirectly promoted turbines with high specific power compared, eg, with a support mechanism based on a number of years of production. Reinforcing this Danish feature, another database of 3606 wind turbines or wind farms commissioned in Europe during the period from 2001 to 2006, which is based mostly on the database provided by GlobalData,[41] shows that Danish turbines had an average specific factor of 420 W/m^2 compared with 396 W/m^2 in Germany and 378 W/m^2 in Spain, the two big markets of the time.

A support mechanism based on the number of years of production promotes that turbines produce as much energy as possible during these years, whereas support based on a number of full-load hours promotes that turbines produce less energy per year in order for support to last longer.

During the second wave, both new and old turbines had similar specific power, albeit the former already below the latter: 373 vs 392 W/m^2. During the third wave, the situation reversed, with new turbines having significantly lower specific power: 354 vs 411 W/m^2. This reversal can be linked both to technological evolution—the average specific power of a wind turbine has been decreasing with time,[42] and because of changes in 2014 to the Danish support scheme, which incentivised lower specific power turbines.[43]

Interestingly, in Germany, average specific power was between 411 and 422 W/m^2 for removed turbines and 461 and 316 W/m^2 for new turbines in 2014 to 2017, revealing a clear downward trend that increased the profile value of new turbines.

It is important to note that the lowest specific power of new turbines in Denmark steadily happens in the 2014 to 2017 time period. This is consistent with the support scheme change in 2014, as mentioned earlier, to reduce the incentive for high specific power turbines. As Lena Kitzing stated, "The change (to the support scheme) in 2014 has also eliminated much of this incentive by using swept area instead (at least for 70% of the support duration calculation)."[44]

Looking forward, we see elements that could differentiate repowering project turbines from greenfield ones that are related to the location of old turbines. In the past, turbines were placed considerably closer to human settlements than new wind farms. Therefore, repowering the old site is unlikely to get planning consent in a number of cases. Even in the cases when planning consent is obtained, it could come with restrictions in hub height or rotor diameter that can be similar to those placed on new projects in much of the United Kingdom (eg, Kelmarsh or Dunmaglass wind farms) or Ireland (eg, Meenadreen Extension), where 2+ MW machines have hub heights limited to 70 m.

4.2 | Electricity production

In this work, a number of wind turbine pairs did not contain reliable production data. Some others did not contain three full years of data. As a result, only 200 pairs make up the energy-production-related analysis. The average number of production years of old turbines was 16 and 12 for new turbines until the end 2018, the end of the data sample.

The German data were not used for studying the effect of repowering on production because they were not available for a time period long enough to obtain reliable results.

4.2.1 | Absolute annual energy production and increase

The annual energy production was calculated as the weighted average of the individual turbines for the years of production, which were considered complete. This includes from the year after commissioning to the year before decommissioning.

$$AAEP_{2001}^{2015} = \sum_{2001}^{2015} \frac{AATP}{m}, \quad (1)$$

where the absolute annual energy production for the whole set (*AAEP*) of turbines commissioned in each of the years between 2001 and 2015 (except 2004, 2006, and 2012 for which there are no valid data) is the sum, for each commissioning year, of the average annual turbine production for each turbine divided by the number of turbines, ***m***.

$$AATP = \frac{\sum_{a}^{b} \text{Annual energy production}}{(b - a + 1)}, \quad (2)$$

where the average annual turbine production (*AATP*) of a removed turbine is the sum of its annual energy production from year *a* (the year following commissioning) to year *b* (the year before decommissioning). In the case of new turbines, *b* is the last year of data (2018).

The increase in absolute annual energy production for each (*t*) repowering turbine is the result of subtracting *AATP* for the removed turbine (*td*) from *AATP* of the removed turbine (*tr*):

$$\Delta AEP_t = AATP_{tr} - AATP_{td}. \quad (3)$$

As expected, the new turbines have increased annual energy production (Figure 8). On average, production increased by 1800 to 2700 MWh between 2001 and 2003; by 5000 to 8200 MWh between 2008 and 2011, and by 6500 to 10 300 MWh between 2013 and 2015. Respective weighted average annual production increases were 2294, 6730, and 7734 MWh. According to annual averages per repowering year, annual electricity production has remained relatively stable for removed turbines from 2001 to 2010 (between 250 and 550 MWh), then picking up to 1400 MWh in 2013 to 2015. New turbines have seen a sharp increase from about 2500 MWh in 2001 to 2003 to almost 10 000 MWh in 2013 to 2015.

The relative increases of annual energy production are more random and range between 8 and 25 during 2001 to 2015, with a nonweighted average of 12.7.

4.2.2 | Specific annual electricity production

Specific annual energy production shows the amount of electricity that a turbine generates irrespective of rotor size, ie, per square metre of swept area. This indicator therefore collects technology improvements mostly due to turbine efficiency, power rating, and hub height.

Results consistently show that new turbines have increased specific energy production: 99% of the cases (197 pairs) show an increase after repowering (Figure 9). The trend in both old and new turbines is towards higher specific electricity production in 2014, but 2015 shows a change.

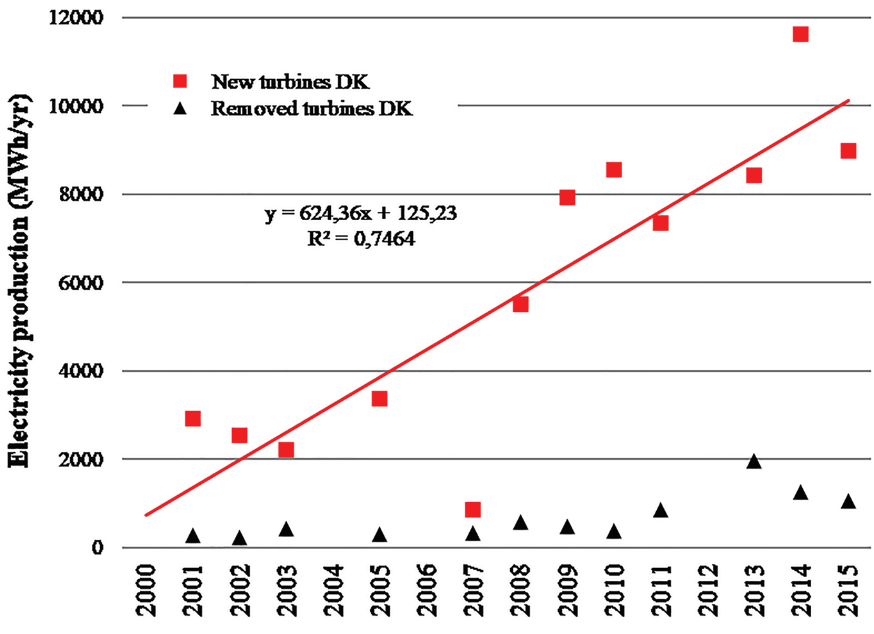

FIGURE 8 Evolution of the average annual electricity production of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

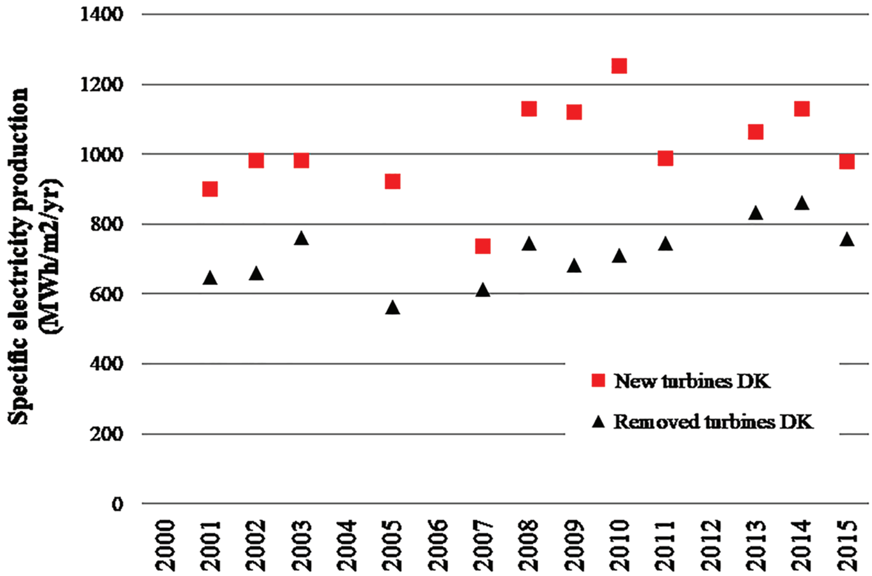

FIGURE 9 Evolution of the average annual specific electricity production of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

With no data after 2015, it is not possible to define whether the 2015 effect is short or long term. On average, specific electricity production increased by 320 kWh/m^2/yr—a 45% increase—from 702 to 1021 kWh/m^2/yr.

4.2.3 | Capacity factor

The capacity factor (CF) is the percentage of actual production to theoretical production should the turbine have been producing continuously at the rated power. It is expressed either as a percentage or as the equivalent number of hours, on annual average.

The net effect of repowering on CF is clearly positive. Figure 10 shows the annual average capacity factor for all the turbines removed or installed based on the year the new turbine was installed. The graph shows the improvements since 2008, whereas previous projects did not achieve significant improvements. The lower CF of the new turbines in the first years under study is the result of the higher specific power of these turbines. One of the reasons behind this could be, as discussed in Section 2.1.4 and elsewhere, the impact of the then Danish support scheme favouring turbines with high specific power. This point is strongly supported by the much lower specific power and much higher CF of the turbines installed in 2014 and 2015 (after the reform of the Danish subsidy system in 2014) which, as shown in Figure 10, is the highest ever (41.1% annual average in 2014).

In Figure 11, the CF of the old turbine is shown on the horizontal axis and the CF of the new turbine on the vertical axis. The black line divides pairs according to whether the new (top left) or old (bottom right) turbine has a higher CF.

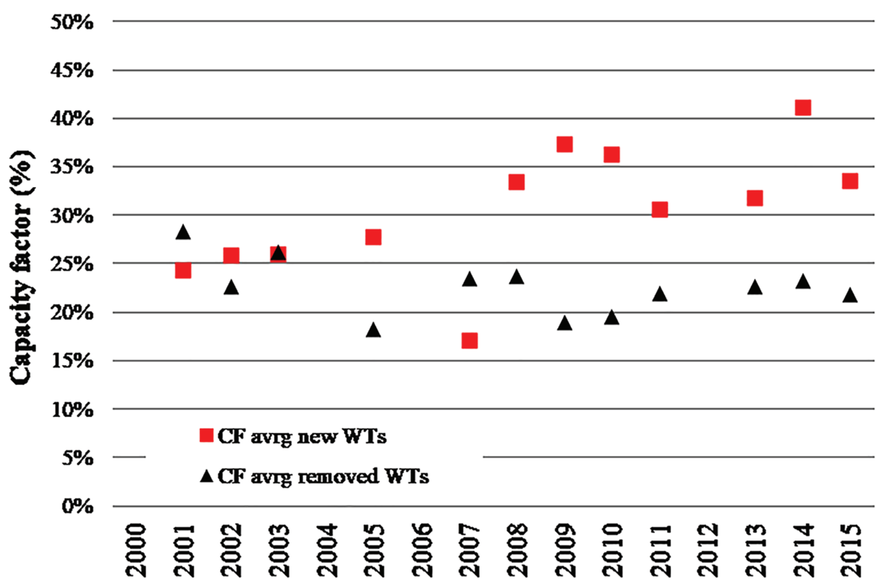

FIGURE 10 Capacity factors of old and new turbines [Colour figure can be viewed at wileyonlinelibrary.com]

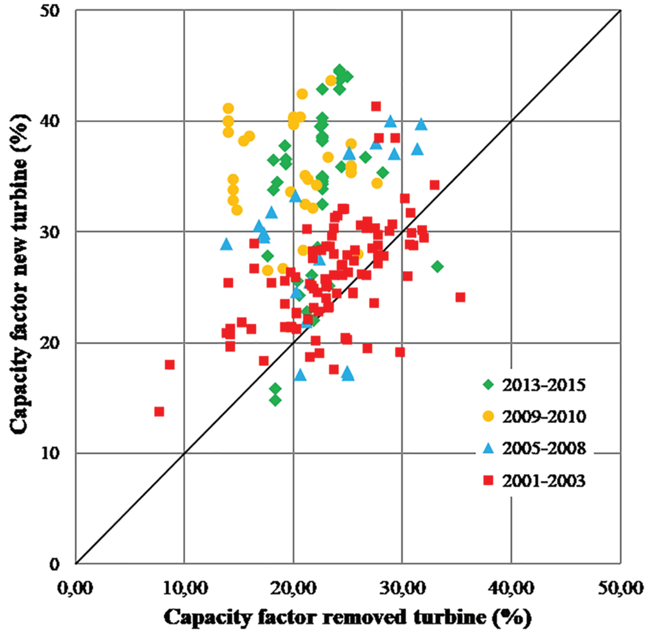

FIGURE 11 Capacity factors of new and removed turbines (colour indicates year of repowering) [Colour figure can be viewed at wileyonlinelibrary.com]

In the large majority of cases, the new turbine has a higher capacity factor. In 14% of the cases, the new turbine had a lower CF than the replaced turbine. Some cases could be explained by data issues (eg, errors in reporting of electricity production). Most often, those cases related to early repowering projects when turbine technology was more similar between the removed and new turbine (Section 2.1).

The results show that the old turbines had a capacity factor of 22.4% on average, whereas the new turbines reached 29.5%. This is a significant 7.1% increase in capacity factor on a per turbine basis.

However, the improvement is even higher if the effect of increasingly larger rotors is taken into account. Calculations based on the whole-fleet annual production identify this effect. The set of old turbines for which energy data are available, where the sum of power rating is 56.5865 MW, produced an average of 109 895.9 MWh annually, which gives an average capacity factor of 22.2%. Similarly, the sum of power ratings of the set of new turbines is 354.16 MW, which means they produce an annual average of 988 146.3 MWh, providing an average capacity factor of 31.85%; an increase of 9.7% on a per production basis.

TABLE 2 Results of the regression analysis

Analysis of Variance					
Source	DF	Adj SS	Adj MS	*F* value	*P* value
Regression	2	1776735939	888367969	1380.38	0.000
ΔTR (kW)	1	961780834	961780834	1494.45	0.000
ΔSP (W/m^2)	1	111166111	111166111	172.73	0.000
Model Summary					
S		R^2	R^2 (adj)		R^2 (pred)
802.227		93.37%	93.30%		93.12%
Coefficients					
Term	Coef	SE Coef	*T* value	*P* value	VIF
Constant	−55	149	−0.37	0.715	
ΔTR (kW)	3.2249	0.0834	38.66	0.000	1.29
ΔSP (W/m^2)	−8.262	0.629	−13.14	0.000	1.29
Regression Equation					
ΔAEP (MWh)		=			−55 + 3.2249 ΔTR − 8.262 ΔSP

4.2.4 | Regression analysis

In order to relate the variation in energy performance to the technological elements that caused them, and to identify the most important ones, we decided to use regression analysis.

Regression analysis has been applied in the energy field, eg, by Lee and Yang,[45] Fumo and Rafe Biswas,[46] and Ma et al.[47] In the wind energy field, Arias-Rosales and Osorio-Gómez[48] have applied regression analysis to wind turbines based on estimates of the cost of energy.

Among the statistical models commonly used, linear regression analysis has shown promising results because of the reasonable accuracy and relatively simple implementation when compared with other methods.[46] Under the multiple linear regression approach, the selection of the explanatory variables is a key issue because irrelevant variables have negative effects on the process.[49] To ensure that the multiple linear regression approach is the appropriate methodology, it has been tested so that the input variables selected are linear (ie, all of them follow a normal distribution) and independent from each other.

The correlation between the technological changes brought about by repowering was explored (ie, the increases with time in hub height, rotor diameter, and power rating) between the repowered and new turbines, and the increases in annual energy production (*AEP*) in each case. The regression analysis took *AEP increase* (*ΔAEP*) as the dependent variable and all other variables as independent variables. The reason for defining *AEP* as the dependent variable is that the final objective of repowering is increased production, which is also the natural result of the changes in technological variables.

The regression analysis used Minitab statistical software. Initially, the following predictor variables were considered:

ΔTR = Change in turbine rating (MW)

ΔHH = Change in hub height (m)

ΔSP = Change in specific power (W/m^2)

YR = Repowering year.

The first analysis trials quickly showed that two variables were not statistically significant (*ΔHH*, *YR*), as the *P* value was above.05 for these predictor variables.

The two remaining independent variables (*ΔTR* and *ΔSP*) were found to be of statistical significance for the regression model.

The coefficient of multiple determination, R^2, takes an acceptable value of 93.37%, and adjusted R^2 is 93.30%. A small Mallows' Cp value of 3.0 was obtained, indicating that the model is sufficiently precise. It was concluded that the model fits the data well.

Other assumptions that are required for multiple regression analysis to give a valid result were checked as well. They are shown in Table 2 and summarised here:

- the independent variables are significant, as *P* value is below.05 for both variables.
- The variance inflation factor (VIF) is 1.29 for the two independent variables of the regression model, indicating that the predictor variables are not correlated.
- The residuals show an approximate constant variance.
- The residuals are normally and randomly distributed.

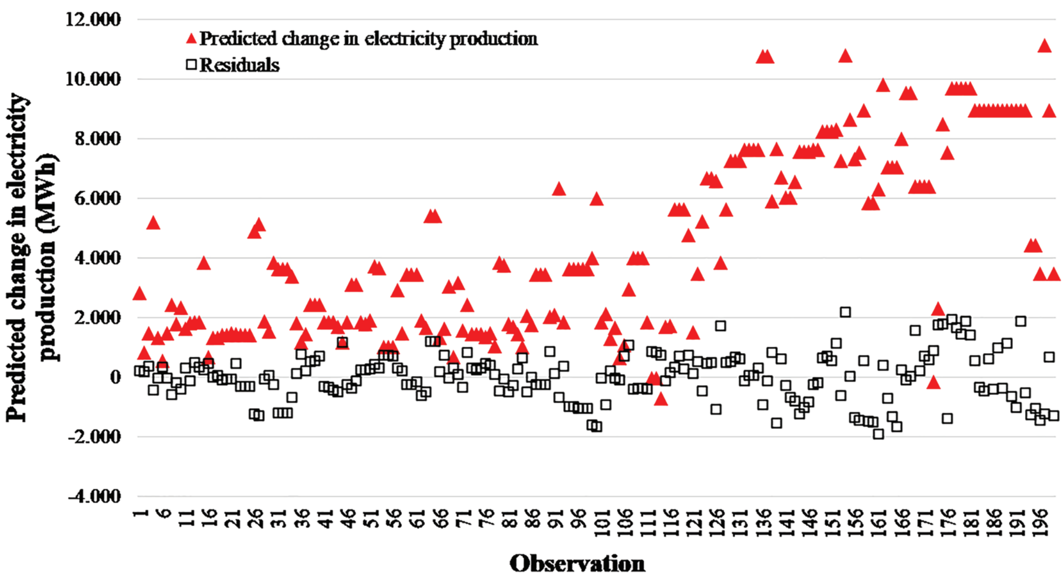

FIGURE 12 Probability plot: predicted change in electricity production and residuals of the regression [Colour figure can be viewed at wileyonlinelibrary.com]

Note that the ratio between turbine rating and swept area is very important: it is used by turbine manufacturers to design products better suited for local wind conditions. For example, Siemens Gamesa currently offers two different rotor diameters (155 and 170 m) for their 5.8-MW wind turbine, and two different rated powers (3.4 and 4.5 MW) for their 132-m rotor diameter turbine.[50] Because of this reason, we carried out further analyses: the swept area (SA, m^2) was tried instead of specific power (W/m^2) in the regression analysis. Somehow, although R^2 reached 95%, the results showed a VIF value of 7.83 for both statistically significant variables *ΔTR* and *SA*, indicating a possible problem of multicollinearity.

Another analysis was based on the previous regression model result that change in hub height (*ΔHH)* was not significantly related to the increase in energy production. To explore this further, the data set was split into two subsets: from 2000 to 2005 and 2007 to 2015, to examine possible partial time correlation. However, the results of the analysis showed again that *ΔHH* remained a nonsignificant variable for the regression model.

The results of the regression analysis are shown in Table 2, whereas Figure 12 shows the adjusted probability plot and the residuals of the regression analysis.

Time-organised, plotted results in Figure 12 confirm what has been observed earlier: because of faster technological progress, repowering effects in the past few years had greater impact on turbine efficiency than early repowering projects. On the other hand, from the regression analysis, variations in increased electricity production can be mainly attributed to variations in two explanatory variables: turbine rating, *ΔTR*, and specific power, *ΔSP*.

The coefficients can be explained as follows:

- for each increase of turbine rating by 1 kW, annual electricity production increases by 3.22 MWh.
- For each decrease in specific power by 1 W/m^2, annual electricity production increases by 8.62 MWh.

The lack of a direct relation between the increase in energy production and the increase in hub height, or with time, came as a little surprise to the authors. This is because the technology has improved over time (YR), and because an increase in hub height is directly related to an increase in energy production. See, for example, a recent statement by Vestas, the market leader, "With hub heights of 152 m, the (…) customised tower solution increases the project's annual energy production by unlocking new wind resources at higher and more consistent wind speeds."[51] We think that the reason is that the impact of the increase in turbine rating and specific power is much more significant than the impact of having higher hubs.

5 | CONCLUSIONS

This study has, for the first time, assessed the technological effects caused by a large set of real repowering projects and their impacts on energy production on a turbine-by-turbine level. The average repowering occurred has brought nearly a three-time increase in rotor diameter, or a nine-time increase in swept area, and a doubling of hub height. New turbines were between 6 and 11.6 times as powerful as decommissioned turbines, depending on how the average was taken.

The results show that repowering has resulted in an increased capacity factor of 7.1% on per turbine basis, or 9.7% on a per production basis.

Interestingly, during the first years of repowering, new turbines had significantly higher specific power than the turbines they replaced, and this trend reversed in the 2014 to 2017 period. This was linked to changes to the financial support instrument being used at the time in Denmark, which from 2014 promoted turbines with low specific power.

New turbines have a higher annual energy production compared with the removed turbines. On a weighted average, production as a result of repowering increased by 2300 MWh between 2001 and 2003; by 6700 MWh between 2008 and 2011; and by 7700 MWh between 2013 and 2015. Because the annual electricity production remained relatively stable for the removed turbines, the increase in additional energy production is because of the sharp increase of the performance of new turbines. The average annual energy production achieved by new turbines was about 4941 MWh, or 9.0 times the production of the removed turbines.

Also, the study shows that specific energy production (per m^2 swept area) has increased in 99% of the cases. On average, specific electricity production increased by 320 $kWh/m^2/yr$.

A regression analysis was performed to assess the impact of the underlying changes in technology on energy output. It showed that the increase in energy production was directly related to the increase in turbine rating and the decrease in specific power of the new turbines. On average, every additional kilowatt of rated power added 3.22 MWh to the annual energy production, and each W/m^2 of lower specific power increased annual electricity production by 8.62 MWh.

Further, this study analysed the effects of repowering on a turbine-by-turbine level. This was done to mitigate the influence of local variations in the wind resource. Of course, it is highly unlikely that in a given wind farm would substitute each turbine with a newer, larger one when repowering in practice. Repowering projects most often concern whole wind farms where both turbine and power grid upgrades are performed and wind farm configuration is optimised for energy production and levelled cost of energy, often by reducing turbine counts but approximately maintaining power density. A follow-up to this study has been proposed to analyse with empirical data repowering of wind farms in order to characterise the actual change in turbine density and energy production resulting from deployment of new modern turbines in place of older facilities at the end of their life. A further research question would also be to analyse the financial aspects of repowering, for example, was the repowering performed at the optimal time from a cost perspective?

From a societal view point, and considering the growing market for repowering in the coming years, it is important to understand if market-driven repowering projects will also deliver the socioeconomic benefits to society. In particular, will the wind resource be utilised optimally? What are indirect economic impacts (eg, on the value of land) of repowering? These questions need answers in order to determine if repowering could be more efficient or steered by policy instruments to bring the additional value for the economy and society.

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Globalization in the wind energy industry - contribution and economic impact of European companies.

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Globalization in the wind energy industry: contribution and economic impact of European companies

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ABSTRACT

This paper explores the globalization of the wind energy industry with a focus on the contribution by European companies and their economic impact in the global wind energy sector.

The global wind energy industry is nowadays a tale of two worlds, China and the rest of the world. In the last five years, China installed between 37 and 48% of the annual world market, and it is all but closed to foreign companies. Consequently, Chinese manufacturers captured between 38 and 47% of the world market whereas European reached between 41 and 50%. European manufacturers led in the rest of the world, serving between 73 and 82% of that market. They localise production and supply chain in the main markets (e.g. India, Brazil, US) or in countries where producing for export is cost-efficient (e.g. China, Mexico). Turbine manufacturers enter new markets through joint ventures, technology licensing, establishing wind farm developing subsidiaries, facilitating access to finance, or by acquiring a local company.

Manufacturers help improve the capability of their suppliers and take them to serve new markets. Still, European turbine manufacturers maintain important manufacturing, sales and R&D centres in Europe, where they keep major procurement, supply chain and employment thus significantly contributing to its economy.

European developers also expanded into other markets, sometimes by acquiring and strengthening a local developer (this was generally the case in the US), sometimes by starting a subsidiary from scratch. They have been particularly active in the US and Latin America.

The European wind industry is a success story of worldwide reach that attracts jobs and growth for Europe. In order to support that this will continue to be so in the mid- or long-term future, the industry needs the support of European and national policy makers with consented, well-targeted actions.

1. Introduction

Globalization[1] has involved huge benefits for humankind, from health improvements to culture diffusion and economic growth [1]. In the latter aspect, globalization is to a large extent responsible for the economic growth of entire countries, e.g. Singapore or China [2,3]. However, where local companies could not compete with foreign companies on a level playing field, globalization has caused loss of jobs and a certain impoverishment locally [4].

The most important economic effect of globalization, other than reducing the prices for goods and taking people out of poverty, is probably the increase in trade. For example, between 1970 and 2002 imports as a ratio to world gross domestic product (GDP) increased from around 12% to above 24% [5]. Other economic effects include foreign direct investment (FDI), e.g. where foreign companies either acquire local companies or set up local branches or production facilities, and the financing of local investment with foreign funds as seen e.g. in offshore wind farms in the North Sea [6]. On the other side, a number of negative effects have affected how people see globalization, from changes in land use resulting in the destruction of forests to make room for cash crops [7] to the delocalisation of manufacturing to countries with lower labour costs and less-strict environmental regulations [8].

One interesting aspect of globalization, one that directly affects the object of this research, is the interdependence between innovation and trade. Innovation is a competitive instrument, with

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[1] In this research "global" is considered equivalent to "international", and refers to economic activity distributed across at least two countries.

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producers trying to fight off rivals with the aid of improved products and processes [9]. Innovation, referred to improvements in processes and products, is also a driver behind better quality and lower cost, the two key competitive elements in any established industry.

The scope of this paper is more limited though: because it is focused on an industrial sector, wind energy, this research is centred on globalization of this industry and within it on the contribution by European companies manufacturing turbines and developing wind farms. As part of the research, some of the economic impacts of these companies at home and abroad are analyzed.

Previous research has explored globalization connected to different industrial sectors. Gourevitch et al. explored the effects on the hard disk drive (HDD) industry [10]. This industry had, at the time, worldwide revenues of $30 billion, which is of similar order of magnitude as the turbine manufacture industry at around $53 billion.[2] Although firms from the US dominated the industry in its beginnings, locally manufacturing around 80% of the world's HDD, and thus proved to be the most innovative firms, production moved to Asia by 1995. That year, while "*over 80% of the world's hard disks were made by US firms, less than 5% of drives were actually assembled in the US*". In terms of employment in 1995 "*only 20% of the world's employees in the HDD industry worked in the United States, yet over 60% of the wage bill paid by US firms were earned in the United States*."

The globalization of the pultrusion technology industry suggests that already some time ago low labour costs stopped being the most significant element behind delocalisation of production to emerging economies. In this case, vicinity to significant markets – as the case of China – was a major reason [11]. Incidentally, the pultrusion industry is indirectly linked to wind energy in that they both use fibreglass, the main material in rotor blades [12]. The globalization of the mechanical industry in Italian industrial clusters shed some additional light on the relationships client company – local suppliers that can help understanding how to promote a local supply chain [13], something that will be reviewed later in this paper.

The analysis of globalization of the energy field can be focused on trade of energy resources and fuels or on means of exploring, transforming and exploiting energy – the latter perhaps linked more to industrial policy that to energy policy. The globalization of conventional energy resources (coal, natural gas, nuclear fuel, and oil and oil products) was explored by Overland (2016) who found that it is growing and accelerating [14]. Renewable energy resources are globally available per nature: solar, wind, water and biomass are present everywhere although to a different extent. Energy products from renewable energy sources (e.g. pellets from biomass) are traded [15] and thus subject to globalization. The energy industrial sector is significantly globalized with multinational corporations operating worldwide. Further, there is evidence of the positive impact of policies in the development of the wind industry [16]. As Kuik et al. found, the competitive advantage of the European wind industry is based on the pioneering character of the related regulation [16], and it is long lasting [17].

This research paper first presents global wind deployment while more weight is put in exploring the key markets. Electricity production from wind turbines is explored in relation to both installed capacity and technical characteristics. Then in Section 3 the globalization of turbine manufacturers is analysed with a focus on key European players, and within it the key enabling factors of home market, financial health, international expansion and the strategies used for it (licensing, joint ventures, taking the role of developer and facilitating access to finance). Mergers and acquisitions are a specific form of globalization with impact on technology transfer between countries, and for this reason it was analysed separately (Section 3.6). Section 4 assesses the impact of globalization in the key aspects of procurement, supply chain, employment, and revenues, based on raw data from a turbine manufacturer and links to more diffuse information from other manufacturers. Section 5 analyses the market for the other key role, the developers of wind farms, and how they have globalized. Finally, Section 6 draws some conclusions.

2. Current situation of the wind energy sector

2.1. World new wind energy capacity installed in 2017 and cumulative

The annual market in 2017 reached 52.6 GW [17], a slight reduction from the 54 GW of 2016 [18]. China installed 37% of global new capacity in 2017 (2016: 43%), followed by the EU with 30% (2016: 23%), the US with 13% (2016: 15%) and India with 8% (2016: 6%) [17,18] (see Fig. 1).

The global annual market reached a record in 2015 with 63 GW installed [19], a highlight in a period (since 2009) when it has remaining at a very high level of around or above 40 GW. In 2017 it dropped to 52.6 GW which is still a very significant figure.

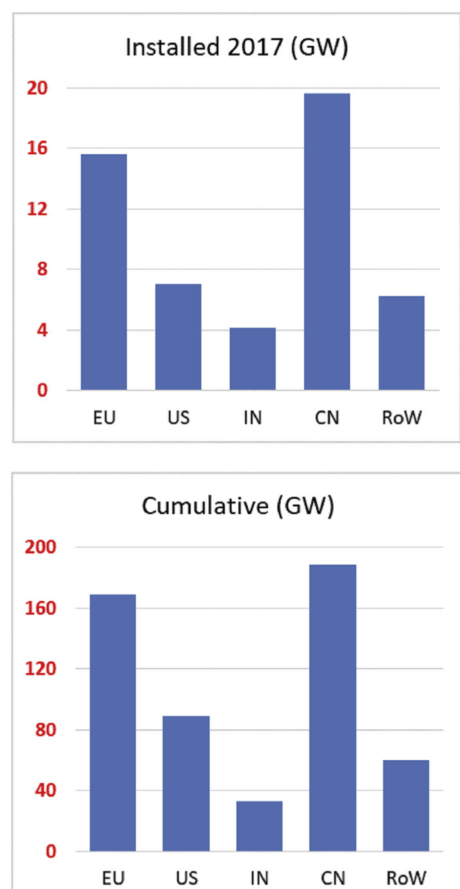

Fig. 1. World wind energy deployment (or market) in gigawatts (GW) of installed capacity, both new installations in 2017 and cumulative at the end of that year [17].

[2] Based on 54 GW installed of which 23 GW in China [18], at an average global turbine cost of 1,13 M$/MW [68] with a 30% discount in China.

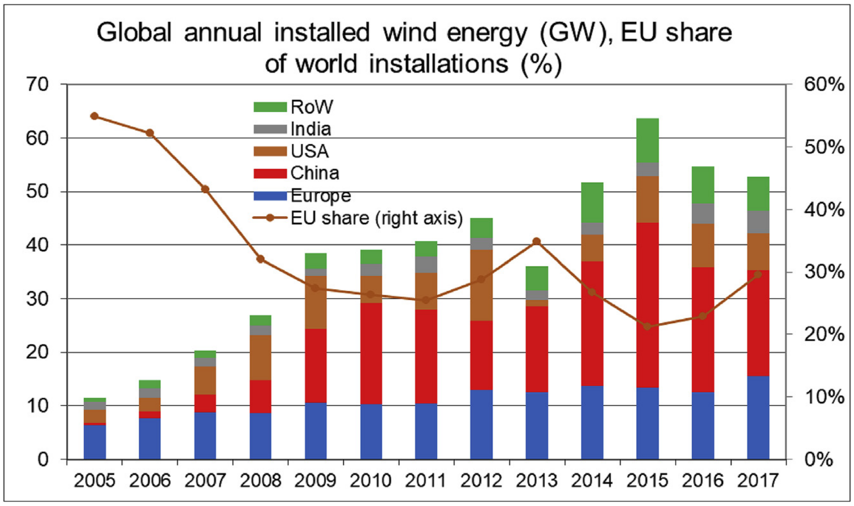

Fig. 2. Global annual installed wind energy generation capacity, and EU share of the annual installations.
Source: GWEC [17], adjusted with Member State data

2.2. World installations evolution and EU share

The European Union, and within it Germany, Spain and Denmark, was the main annual market until 2008 and then it passed on this lead to China (Fig. 2). However, the EU has remained a significant force at 20–30% of annual installations.

In terms of cumulative installed capacity, in 2016 China overtook the EU, 169 GW vs. 154 GW. However, 12% of Chinese installations (20 GW) were not connected to the grid at the end of the year [20]. One year later, China reached 188 GW, the EU had 169 GW and the US was placed third with 89 GW (Fig. 1). They were followed at long distance by India with 33 GW [17,18].

It is perhaps interesting to mention that the three dips in annual growth, in 2013, 2016 and 2017, were due to significant contractions in a key market: the US in 2013 and China in 2016 and 2017. This shows that the sector is heavily dependent on major markets.

Fig. 2 shows the evolution of the main markets in the global market. It shows that China became the major market in 2009 and since then it has remained as such: it has consistently installed between 40 and 50% of global capacity since [18]. The other large market, the US, until 2017 was subject to much instability due to the situation of its support framework in the midst of political battles. This instability seems now over with legislation that disposed an orderly and gradual (20% per year) phase out of the main support measure, the Production Tax Credit (PTC) [21].

Due to strong support policies, China will continue leading the world market for the foreseeable future. The EU will probably increase installations towards 12–14 GW per year thanks to the offshore sector. The US could install between 8 and 12 GW per year up to 2022.

China is therefore the main player. However, it is important to explore how would the market look like without China. Fig. 3 is based on Fig. 2 but removes the effect of Chinese installations, showing what a less concentrated market could be.

The figure shows a smaller global market where the effect of the US instable support scheme is more profound e.g. in 2013 only 62% of the 2012 installation took place, a reduction of 38% year-on-year. Without China, the world wind power deployment clearly depends on two pillars, the US and the EU.

A key factor determining future trends is the level at which the cost of generating wind energy will continue to fall [22]. However, the analysis of this factor is beyond the scope of this research.

With that limitation in mind, prospects are that, in the medium term, China, the US and India will accelerate deployment. In the first two countries a main driver is the forthcoming radical changes to their support systems, feed-in tariffs (FiT) and production tax credits (PTC) respectively, which will reduce the revenue for future wind farms and thus trigger a flux of new projects trying to get the current levels of remuneration. In the case of India, the main driver is government push towards carbon-free, indigenous electricity generation, coupled with lowest-ever costs achieved through auctions. Both China and India have set ambitious wind deployment targets: China's Strategic Energy Action Plan 2014–2020 set a target of 200 GW by 2020, although recent reports point out towards an increase to 210–250 GW [23], and India's 60 GW by 2022 [24].

In the EU, offshore wind is currently receiving a significant push (see Fig. 8 in Ref. [25]), but the long-term perspectives are less clear, as a new low-cost paradigm makes governments re-consider how to fit new projects and to absorb large amounts of offshore wind electricity in the respective electricity systems.

2.3. Wind electricity generation in 2017 vs. installed capacity

Wind electricity production in 2017 was in the EU (346 TWh), higher than in China (306 TWh [26]) or the US (254 TWh [27]), see Fig. 4. However, it is in the US where the average turbine produced more electricity: US capacity factors in 2017 reached 33.9% compared to 22.3% in China,[3] and 24.5% in the EU.[4]

Main reasons for these differences include wind resources and electricity system limitations. The wind resource in the US is significantly higher than in Europe, in particular in their mid-West states which is where most wind deployment has taken place: in 2016 64% of new capacity was installed in 10 states, according to the

[3] Capacity factor considered over grid-connected capacity only. If CF was calculated on the (larger) installed capacity the figure for China would be significantly lower.

[4] Calculations based on the respective country and industry sources, see Fig. 4.

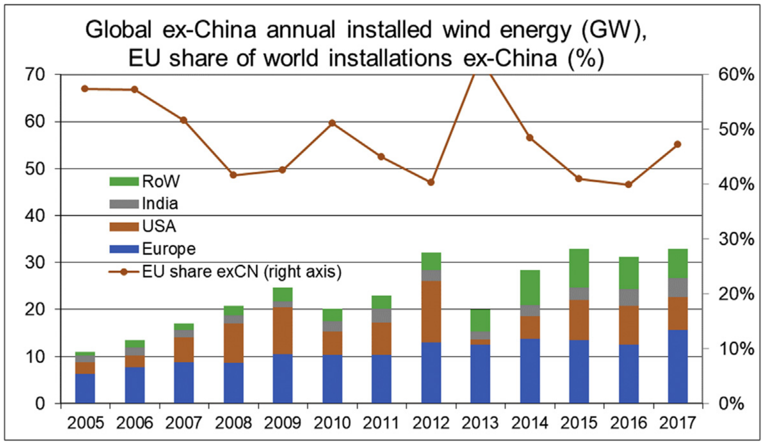

Fig. 3. Global excluding China annual installed wind energy generation capacity, and EU share of the installations.
Source: GWEC [17], adjusted with EU Member State data

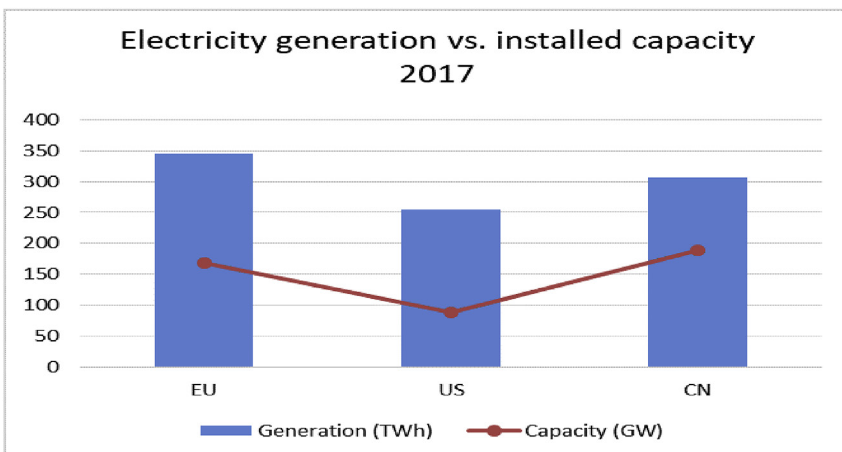

Fig. 4. Electricity generated in the three main markets in 2017 compared to their respective installed capacity at the end of 2017.
Sources: US Energy Information Administration [27], ENTSO-E [69], GWEC [17], China National Energy Administration [26], CWEA [70].

American Wind Energy Association[5] [28]. In Europe, only the North Sea area (including both onshore and offshore) reaches high average wind speeds. Rather than to its wind resource, the problem causing very low capacity factors in China relates to limitations in its electricity grid which obliges to curtail production: wind resource-rich areas, in the north of the country, are heavily affected by grid constraints to export electricity to the demand areas in the south and the east.

Wind electricity production naturally increases with increased deployment. Interestingly, on a turbine-by-turbine basis, electricity production from new wind turbines is increasing as well because new technologies (essentially larger rotors and taller towers) boost production and capacity factors, all other factors remaining equal.

Specific power is the ratio of the size of the electricity generator of the turbine (in Watts) to the size of its rotor (in m^2). Specific power downwards evolution (Fig. 5) involves that rotors are getting larger related to the electricity generator of the turbine. In addition, the swept area of larger rotors is larger, and thus more energy is extracted by a single turbine.

3. The global turbine manufacture market

3.1. Wind turbine manufacture market in 2017

The group of the top ten wind turbine manufacturers in 2017 includes the presence of five European companies: Vestas, SGRE,[6] Enercon, Nordex-Acciona and Senvion [29,30]. Based on FTI , the share of European OEMs in this top ten has increased from 50% in 2015 to 61% in 2017. This was partly due to their increased installations (from 22 to 25GW) but mostly due to the reduction in home market for Chinese manufacturers (down from 30 to 20 GW) which naturally resulted in a higher relative share of the rest of the world market.

Three of the other top ten manufacturers per installed capacity (MW) are Chinese. GE of the US and Suzlon of India complete the top ten. The former company could partly be considered European after it acquired in 2015 FR/ES manufacturer Alstom Wind.

In addition to showing this ranking, Fig. 6 shows that concentration in the turbine manufacture market was significantly higher in 2017 than in 2015: in 2015 the top 10 gathered 70% of global installations ("others" was the remaining 30%) whereas in 2017

[5] In the states of ND, MN, WY, SD, IA, CO, KS, NM, OK and TX a total 52.54 GW were installed at the end of 2016, over 82.18 GW in total. Source: AWEA's US Wind Industry Fourth Quarter 2016 Market Report.

[6] Note that the merger Siemens – Gamesa was finalised in early 2017.

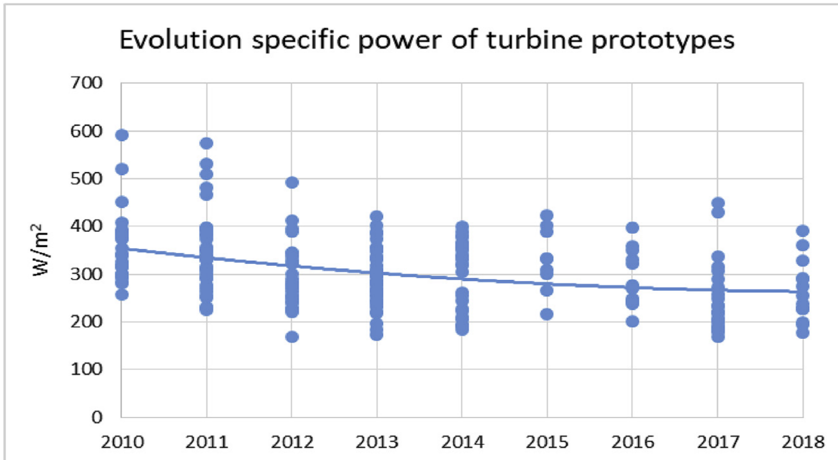

Fig. 5. Evolution of the specific power factor in 215 prototype wind turbine models introduced between 2010 and 2018. Note: not all turbines were eventually commercialised. Source: own database.

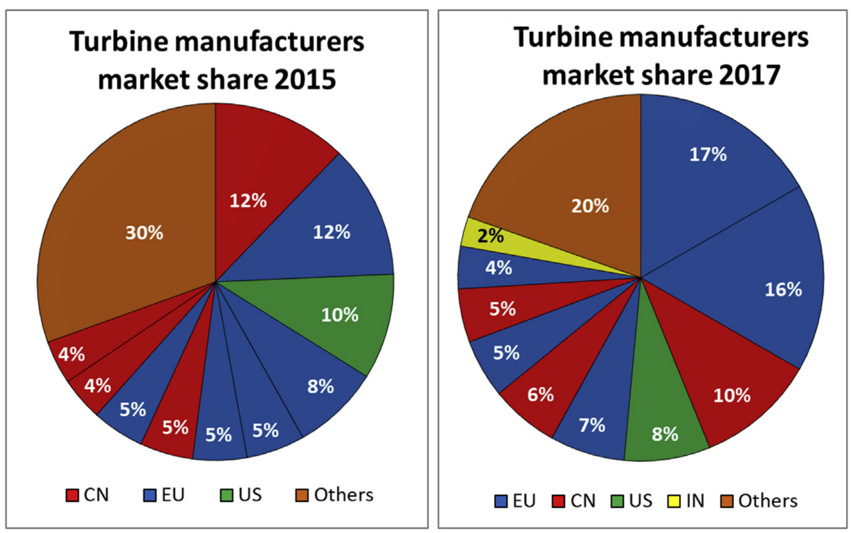

Fig. 6. Turbine manufacturers market share in 2015 and 2017, per country or region. Note: For comparison purposes, Nordex includes its acquisition Acciona in both 2015 and 2017, even when in 2015 Acciona was not yet part of Nordex. European companies in blue and Chinese in red.
Source: Global Wind Market Update 2016 & 2017 [29,30], adjusted with own data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

they reached 80%.

In the medium term it is possible that Suzlon (IN) and Goldwind (CN) take market share from EU manufacturers. Suzlon has a past international footprint and it has stated a strategy to recover in those markets. Goldwind's turbines are reaching bankability outside China, a difficult task [31]. This is less likely to happen with other Chinese manufacturers as they are only starting to expand outside China – this is the case of Envision, Ming Yang and United Power.

In the long term Envision and perhaps SEwind from China might also take a significant international market share.

3.2. *Evolution of the global market and role of European companies*

There are two figures whose comparison is probably the simplest way to measure how successful European turbine manufacturers actually are. As shown in Fig. 7 these two figures correspond to:

- Share of installations in the EU within global installations (EU share of deployment)
- Market share of EU manufacturers (OEM) within the annual global market.

In the last five years (2013-2017) European manufacturers consistently held between 41 and 50% (average 45.2%) of the world market, whereas the EU market was only between 20 and 32% (average 25.5%) of the world market. Therefore European turbine manufacturers capture an average 19.7% world market share above the EU market.

If installations in China are discounted ("ex-China"), European manufacturers enjoy an even greater success, as they have held between 73% and 82% of ex-China world installations since 2013. They have the enormous merit of having withstood the threat of low-cost Chinese turbines exporting to world markets, something not achieved by other related industrial sectors such as photovoltaic solar panels.

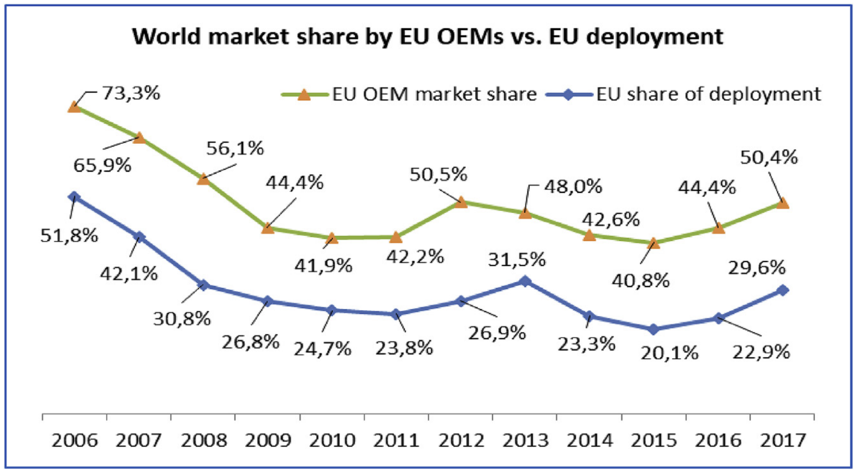

Fig. 7. Whereas the share of EU deployment is relatively low, the share of European turbine manufacturers (OEM) in the global market is much higher. Notes: Percentages vary slightly depending on the exact milestone (installation, commissioning …) and source (GWEC, FTI, own data) used.

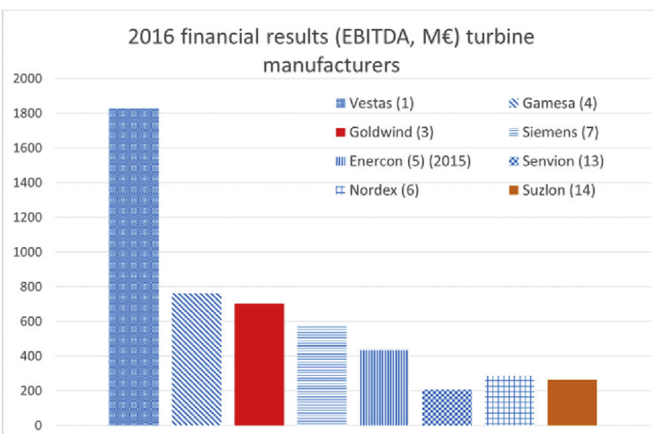

Fig. 8. Profit of turbine manufacturers, as reflected by EBITDA figures, 2016. European companies in blueish. The numbers between brackets correspond to the company market ranking in 2016 installed capacity. Sources: [32,33,55,56,62,70–74]. Note: Enercon EBITDA corresponds to 2015.

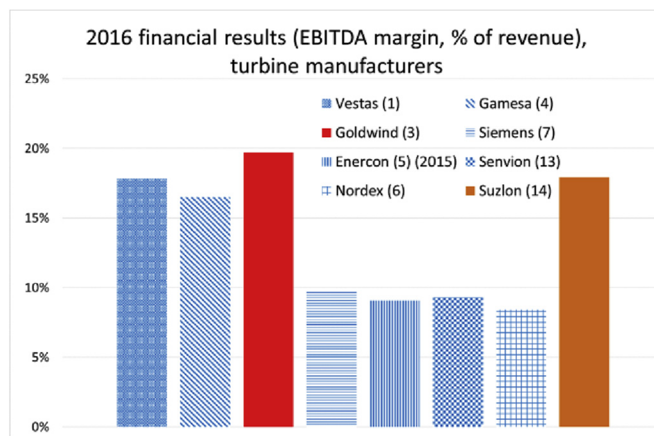

Fig. 9. 2016 EBITDA margin as percentage of revenue, selected turbine manufacturers. Sources: [32,33,55,56,62,71–74]. Note: Enercon figure corresponds to 2015.

3.3. Turbine manufacturer financial health

In general wind turbine manufacturers presented a very healthy financial situation in 2016.

Fig. 8 shows the financial health of a group of wind turbine manufacturers including six European companies. Companies part of the top ten that are missing here include General Electric because it is a big industrial conglomerate that does not present a breakdown per business areas; and Chinese companies Envision and Ming Yang because of lack of data. Enercon (DE) is privately owned and thus it does not present annual results in public, still Enercon made public some figures in interviews with sector magazines [32,33].

Vestas, the market leader, presented the highest EBITDA. European manufacturers Gamesa, Siemens (in 2016 they still were separate companies) and Enercon present significant EBITDAs, along with Goldwind of China. A third group could include Nordex and Senvion (DE) and Suzlon (IN), with lower margins.

However, if we look at another financial indicator (Fig. 9), the profit margin (EBITDA margin) or margin of EBITDA on total revenues, Asian companies showed higher figures at 19.7% (Goldwind) and 17.9% (Suzlon). This suggests that those Asian competitors would be in a stronger position to face price competition, i.e. they can reduce prices —and still make a profit- further than European companies.

Profits have greatly improved across the board since the 2012/3 crisis.

3.4. Manufacturers going global

In a sector undergoing global expansion such as wind energy is, most players have expanded to new markets. Fig. 10 shows this global trend: in general all manufacturers (represented by coloured bubbles) between 2008 and 2016 have increased the number of markets where they have made annual sales totalling more than 50 MW of turbines.

European companies Vestas, Enercon, Siemens, Gamesa and Nordex have increased the number of markets served, as so has General Electric. The data shows as well that Suzlon retreated into its home market in 2013 (even when it had some exports in 2014/2015). Chinese companies show very limited expansion to other markets, with only Goldwind showing a certain presence abroad.

Several reasons lie behind this situation. First, EU markets are generally small and sometimes subject to political negative policy changes (e.g. Spain, Italy), thus European manufacturers have to

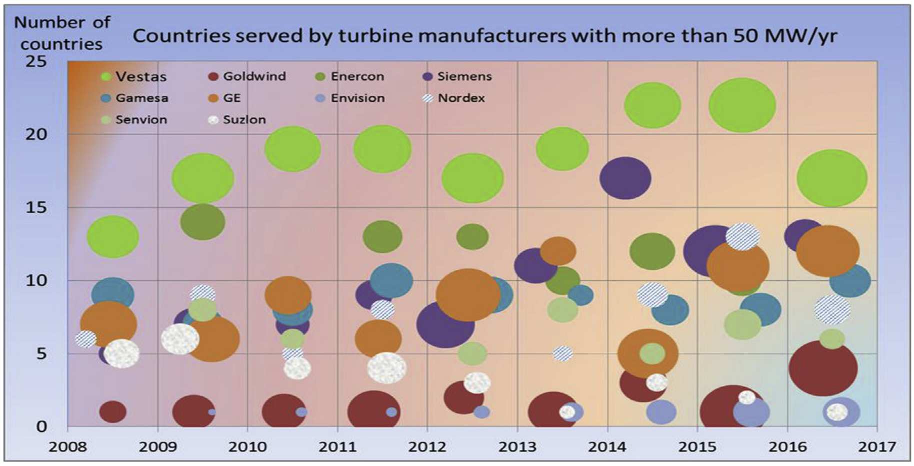

Fig. 10. Number of countries served by turbine manufacturers 2008–2016. Notes: The vertical axis represents the number of countries for which each turbine manufacturer installed, in the given year, at least 50 MW of wind turbines. The area of the bubble represents total installed capacity by the given manufacturer in those countries. Source: Bloomberg New Energy Finance database of wind farms.

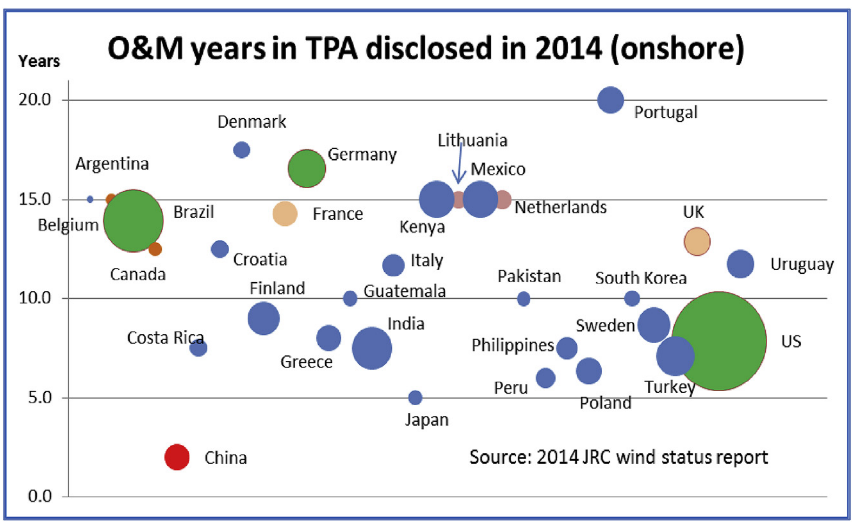

Fig. 11. Length of O&M contracts included as part of turbine purchase agreements (TPA). The thickness of the bubbles represents the country volume in MW. *Source:* [35].

focus growth on international expansion. In addition, they enjoy the first-mover advantage [34] and recognised technological quality which are enablers for this expansion.

Chinese companies' difficulties to expand abroad could be caused by a certain lack of trust in the long-time performance of Chinese-made turbines. This view is probably supported by anecdotal evidence: Chinese wind turbine contracts traditionally do not include any maintenance beyond the two years of customary guarantee (see Fig. 11 borrowed from reference [35]), which suggests that maintenance after the second year of operation is not carried out by the turbine manufacturer, who is (in theory at least) well placed to do proper maintenance.

3.5. Strategies for entering new markets

As in any other industrial sector, wind turbine manufacturers have expanded abroad by following different strategies. These include licensing, joint ventures, acquisitions, developing wind farms, or contributing to financing the wind farm projects.

3.5.1. Licensing

Licensing turbine designs is an approach followed by engineering, non-manufacturing companies focusing on a “design and license” business model as well as by wind turbine manufacturers.

Among the former the most successful are Aerodyn (DE) who licensed to BARD (DE), Ming Yang (CN), SEwind (CN), United Power (CN), Hyosung (KR) and HEAG (CN)[7] and Dongfang [36]; MECAL NV (NL) who licensed to HEAG and CSIC Haizhuang (CN) and in particular Windtec (AT) which, under its parent company American Superconductors (AMSC) licensed to more than 10 manufacturers worldwide.

A few turbine manufacturers have resourced to licensing as a way to enter new market and increase the profitability of their intellectual property investment. The following could be highlighted:

[7] Until here data from our own database.

- Vensys (DE), 70% property of Goldwind, has licensed as well to Regen (IN), IMPSA (AR), GenesYs (DE) and Eozen (ES). The last three are no longer in business, whereas Vensys continues to develop and sell turbines.
- Senvion (DE) licensed (as REpower, its name to 2013) to Goldwind, Windey and DEC, all Chinese.
- Lagerwey (NL) licensed to CASC (CN) and EWT (NL).
- Fuhrländer (DE) licensed to A-Power, Huide and Sinovel (all Chinese).

A variation of licensing is an activity that is called “joint development”, or “joint R&D” in China. This activity is an extension of licensing where the technology company is a turbine design company (e.g. Aerodyn, MECAL, AMSC). The activity was analysed by Zhou et al. [36] who concluded that “*joint R&D has improved Chinese companies' technical capacity, human resources and financial growth. However, the effect on Chinese companies' innovation capacity is still limited because of unequal technical capacities of the two sides in collaboration, as well as their preference for augmenting profits rather than technical capacity. Current joint R&D mode is only the extension of licensing mode in wind-turbine manufacturing industry.*”

3.5.2. Joint ventures

Joint ventures have used to enter new markets as different as Spain and China — but they have not proven successful in the long time, they have been rather problematic. One key difference with licences is that licences commonly give licensees more control but it is thought that “*the most accessible technology is usually somewhat outdated*”. Cooperative development as joint ventures, by contrast, “grants *domestic turbine manufacturers access to newer designs and the right to manufacture turbines locally, albeit with greater foreign involvement*” [37].

In joint ventures (JV) foreign corporations contribute technology and knowhow, sometimes capital and marketing, whereas the local partner contributes manufacturing capacity, relationships with the national government and/or understanding of the local context.

Gamesa Corporación Tecnológica (“Gamesa”) wind turbine manufacturer, now part of Siemens Gamesa Renewable Energy, was created as “Gamesa Eólica” in 1994. Gamesa Eólica was a joint venture between Gamesa's local owners (51%) and Vestas (40%) with a focus on manufacturing and selling turbines in Spain, Latin America and Northern Africa [38]. In 2001 Vestas sold its share to its partner and Gamesa became free to enter other markets in direct competition with Vestas [39]. Part of the agreement included technology transfer for turbines G52, G58, G66 and G80.

Joint ventures have been a key strategy for the expansion of European manufacturers to enter the Indian and Chinese markets, although with very different results. In India, Vestas joined RBB Consultants and Engineers Private Ltd in 1987 to form Vestas RBB India on a 49/51% share, where Vestas contributed the V27-225 kW, V39-500 kW and V47 technologies. The JV was dissolved in 2006, changed named (now RRB Energy Ltd) and claims to continue manufacturing V27, V39 and two new models (600 and 1800 kW). Since then Vestas did not enjoy any significant success in the country judging by their own orders announcements: only 99 MW in 2009, 129 MW in 2010, 78 MW in 2011, 51.8 MW in 2013, and 86 MW in 2015.

In 1995 Enercon joined the Mehra family of Mumbai in a 56/44% JV called Enercon India Ltd, with negative results as it finished in a series of court cases. In effect, after a dispute arose in 2008 on the terms and royalty payments due after the linked technology licence agreement [40], Enercon became unable to sell in the Indian market while the court case lasted. It was only in 2017 that the case finished and Enercon could enter the Indian market again [41].

In China nine joint ventures started in the 2000s and all of them have been dissolved [42]. For example, Harakosan of Japan and state-owned XEMC (CN) formed Hara XEMC Windpower in 2006 and by the end of 2008 Harakosan had sold all shares to XEMC [43]. It is perhaps interesting to see some the arguments given by Harakosan when in 2007 it sold to XEMC 23% of its initial 50% in their joint venture: “*1) Since most wind-power generation projects in China are for electric utilities, the operation of these businesses is closely associated with policies of the Chinese government. Consequently, using a majority-owned Chinese company results in a more advantageous position for negotiations of all types*” [44]. This is consistent with the situation for Chinese state-owned enterprises (SOE) as described in the analysis of the developers market in section 5.3.

The following lists all wind turbine manufacturers joint ventures in China:

- Yituo-MADE (Luoyang) Wind Turbine Co. Formed by China YiTuo Group and MADE (ES) [37].
- Xi'an Nordex Wind Turbine Co. Ltd. Formed by Xi'an Aero-Engine Group and Nordex (DE)
- Nordex (Yinchuan) Wind Power Equipment Manufacturing Co. Ltd. Formed by two Chinese partners (Ningxia Electric Power Group and the Ningxia Tianjing Electric Energy Development Group) and Nordex [37].
- Hara XEMC Windpower: XEMC, Harakosan (JP)
- Nantong CASC Wanyuan Acciona Wind Turbine Manufacture Co., Ltd.: CASC and Acciona (ES)
- REpower North. Formed by North Heavy Industry Corp. and two Western partners, developer Honiton Energy Ltd. (UK) and REpower (DE)
- Harbin Hafei-Winwind Wind Power Equipment Co. Ltd. (also called Hafei in Harbin) Formed by Harbin Power Equipment Group and WinWinD (FI)
- Guangxi Yinhe Avantis Wind Power Co., Ltd., Formed by Yinhe group and Avantis Group (DE)
- Shandong Swiss Electric Co., Formed by Weifang Zhongyun Machinery Co., Ltd. And unidentified Swiss and German partners.

Licensing and joint ventures sometimes occur successively. In 2011 Siemens constituted two JVs with Shanghai Electric to build blades and assemble nacelles in China [45]. Later these JVs were terminated and then Siemens licensed to Shanghai Electric the construction of all models of blades, and the entire rotor-nacelle assembly of the 4 MW offshore machines in China. The licensing agreement was later extended to the 6 MW direct-drive machine [46]. With that, all the business of Siemens Wind Power (SWP) in China was reduced to the licensing of its technology (previously the licensing agreement was focused only in the smaller onshore G2, and D3 turbines whereas blades were supplied directly by SWP, who had set blade manufacturing facilities in the country).

3.5.3. Manufacturers taking the role of developers

Several turbine manufacturers including Vestas and Gamesa resourced to developing wind farms as a way to sell their turbines abroad as well as at home (section 5.3 includes some details on how OEMs inroads into the developer market). Suzlon since the 2000s, and several Chinese companies more recently, have adopted this strategy with which they are supporting their foreign expansion.

Envision and Goldwind in particular have pursued the strategy of developing wind farms. Goldwind has been particularly active in

Australia and the US, and Envision in Chile and Mexico.

Given that the competitive advantage of Chinese manufacturers is the lower cost of manufacture in China, they have enjoyed most success in markets where a local content is not required. On the contrary, in countries like India and Brazil[8], Chinese manufacturers have hardly had any deployment. One exception, from the period before local content rules existed in Brazil, is Sinovel's 34.5 MW Barra dos Coqueiros wind farm (2012).

3.5.4. Facilitating access to finance

Under certain conditions access to finance is a limiting factor in the development of new wind farm projects. One example is when the country risk[9] is high or very high whereas in other cases it is the specificities of the project that create the risk. Under these conditions, turbine manufacturers that can facilitate access to finance as part of a turbine supply package are better positioned to get the contract and thus to expand internationally. This is a strategy used generally in countries like Pakistan, but lately exploited widely by Chinese turbine manufacturers and GE.

The Sapphire wind farm in Pakistan is an example. Mr Nadeem Abdullah, owner of the wind farm, declared "*we chose GE wind turbines because (…). GE has been instrumental in* supporting *Sapphire to achieve financial closure with OPIC.*" "*OPIC is the U.S. Government's Development Finance Institution, which mobilizes to provide capital to global development in order to assist U.S. foreign policy efforts, including helping develop renewable energy as a mutual American-Pakistani goal. OPIC's funding will help assist in the development of the wind farm*" [47].

Chinese manufacturers are backed by significant financial possibilities stemming from the internationalisation policies of their government. China's Belt and Road initiative [48], or OBOR (One Belt One Road), supports financing of infrastructure projects including wind farms, and this has had an impact already e.g. in Pakistan, as shown in Table 1.

Irrespectively of whether the funding is coming from the state, multi-lateral or private banks, well-funded turbine manufacturers can offer the developer some kind of financial package: as St. James puts it "his is perhaps why we see them more successful in markets with difficult access to capital" [49].

The strategy of partial financing or facilitating access to finance is not limited to countries with a high risk profile. For example in the US, GE Energy Financial Services (the financing business unit of GE) invests in wind farms partly because the synergy to do the financing and the equipment allows the turbine manufacturer "to sit with project developers at an earlier stage than we otherwise might" [50].

3.6. Merger and acquisition processes[10]

One of the most typical and more critical aspects of globalization is that it normally comes with merger and acquisition (M&A) of companies. This has severe consequences for the industry and the economy of countries that lose ownership of decision-making in their companies when they are acquired by foreign ones.

In the wind sector, very often foreign companies have bought European companies with the objective of absorbing their technology. In most of those cases small European companies are incorporated into a big industrial conglomerate.

Table 2 shows some examples of M&A –focusing in those having the most important industrial or technology impact-since 2000, highlighting in bold the cases in which foreign companies have acquired European technology.

There were 42 large transactions completed in the wind industry between 2001 and 2017.

The table shows that M&A activity of significant market players has accelerated, with annual transactions peaking at 12 in 2016. Seventeen among those transactions have been between European companies. This could be due to the large European history in wind industry, the financial crisis and the subsequent consolidation happening among a broad number of agents in Europe.

Seventeen is also the number of operations in which European technology was acquired by foreign companies, in most cases American (7 cases) or Chinese (4[11]) but also from Japan (3), South Korea (2) and India (1). The consolidation of the wind industry is taking place, and companies of the largest world economies are acquiring European technology in order to accelerate, improve and expand their business.

It is significant that no acquisition of American or Asian technology companies by a European company was identified.

Fig. 12 shows that there has been a recent increase in M&A activity, concretely since 2014. This activity has affected the sector with higher impact that it has targeted European technology.

M&A activity has demonstrated that consolidation can help turbine OEMs achieve greater economies of scale, for example through geographic expansion and the exploitation of a larger resource capacity to create synergies and diversify product offering. Moreover, it also offers the opportunity for large industry conglomerates to enter the wind industry (e.g. Daewoo, General Electric) or to set up joint ventures reaching global leadership as demonstrated by those in the offshore wind industry (e.g. Vestas and Mitsubishi). This might contribute to increasing the competitiveness of the entire wind sector against other renewable or conventional energy industries.

This consolidation of the wind industry very often comes naturally accompanied by restructuration plans that benefit from all synergies of merging two companies, or of acquisition of a small company by a large industrial conglomerate. In the case of foreign companies acquiring European technology companies, the result is that the EU risks to lose (a) highly-paid industrial jobs, (b) the corresponding industrial fabric (c) long-term investment in the projects that supported these companies, and (d) intellectual property rights of innovations. Another concern is that the capital or R&D investment lost to foreign owners was in part or in all publicly funded -through universities, EU or national public research programmes and/or company R&D tax relief.

With the wind turbine technology sector becoming more mature, European turbine manufacturers are facing increased pressure mostly from GE and Chinese turbine manufacturers. In addition, competition from solar photovoltaic (PV) technology is becoming increasingly intense [51] due to the faster cost-reduction pace of solar PV.

In order to gain a strong or dominant position in the markets which are seeing fast growth while being competitive in cost of

[8] Brazil, like Russia and previously China, has local content rules which forces the establishing of local manufacture plant and/or the purchase of local components, both sourcing strategies not favoured by Chinese OEMs.

[9] Country risk is "the risk of investing or lending in a country, arising from possible changes in the business environment that may adversely affect operating profits or the value of assets in the country. For example, financial factors such as currency controls, devaluation or regulatory changes, or stability factors". Source: Wikipedia.

[10] The author would like to warmly thank Mr Daniel Román Barriopedro for his significant contribution to this subchapter.

[11] Two more Chinese acquisitions focused on developers, not considered technology companies here, even when it is acknowledged that the acquisition gave foreign companies access to the technology in the European turbines installed in their wind farms.

Table 1
Projects financed by the Chinese OBOR initiative in Pakistan, financial information. Note: RoE means return on equity. Sources: [75–81]; own database; financial information from Reynolds et al. [82].

Project	Capacity (MW)	Cost (M$)	Debt/Equity	RoE (%)	Developer	Equipment manufacturer	Status
Hydrochina Dawood	50	125	–	–	HydroChina (CN)	Ming Yang (CN)	Operational (2016)
United Energy Pakistan	99	250	–	30.14	UEP (PK)	Goldwind (CN)	Operational (2017)
Sachal	49.5	134	80/20	18	Arif Habib (PK)	Goldwind (CN)	Operational (2017)
Three Gorges 2 & 3	99	260	75/25	28.85	Three Gorges (CN)	Goldwind (CN)	Operational (2018)
Cacho	50			24.6			Announced
Western Energy	50						Announced

Table 2
Mergers, joint ventures and acquisitions in the XXI century. Notes: bold highlight denotes that European technology is acquired by foreign companies; Enron Wind's (US) technology was European after its acquisition of German Tacke in 1997, and Harakosan of Japan is considered to have European technology when it was acquired by STX in 2009; OEM denotes wind turbine manufacturer.

Buyer	Buyer sector	Target company; merge with; JV name	Target sector	Announced
Gamesa (ES)	OEM	Gamesa JV (ES) (buy 40% Vestas share)	OEM	2001
GE (US)	**Industrial conglomerate**	**Enrond Wind (US)**	**OEM**	**2002**
Gamesa (ES)	OEM	MADE (ES)	OEM	2003
Vestas (DK)	OEM	NEG Micon (merge) (DK)	OEM	2004
Siemens (DE)	Industrial conglomerate	Bonus (DK)	OEM	2004
Harakosan Co Ltd (JP)	**Building developer**	**Zephyros (NL)**	**OEM**	**2005**
Suzlon (IN)	**OEM**	**86,5% REpower (DE)**	**OEM**	**2007**
Alstom (FR)	Industrial conglomerate	Ecotecnia (ES)	OEM	2007
Goldwind (CN)	**OEM**	**Vensys (DE), 70%**	**OEM**	**2008**
XEMC (CN)	**OEM**	**Darwind (NL)**	**OEM**	**2009**
GE Wind (US)	**OEM**	**ScanWind (SE)**	**OEM**	**2009**
STX Heavy Industry (KR)	**Industrial conglomerate**	**Harakosan (JP)**	**OEM**	**2009**
Daewoo (KR)	**OEM**	**DeWind (DE)**	**OEM**	**2009**
AREVA (FR)	Industrial conglomerate	Multibrid (DE)	OEM	2010
TOSHIBA (JP)	OEM	Unison (KR) 40%	OEM	2011
GE Power Conversion (US)	**Industrial conglomerate**	**Converteam (UK)**	**Generator & converter manufacturer**	**2011**
Hitachi (JP)	OEM	Fuji HI Wind (JP)	OEM	2012
MingYang (CN)	OEM	GWPL (IN)	OEM	2012
Titan Wind Power (CN)	**Tower manufacturer**	**Vestas' tower business (except US)**	**Tower manufacturer**	**2012**
MHI (JP) & Vestas (DK)	OEM	JV Offshore (DK)	OEM	2013
Gamesa & Areva	OEM	JV in Offshore	OEM	2014
Yaskawa (JP)	**Industrial conglomerate**	**The Switch (FI)**	**Generator manufacturer**	**2014**
GE Renewable Energy (US)	**OEM**	**Alstom Wind (FR)**	**OEM**	**2015**
GE Renewable Energy (US)	**OEM**	**Blade Dynamics (UK)**	**Blade Manufacturer**	**2015**
Cheung Kong Infrastructure (CN)	**Developer/Operator**	**Iberwind (PT)**	**Developer/Operator**	**2015**
CSR (CN)	**Industrial conglomerate**	**Soil Machine Dynamics (SMD, UK)**	**Subsea vehicles**	**2015**
Centerbridge (US)	**Investment house**	**Senvion (DE)**	**OEM**	**2015**
GE Renewable Energy (US)	**OEM**	**LM Wind Power (DK)**	**Blade manufacturer**	**2016**
Three Gorges (CN)	**Developer/Operator**	**WindMW (DE)**	**Developer**	**2016**
Envision Energy (CN)	OEM	Portfolio of 600 MW of projects by Vive Energia (MX)	Developer	2016
Siemens & DONG	OEM/developer	A2Sea (DK)	Offshore installation	2016
Nordex (DE)	OEM	Acciona (ES)	OEM	2016
Vestas (DK)	OEM	Upwind (US)	Independent Service Provider	2016
Vestas (DK)	OEM	Availon (DE)	Independent Service Provider	2016
Nordex (DE)	OEM	SSP (DK)	Blade manufacturer	2016
Senvion (DE)	OEM	Euros (DE)	Blade manufacturer	2016
Senvion (DE)	OEM	Kenersys (IN/DE)	OEM	2016
State Grid (CN)	**Developer/Operator**	**CPFL Energia (BR)**	**Developer**	**2017**
Gamesa (ES)	OEM	Adwen, 50% Areva stake	OEM	2016
Siemens (DE)	OEM	Gamesa (Merge)	OEM	2016
Nidec (JP)	**Generator manufacturer**	**Leroy-Somer (FR)**	**Generator manufacturer**	**2017**
DEME (BE)	Offshore installation	A2Sea (DK)	Offshore installation	2017

energy terms, in the past three years European turbine manufacturers streamlined production and significantly reduced costs. In this context, those M&A deals have had a significant impact on turbine OEMs' competitive landscape both in the short and in the medium term. The main impact that M&A activity is introducing to the competitive landscape of EU OEMs are, in the short term:

1. GE-Alstom, Nordex-Acciona and Siemens-Gamesa are three major operations that have a significant impact on the competitive landscape of the turbine manufacturing sector. For example, although the acquisition of Alstom's power business did not boost GE's global wind market share dramatically, it brought GE back to the offshore wind sector with nearly 2 GW offshore wind pipelines in the European waters. The other two cases had an impact mostly in providing de acquiror access to additional markets.
2. Nordex returned to the top 10 OEMs after its acquisition of Acciona's turbine business, approved by the European Commission in 2016.

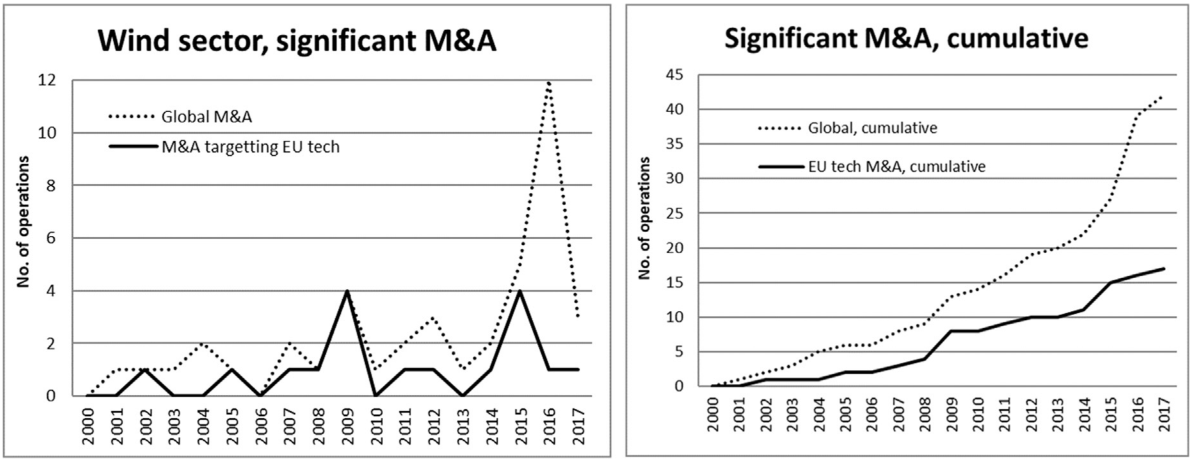

Fig. 12. Mergers and acquisitions (M&A) in the wind sector, no of operations per year and cumulative since 2000.
Source: Daniel Román Barriopedro, own data, press releases and news.

3. The merger between Siemens Wind Power and Gamesa makes a global leader in the wind market. According to FTI Consulting [29], the combined entity accounted for more than 13% of global wind turbine installation in 2016 and 16.6% in 2017 [52], making it the second largest OEM in the world.

In conclusion, the global market will favour larger players in the medium term, especially in onshore wind. Offshore, the limited number of markets will play a role but it is unlikely to support consolidation in the OEM market. As a consequence during this process of consolidation Europe is losing some of its core technology industrial fabric, and with it a relevant piece of its economic activity.

4. Impact of globalization of turbine manufacturers

From a policy point of view probably the most important economic impacts of globalization are related to "***where***": where companies create employment, both direct and indirect in their supply chain, and where they pay taxes. It is perhaps worth noting in this respect that in its recent *Reflection paper on harnessing globalization* [53], the EC suggested that every billion euro of exports supports 14 000 jobs.

Information on where OEMs pay taxes is essentially non available for this research, perhaps it is not publicly available at all. Information on where companies create employment is available in a patchy way as some manufacturers are more transparent than others.

Gamesa's corporate social responsibility (CSR) reports detail elements that can be used to answer the first question above. Other manufacturers give less details, but the information they give is key to confirm -and at times modulate- the trends shown in [54]. Therefore, the approach followed in this part of the research is to use Gamesa's data to define a trend and then to contrast that trend with the available data and information by other turbine manufacturers.

European turbine manufacturers have access to a limited market at home (see section 3.1), and thus in general most of their revenues come from third countries. Fig. 13 shows that this OEM obtained only 16% of its global income in the EU in 2016, but it spent 34% of its procurement there [54]. EU countries specifically accounted for by Gamesa are Germany (2.61% of total procurement), France (0.82%), Spain (25.14%), Italy (1.04%), the UK (1.14%) and Denmark (0.59%).

Another European manufacturer, Vestas, installed 37% of its turbines in the EU [55], Nordex 53% in the EU [56] and Enercon 48% in Germany [57]. They all show higher dependency on the EU (or any of their Member States) as home market.

The weight of EU purchases in total procurement can be considered a partial proxy for competitiveness of European subsuppliers (or supply chain). Fig. 14 shows that in the particular case of this OEM the weight of the EU in procurement has eroded during the last few years, while the weight of China and India —and, to a lesser extent, Brazil-has increased. The increases in the case of India and Brazil can be understood as a need to localise production in these large markets.

Whereas the latter localisation argument also applies to China, however, in the Chinese case procurement share (17% in 2016) largely exceeds revenue (4% in 2016). It can be concluded that a significant part of the goods procured in China are actually used in other markets.

Vestas expresses as well the need for localisation in target markets Brazil, China and India: "local presence and local sourcing is of great importance in these countries, be it for reasons of proximity to customers, cost-effectiveness, or fulfilling local content requirements in manufacturing" [55].

Furthermore, Vestas has a strategy to have closer ties with large suppliers because "*involving these in the development of products and processes, as the suppliers often possess many years of knowledge and experience that can be utilised to the benefit of both parties*" [55]. This kind of strategies could be a threat for Vestas' European suppliers even when it offers them an opportunity to expand abroad because of the required supplier size: some foreign suppliers, most commonly Chinese ones,[12] do have the required size, and thanks to this strategy they may conquer part of the market share currently in the hands of European suppliers.

The decision of where to set up components manufacture comes therefore hand-by-hand with supply chain decisions, and they both are partly the result of the size of the focus market.

Data on number and location of suppliers corresponding to both tier 1 and tier 2 suppliers are shown in Fig. 15. Gamesa kept in the EU the largest share of world suppliers (48%) despite having only 16% of revenue from EU markets. A comparison with Fig. 13, which

[12] Gamesa's figures show that procurement from the average Asian supplier reaches significantly higher unit value tan procurement from the average European supplier. In a loose average, the ratio would be 3.3 to 1. Source: own calculations based on [54].

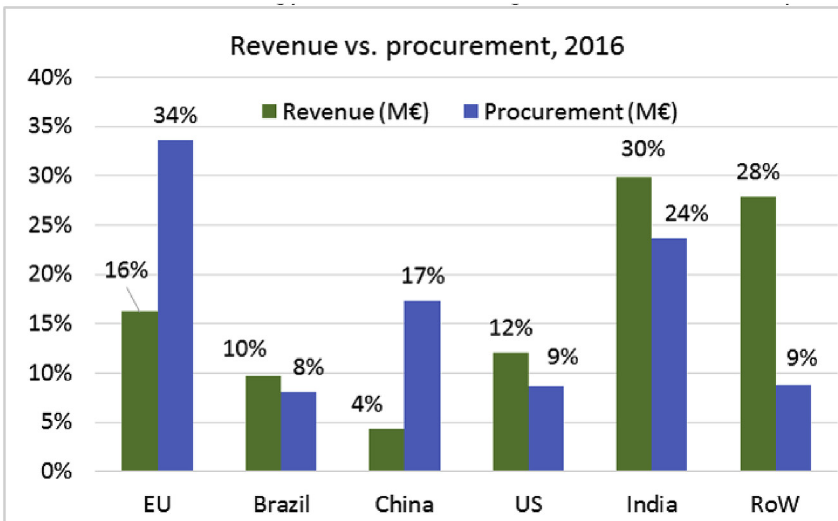

Fig. 13. Revenue vs. procurement split, Gamesa. Note: 4.43% of procurement in the original data set is unassigned. Following a principle of proportionality, here these have been allocated to the EU and RoW on a 50/50 basis.
Source: [54].

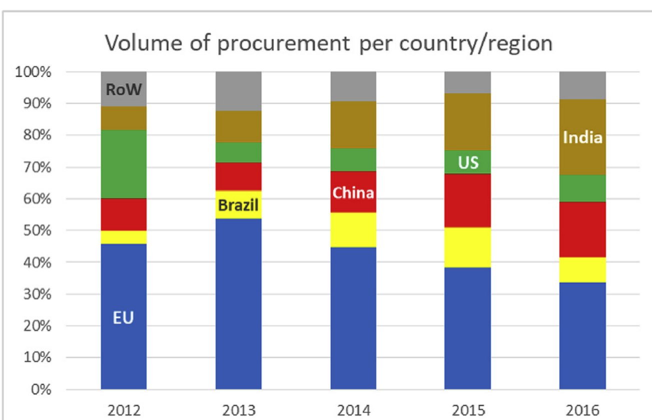

Fig. 14. Evolution of procurement per region, Gamesa. Note: Between 4.5% and 9% of procurement is not allocated to a country in the original. Here it has been added to the EU and to the rest of the world (RoW) on a 50/50 basis.
Source: [54].

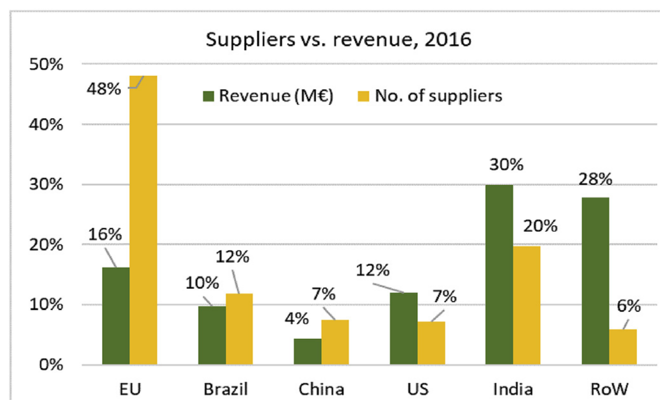

Fig. 15. Location of suppliers vs. origin of revenue. Most suppliers are EU-based, whereas most revenue is created abroad. Remarks: comparison is only loose because suppliers statistics show "EMEA" figures (vs. "EU" in revenue statistics), and "LATAM" (vs. "RoW").
Source: [54].

shows similar breakdown for procurement amounts, suggests that a lower number of Chinese suppliers obtain a higher share of procurement, thus reaching higher average individual share of procurement. Similarly to Chinese suppliers, US, Indian and RoW suppliers are larger than EU or Brazilian ones.

Some EU OEMs follow a strategy to "develop" foreign suppliers in an effort to localise the supply chain [58]. In these cases, OEMs assign their own materials and quality development engineers to suppliers' facilities in order to ensure their technological development and competitiveness. During this process foreign firms learn and improve, thus increasing the quality of their products while maintaining the price-based competitive advantage of lower-cost countries and social systems. When a third-country supplier proves to be of outstanding quality and price, the OEM uses its products beyond the host country, actually integrating the supplier as a new member of its global supply chain. Whereas this process helps the OEM become more competitive globally and reduce the cost of energy, there are two drawbacks for the EU economy: first, European jobs are lost as they are transferred to the third country; second, there is a risk that the supplier offers its newly-acquired knowhow to competitors of the OEM who would eventually better compete with the European OEM, thus eroding the latter's competitive advantage.

Therefore, one strategy to create additional added value in Europe would be to implement programmes that promote OEMs to develop their European supply chain in the same way as they develop suppliers elsewhere. Initial exploration of this option suggests that a crucial enabler of this process is the attitude of the local workforce, as perhaps measured by productivity ratios. Indeed, the relationship between productivity and competitiveness is strong: competitiveness has been defined as "the set of institutions, policies, and factors that determine the level of productivity of a country" [59].

Emerging (Latin America, South Africa) and open (Australia, US) markets are first in the list of non-localisation-required markets: "entry barriers are lower, local financing is hard to obtain, and, perhaps more importantly, manufacturers can compete on price" [60].

Some European manufacturers have the strategy to internationalise without creating a local supply chain. This is the example of Senvion (DE) who, with this approach, is entering Australia, Chile, Argentina, Japan and the US among others. The advantages that are claimed for this strategy include: no expenditure in building up local facilities (unless economically feasible); faster product time to market; and benefits of scale in manufacturing via consolidation of existing factories [61].

Finally we will explore figures comparing the creation or maintaining of employment at home to where revenue is earned, as the amount of jobs being kept in Europe is the key benefit of European wind energy companies' success in globalization.

Vestas, with more than 22 000 employees in over 34 countries, had at the end of 2016 54.3% of them based in the EMEA region (Europe, Middle East and Africa), an area where it earns just 45% of its revenues [55]. However, despite maintaining the majority of employment in Europe, Vestas also shows that European companies are subject to the pressures of globalization: in 2016 the blade factory in Lem (DK) had to reduce 300 staff due to "*its high manufacturing costs compared to the market level as well as the need to strengthen Vestas' overall manufacturing and supply chain competitiveness in response to evolving market conditions*".

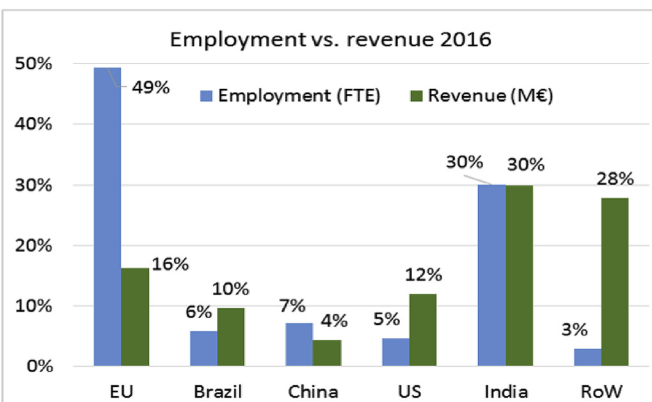

Fig. 16. Location of jobs in full-time equivalent (FTE) vs. origin of revenue. Most of the employment is maintained in the EU, whereas most of the revenue is raised abroad. Source: [54].

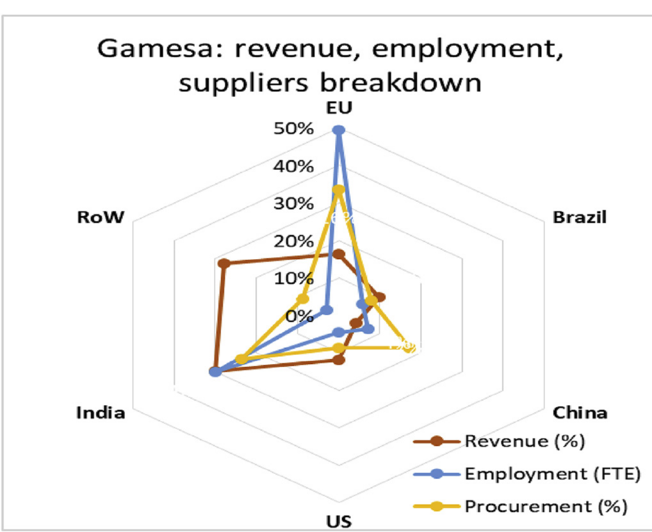

Fig. 17. Comparison of where revenue is earned, where procurement takes place and where employment is maintained, 2016

Fig. 16 shows data for Gamesa which could be the extreme case save, perhaps, Enercon, whose data are not public. The former concentrates in the EU 49% of their workforce whereas only 16% of its global revenue originates in the EU. Further, Fig. 17 compares the percentages of revenue (€), employment (no. of jobs) and procurement from suppliers (first and second tier) for the company, and reinforces the conclusion that this company maintains a very significant base at home even when most of its revenue (84%) originates outside the EU.

With regards other European OEMs in the top-15 ranking of manufacturers in 2016, data for Enercon and Siemens were not available. Nordex-Acciona maintained in Europe, at the end of 2016, 83% of its employees, whereas 61% of orders came from Europe [56]. Senvion, whose 2016 revenue in the EU was 80% of total revenue (the remaining being Canada and the US) [62], does not provide a breakdown of its workforce per country/area in its annual report.

5. Global wind farm developer market

The role of the developer is crucial for the success of a project, and it has certain characteristics that are interesting to highlight in the context of this research.

Wind energy projects normally consists of two major elements: the turbines, which are generally supplied from towers to blades by the turbine OEM, and the balance-of-plant (BoP) which includes civil works, electrical connections among turbines and to the grid, and an electricity substation if necessary. Transport and installation of the turbines could be part of either element. In China, a dual system of contracts makes that it is not the turbine OEM that supplies the tower nor the turbine transformer, but the BoP contractor.

BoP is provided by very varied companies including legal consultants, builders, cable manufacturers, etc. Therefore, the developer has to have deep knowledge of the local market, legal, economic and social context. This knowledge is naturally held by local companies and thus the developer market is highly localised.

5.1. Methodology

This part of the research is based on data from Bloomberg New Energy Finance (BNEF) wind farm database received in May 2017.

This database contained both onshore and offshore projects commissioned between 2007 and 2016 or that were under construction by the end of 2016. Projects below 5MW were removed as they were considered local projects. This resulted in a total capacity in the database was 401 662 MW.

5.2. Details of the developers market

Based in the need to be local, the developers market is much more diversified than the turbine manufacturer market. The 20 largest developers only sum 35% of wind energy commissioned in the years 2007–2016 (see Figure 18), which can be compared with 97% of the wind turbine market held by the 20 largest manufacturers, according to the same database.

Most large developers are business units of either Chinese state-owned enterprises (SOEs) including Guodian/Longyuan, Huaneng, Datang, Huadian, China General Nuclear (CGN), or of traditional European utilities such as Iberdrola, EDP, EDF, E. ON, Enel, Dong, SSE Renewables. Two American developers, owned by utilities, are among the leading developers by volume installed: NextEra and Invenergy.

The five largest Chinese developers are active essentially only in

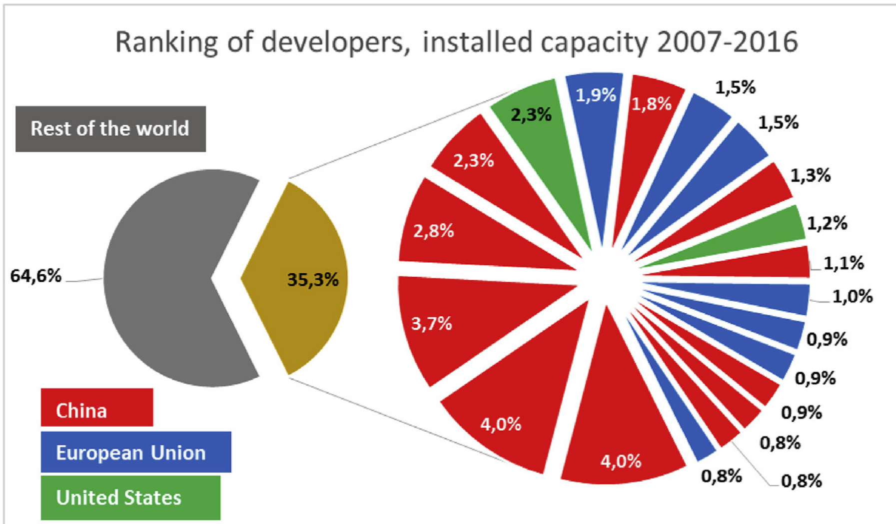

Fig. 18. Developers market per installed capacity, last 10 years. Based on 402 GW of onshore and offshore projects deployed between 2007 and 2016 or under construction at the end of that year. Source: BNEF database of wind farms adapted with own market knowledge.

China: Guodian/Longyuan (5.3% of the global market), Huaneng (4%), Datang (3.7%), Huadian (2.8%) and CGN (2.3%). Next is US company NextEra (2.3%, 95% of which in US and the rest in Canada), followed by Spanish developer Iberdrola (1.9%). Chinese Guohua follows and EDP Renovaveis and EDF Energies Nouvelles from the EU complete the top ten in this database.

5.3. Globalization of developers

European developers, although overall not the largest in size, have expanded operations through several markets whereas Chinese and US ones only marginally or moderately expanded abroad. For example, US developers have expanded, e.g. to 1–3 countries in the case of NextEra and Invenergy, whereas Chinese developers have only recently started to expand into Canada, Pakistan, Australia, South Africa, the US and other countries.

At first sight it feels surprising that Chinese developers, with plenty of financial muscle, have not expanded abroad significantly. Cui and Jiang [63] argue that state ownership is a problem for those developers to invest abroad as it "*creates the political affiliation of a firm with its home-country government, which increases the firm's resource dependence on home-country institutions, while at the same time influencing its image as perceived by host-country institutional constituents*." This point is reinforced by Huang et al. [64] who, based on resource dependence theory, suggest that SOE's dependence from state resources "*may also reduce these firms' willingness to expand internationally*".

Part of developers' international expansion took place through acquisitions, in particular into the US market. Iberdrola acquired local developers MREC Partners and Midwest Renewable Energy Projects and utility Energy East. EDP and EDF acquired Horizon Wind Energy and enXco respectively. In other cases, developers expanded with organic growth, setting up country subsidiaries. This was most common in markets with closer cultural ties, e.g. Gestamp from Spain into Brazil.

Another form of expansion to new markets is the acquisition of projects. For example, Acciona (ES) in 2016 acquired the San Roman wind farm (93 MW) in Texas, US, from American developer Pioneer Wind Energy [65].

European developers lead in terms of number of countries present. This ranking is led by Spanish Gamesa Development and Acciona Energía who are present in 14 countries each. They are followed by Iberdrola (ES) and ENEL (IT), who are present in 13 countries, EDF (FR) in 11, E. ON (DE) in 10, Engie (FR) in 9, and EDP (PT) in 8 countries. Present in 7 countries are RES (UK), Vestas (DK), and four more European companies follow with presence in 6 countries: Innogy, ABO and Nordex from Germany and Gestamp from Spain.

It's only in position 16 of this ranking of countries present that the first non-EU developer present in 5 countries is found, AES from the US. AES is accompanied by yet more European developers: juwi, WKN and BayWa (DE), Vattenfall (SE) and Global Wind Power A/S (DK), all of which are present in 5 countries.

Purchases of EU assets by non-EU firms.

Recently, a consortium of three Japanese entities (investment trading company Sojitz Corporation, Mitsubishi UFJ Lease & Finance and utility company Kansai Electric Power) bought 60% of a portfolio of five Irish wind farms (four of which already in operation and one under development), with a total 223 MW capacity, for 300 M€ [83]. This involves a valuation of the assets of 2242 €/kW, significantly higher than the estimated CapEx of 1200–1400 €/kW.

Within the EU, Irish assets have been particularly attractive for non-EU investors, with China General Nuclear Power Group buying 230 MW of wind farm assets from Gaelectric in December 2016.

The analysis of the global number of installations (in MW) per year shows the companies that have become more active or successful than others. Chinese developers, focused only on their domestic market, have been subjected to the ups and downs of that market, and generally show peaks in 2010 and 2015 and drops in 2011–2014 and 2016.

Large developers from the European Union have reduced their investment and thus show a negative trend in the period studied: Iberdrola, E. ON, Gamesa Development, Acciona, and BP. EDP and EDF, although generally having less new installations recently than at the beginning of the period, have picked up slightly in 2016.

American developers show strong growth lately, led by NextEra and Invenergy, as have European Enel, Renewable Energy Systems and wpd.

The description, based on BNEF data, shows how selected European developers internationalised.

- Iberdrola. Based on its home country (ES) and on the home country of its acquisitions (see above, mostly UK and US), Iberdrola expanded into other EU countries (to FR, DE, PL) at the beginning of the period but new onshore EU projects became rarer, and something similar occurred in the US. In 2015 Iberdrola entered the Asian market (TR). Overall, Iberdrola has reduced investment in wind farm deployment over the years.
- EDP (*Energias de Portugal*) Renovaveis has expanded mostly in the US, significantly more than in ES, RO, PT, PL, and FR. Originally EDP was present in the US, Spain and France, and over the 10 years under study it diversified to a total 8 countries.
- EDF (*Electricité de France*) Nouvelles Energies had diversified prior to 2007 with presence in FR, IT, PT, GR, US. After 2007 EDF further diversified to CA, MX, PL and the UK. Significant markets for EDF are the US, PT, IT, FR and CA.
- E. ON (DE) somehow surprisingly did not start developing wind farms in its home country but in the US, and it still has a very low basis in Germany. E. ON expanded to DK, PL, PT, ES and SE, although the bulk of its assets during this period (68%) are in the US.

Chinese developers have as well made attempts to go global, with mixed results. For example, China Longyuan Power Group Corporation Limited, a minority stock market-listed subsidiary of Chinese state-owned utility China Guodian Corporation with 58% of capital, has as main business the development and operation of wind farms. By mid-2017, Longyuan had a consolidated wind capacity of 17.4 GW [66].

In 2011 Longyuan and Gamesa signed a memorandum of understanding (MoU) for Gamesa to support Longyuan's internationalisation [67]. Shortly afterwards Longyuan acquired its first operational foreign project, the 99 MW Dufferin wind farm in Canada, which was developed … with GE turbines. The other Longyuan overseas project, the 245 MW Mulilo De Aar in South Africa, is being built with Guodian wind turbines.

The MoU was therefore never put in operation.

Internationalisation of the development activity of turbine manufacturers

European turbine manufacturers have traditionally included a wind farm development business unit or activity focused on the onshore subsector that developed as well projects outside the EU. These projects often took place in partnership with local companies, e.g. offering turnkey installations.

Table 3 shows the countries where the wind farm development businesses of European turbine manufacturers are or have been active. It is perhaps interesting to mention some details:

- Gamesa was originally present in some EU countries (ES, PT, IT, DE) and expanded within the EU, then the US, China and Mexico. However, similarly to Iberdrola, towards 2013 it reduced very significantly its developing business.
- Acciona Energía concentrated most activity in its home market (ES) but already at the beginning of the period it had some activity in other EU countries and beyond. After the crisis in the Spanish renewable energy sector, Acciona expanded to other American markets although its development activity was significantly less.

Table 3
Wind farm development activity of European wind turbine manufacturers outside Europe. Source: BNEF database of wind farms.

	Acciona	Gamesa	Nordex	Vestas	Enercon
Argentina					X
Australia	X	X			
Brazil					X
Canada	X				
Chile	X			X	
China		X	X		
Costa Rica	X				
Egypt		X			
India	X	X		X	X
Jordan				X	
Mexico	X	X			
Morocco	X				
New Zealand					X
Philippines		X			
South Korea	X				
Turkey			X		X
Uruguay					X
US	X	X	X		
Venezuela		X			

6. Conclusions

Globalization goes hand-by-hand with localisation. In order to compete in large markets (India, China, US, Brazil), EU companies have had to grow local manufacture and a supply chain. The US is somehow the exception and this could be due to its openness as a market. Smaller markets are supplied from the main production centres (whether the EU or factories in China) and do not require localisation.

Vestas, Gamesa, and other European companies to a lesser extent have been successful at localisation whereas Suzlon and Chinese companies are generally less able to localise supplies, perhaps due to the low-cost production achieved in their home countries.

OEMs in the EU contribute to the economy significantly thanks to their exports, but China is emerging as a manufacturing hub for them. Eventually, this could result in Chinese suppliers offering products of higher quality which risks increasing competition from Chinese OEMs using this modality of technology transfer.

Whereas seven acquisitions of EU technology firms by US companies, and four acquisitions by Chinese companies were identified, no European company acquired a US or Chinese technology firm. This can be the result of the longer history of EU companies in the business, of the quality of their technology, of the successive crisis affecting the sector in Europe, of the availability of funding on the side of the American and Chinese, or a combination of these. Significantly as well, General Electric of the US has been the acquirer of all but one European technology companies bought by US firms.

The European wind industry is a success story of worldwide reach that attracts jobs and growth for Europe. In order to ensure that this will continue to be so in the mid- or long-term future, the industry may need the help of European and national policy makers with consented, well-targeted actions. Support programmes could help maintaining technological leadership through research, development and innovation programmes feeding on cross-industry knowledge and knowhow. They could support industrial leadership also in the manufacture of components. Instruments to financially and politically back the expansion of the industry to new and existing foreign markets may also be required.

Further reflection of policy makers with developers, turbine manufacturers and other key players may be needed so as to increase the impact of the sometimes already existing programmes (e.g. Horizon 2020) and make their implementation more comprehensive.

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Declarations of interest

None.

This research uses ISO 3166 2-letter countries codes, always written in capital letters. ISO codes are available at https://www.iso.org/iso-3166-country-codes.html.

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List of abbreviations and definitions

BNEF: Bloomberg New Energy Finance, a Bloomberg company
BoP: Balance of plant of a wind farm
HDD: Hard disk drive
FTE: Full-time equivalent (jobs)
LATAM: Latin America
M&A: Merger and acquisition
O&M: Operations and maintenance
OEM: Original equipment manufacturer, in this report OEM refers to the turbine manufacturer
PV: Photovoltaics
RoE: Return on Equity
RoW: Rest of the World
SGRE: Siemens Gamesa Renewable Energy
SOE: state-owned enterprise
SWP: Siemens Wind Power

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Measuring the internationalization of the wind energy industry

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ABSTRACT

Wind energy has grown from less than 20 gigawatts (GW) in 2000 to 590 GW by the end of 2018 and already provides 6% of the electricity consumed in the world. During this period, the wind energy technology industry has evolved from a local to a global business. To illustrate the globalization of this sector, this research assesses the effectiveness of the firms' international strategies based on empirical indicators. The intensity, the speed of internationalization, the geographic extensity and diversification are calculated and analyzed. The results indicate that the most successful firms are the market leaders Vestas and Siemens Gamesa Renewable Energy, and they are characterized by leading in both the depth (sales abroad/total sales) and width (number of countries) of internationalization as well as in geographic diversification. These companies are closely followed by four European and American firms: Enercon, Nordex, General Electric and Senvion. To date, Chinese firms, leaders in the largest market (China), are in general unable to internationalize as effectively as firms from other constituencies. Our results reveal that strong rivalry pressure in the domestic market is not a guarantee for the international competitiveness of its best-performing firms in the case of the wind energy industry – unless there are special characteristics in that domestic market.

1. Introduction

Many theories about the process of firm internationalization can be found in the literature. Among the best known is the Uppsala model, which presents growth in the international activities of a company as a gradual process of expansion into new markets [1,2]. This expansion occurs through a series of successive stages that result in an increasing degree of international operations. A second approach explains internationalization as a process of learning or the development of company capabilities to recognize opportunities in international markets [3]. Researchers have focused on the importance of establishing relationships [2,4]; firm growth is seen as a dynamic process, strongly dependent not only on a competitive product or service but also on the opening and strengthening of relations with players in other markets. Research has also focused on technical know-how, location [5] and international entrepreneurship [6], in which both emerging and consolidated companies can create value based on the use of their entrepreneurial skills in their internationalization processes.

Time is a key factor of competitive advantage, as the first company entering a new country positions itself better in this market. Management of time in terms of the order, timing and speed of the process is an essential aspect of a firm's international expansion [7]. The speed of internationalization is therefore a matter of interest in the study of business globalization, and most studies analyze the process only until the moment the company starts to internationalize [8,9]. However, some works have argued that it is necessary to consider not only the time a company takes to establish its business in the first foreign market but also the time that elapses until it consolidates its international activity [10,11]. Furthermore, some studies have suggested that speed does not always positively influence performance [12]. Finally, firm size, firm age and other factors influence the success, measured in terms of profitability, of the international activity of a firm [13].

In the case of the wind industry, there are hardly any references that address how the international expansion processes of the companies occurred [14]. In this sector, there have been asymmetric developments in different regions, mainly depending on specific political support and the economic and industrial background. On the one hand, Europe has led technological development for 40 years, using first the local market for wind energy deployment and later expanding to other regions based on the

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experience gained. Innovation has been, and still is, a key factor in the growth of companies beyond their national borders. On the other hand, China has become an important player in recent years, capturing almost half of the new capacity installed annually, which has allowed the technological and business growth of local companies.

The wind industry is relatively young, since it has only reached a significant size during the last 20 years; in terms of its main indicator, cumulative installed capacity in gigawatts (GW), it has grown from less than 20 GW in 2000 to 590 GW by the end of 2018 [15]. By considering this deployment as well as the unit costs from, for example, IEA Wind [16,17], Bloomberg New Energy Finance [18] and Joint Research Centre [19], we estimate that the approximate equivalent cumulative investment reached $50 billion by 2000 and $1370 billion by 2018.

Some research papers have confirmed that the creation of a domestic market in renewable energies has been decisive for the competitiveness and internationalization of companies [20–23]. This impact of the local market is particularly true in the case of companies in Europe and the USA, whereas the large Chinese market has not been decisive for its companies to actively participate in the global industry, at least until now [14].

Indicators for measuring the degree of internationalization of firms include the transnationality index [24], the network spread index [25], the Herfindahl-Hirschman index and other indices. Those indicators have been used to measure the degree of internationalization intensity, geographic extensity or geographic concentration of the firm's international activity, respectively [26] (cited by Ref. [27]).

However, there is little research on the internationalization of the wind energy industry in general and of wind turbine manufacture in particular, and none of this research used internationalization indices. Yet, quantitative assessment is necessary to enable robust, unbiased research to identify the international strategies of wind companies and to increase the understanding of the historical evolution and current trends.

The objective of this paper is to select the appropriate indices for assessing the globalization of the main wind turbine manufacturers worldwide. In this way, we address the internationalization effectiveness of these companies that eventually result in the global deployment of wind energy.

The novel contributions of this paper are (a) the proposal of a set of indicators to measure the degree of internationalization of wind turbine manufacturers, which combine structural indicators with indices for measuring the speed of internationalization, and (b) their application to data of the installed capacity by the 15 major manufacturers in 112 countries and territories over the past 40 years.

Section 2 presents and discusses the methodology used. Indicators such as the intensity and speed of internationalization, geographic extensity and diversification are described, and the results of modeling of these indicators are presented in Section 3. A discussion follows in Section 4 along with the ranking of the firms. Finally, Section 5 presents the conclusions.

2. Methodology

The indicators to assess the internationalization of enterprises that have been proposed in the scientific literature can be classified as structural, performance-based and attitudinal [27]. Composite indices have been created with the individual indicators [25]. Of these types, structural indicators are the most widely used. Performance indicators represent the economic results and market success of the company brought about by its international expansion. The indicators of attitude refer to the management styles and the decision-making processes leading to the globalization of the company.

Structural indicators are the preferred measures of the degree of internationalization, perhaps because they rely on numerical values to provide an empirical view, and for this reason, they are used in this research. As there is not an individual indicator that satisfactorily measures the overall degree of the internationalization of a firm [27], we propose the use of several structural indices that help with assessment, lead to a useful analysis and together present a meaningful picture of the process.

One of the most popular indicators is the transnationality index (TNI), which was introduced by a United Nations report (World Investment Report 1995. Transnational Corporations and Competitiveness) at the United Nations Conference on Trade and Development in 1995 [24]. The TNI is a composite indicator calculated as the average of three ratios: foreign assets to total assets, foreign sales to total sales and foreign employment to total employment. This index belongs to the group of measures of internationalization intensity, focusing on the intensity of foreign activities in relation to the quantity of domestic activities.

However, other interesting dimensions can be provided for the assessment [28]. Geographic extensity indices consider the number of countries and operations to calculate the spread of a firm, while geographic diversification indices estimate the degree of concentration or diversification of a firm's business among different countries. As a third dimension, measuring the speed of internationalization could help to explain not only the success but also the different nature of firms' strategies [29–32].

The data about the installed capacity, in megawatts (MW), from each of the 15 primary wind turbine manufacturers in 112 countries and territories worldwide from 1978 to 2017 was used for the purpose of this study [33]. The database is nearly complete, as it includes a total of 517.7 GW of wind turbines installed or commissioned during this period, including old turbines that have already been decommissioned. This figure is 96% of the most accurate estimate of the worldwide installed capacity, 539.6 GW, by the Global Wind Energy Council [34]. The main gaps in the database correspond with Chinese installations; for example, a total of 32.6 GW of installations were assigned to Goldwind of China, whereas its actual installations were 42.7 GW in China [35] plus 1.3 GW abroad. The installed capacity by the top 15 turbine manufacturers, also called original equipment manufacturers (OEMs), in the database was 458.5 GW, or about 85% of the worldwide installed capacity by the end of 2018.

The consideration of what constitutes the "home country" required a methodological decision. The history of the wind energy sector includes many mergers and acquisitions between OEMs, and, in some cases, the result is an OEM with a large installed base in several countries, such as the merge of Siemens Wind Power and Gamesa into Siemens Gamesa Renewable Energy (SGRE) in 2016. Siemens Wind Power was, in turn, the acquisition of the Danish company Bonus by German Siemens in 2004. Assuming that SGRE (now a Spanish company with Siemens as a majority German stakeholder) has Spain as a single home country is incorrect; it is more accurate to assume that SGRE has three home countries (DK, ES and DE).

In the same way, General Electric (GE) is mostly the result of the acquisition of the U.S. companies Zond and Kenetech and the German company Tacke (see Fig. 1), and thus it was assigned two home countries (DE and US). Although GE acquired the Swedish company ScanWind, the contribution of this firm was not significant, and Sweden was thus not considered a home country for GE. Following this criterion, Nordex was assigned Spain and Germany as home countries, but Goldwind was not assigned Germany (following the acquisition of 70% of Vensys) as a home country.

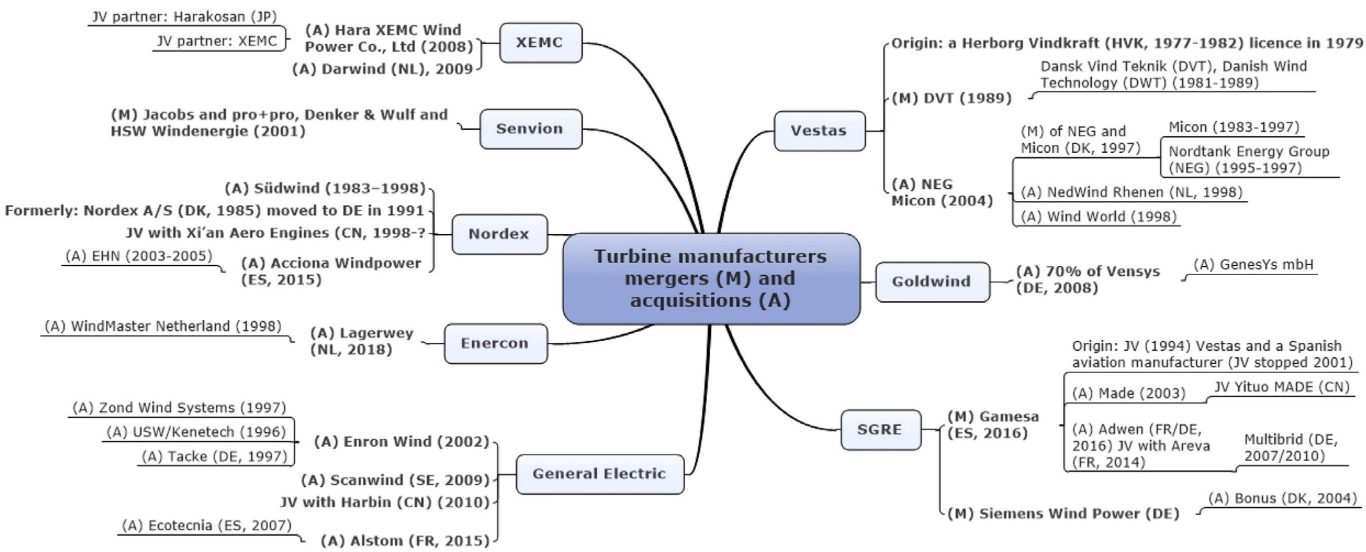

Fig. 1. The most significant mergers and acquisitions among wind turbine manufacturers.

Fig. 1 lists the most significant mergers and acquisitions among wind turbine manufacturers.

After having worked with wind installation databases from five different industrial intelligence suppliers since 2009, we found that the MAKE database is the most complete in terms of the number of installations (in MW) that are allocated to each turbine manufacturer. However, the database still retained some elements that had to be refined. This refining work consisted of screening the initial installations in the database against the company's history on either its website or wind energy-related books of the 1990s [36,37] and against some of the other databases from industrial intelligence suppliers [38–41].

The data therefore allows the assessment of certain structural measures of the internationalization of these wind firms. The indicators aid in understanding the evolution of market dynamics, firm expansion and the influence of the domestic renewable policy on boosting a firm's global activity. Hence, we selected and applied the following structural indices to the analysis of wind turbine manufacturer internationalization.

2.1. Internationalization intensity

For a measure of the intensity of internationalization, we focused on the ratio of the installed wind turbine capacity abroad ("exports") to the company's total installed capacity ("total sales"). This index is one of the three that constitute the TNI [24], and it is one for which the available data allows full research. This index can effectively measure the *depth* of the foreign expansion for each firm.

First, we calculated this index for each year in the sample, from 1978 to 2017. Then, the intensity index I_{firm} was obtained for the total amount of the installed capacity by each firm in all 112 countries and territories. In addition, a second indicator $\overline{I}_{firm}$ was calculated, averaging the annual intensity index.

$$I_{firm} = \frac{\sum_{yr}\sum_{co\in foreign} P_{firm,\,co,\,yr}}{\sum_{yr}\sum_{co} P_{firm,\,co,\,yr}} \tag{1}$$

$$\overline{I}_{firm} = \frac{1}{40}\sum_{yr=1978}^{yr=2017}\frac{\sum_{co\in foreign} P_{firm,\,co,\,yr}}{\sum_{co} P_{firm,\,co,\,yr}} \tag{2}$$

Where $\sum_{yr}\sum_{co\in foreign} P_{firm,\,co,\,yr}$ is the installed capacity abroad by each wind turbine *firm*, in each country *co*, in each year *yr*, while $\sum_{yr}\sum_{co} P_{firm,\,co,\,yr}$ is the total installed capacity by each wind turbine *firm*, in each country *co*, in each year *yr*, including the domestic and foreign capacity.

2.2. Geographic extensity

The number of foreign countries and territories in which each company has installed wind turbines is the relative spread of each firm worldwide [25]. This spread is directly related to what can be called the *width* of internationalization of a company, which is measured by the network spread index (NSI), a ratio for each firm of the absolute number of foreign countries where the firm ever deployed wind turbines to the similar figure for the firm that installed turbines in more foreign countries [42].

$$NSI_{firm} = \frac{Ncountries_{firm}}{\max\limits_{1\le firm\le 15}\left(Ncountries_{firm}\right)} \tag{3}$$

Where $Ncountries_{firm}$ is the absolute number of different foreign countries that a firm has ever done business with.

2.3. Geographic diversification

A firm whose foreign activity is diversified does business in each market in a balanced way. This balance protects the firm against the ups and downs of individual markets. This protection is unlike a firm whose business mostly depends on a few of its export markets. We propose the use of a geographic diversification index GD_{firm} to measure how the activity is split among those countries.

First, for every firm and year, we calculated the ratio of the installed capacity in each country $(P_{firm,\,co,\,yr})$ to its total installed capacity. Second, we used the well-known Herfindahl-Hirschman index (HHI) [43] to obtain a measure of the diversification of the firm activity for each year $GD_{firm,\ yr}$. Finally, we computed the mean of the annual HHI values to obtain an average value of the geographic diversification index of each company in the whole period $\overline{GD}_{firm}$. This average index can also be calculated for a different number of years.

$$GD_{firm,\ yr} = \sum_{co=1}^{112} \left(\frac{P_{firm,\ co,\ yr}}{\sum_{co=1}^{112} P_{firm,\ co,\ yr}} \right)^2 \tag{4}$$

$$\overline{GD}_{firm} = \frac{1}{40} \sum_{yr=1978}^{yr=2017} \left[\sum_{co=1}^{112} \left(\frac{P_{firm,\ co,\ yr}}{\sum_{co=1}^{112} P_{firm,\ co,\ yr}} \right)^2 \right] \tag{5}$$

The index varies between 0 and 10,000, where 10,000 indicates that the company concentrates its sales in a single country, while values closer to zero indicate greater international diversification.

2.4. Speed of internationalization

Internationalization studies using structural indicators do not usually include a measure of speed. However, this speed is an important issue and a key aspect of a firm's international strategy [7,10]. Hence, we discuss here a set of indicators based on proposals in the literature that quantify the average speed at which the company has expanded internationally.

Hilmersson et al. [19,20] have suggested several possible indices to measure the speed of internationalization: the mean number of markets exported per year since inception, the ratio of exports to total sales and the share of the firm's assets abroad. Concerning the first index, Mohr [21] has proposed a variation as the average number of foreign markets divided by the number of years since the firm's first international expansion. Using the date of the first international expansion fits better with the wind industry than the date of inception since sales abroad started after a long period of technology development.

The ratio of exports to total sales is the internationalization intensity defined in Section 2.1. How this element evolved over time can be a useful indicator for the assessment of the internationalization dynamics of a firm. In the case of wind turbine manufacturers, the indicator is defined as the percentage of the foreign against the total rated capacity (in MW) of the turbines installed.

Speed could also refer to the length of time until a certain milestone is achieved. The literature suggests using between 10% and 20% of the total number of countries and territories exported to for this indicator [32,44,45]. After analyzing the historical data series from the database, we propose this milestone to be 20%, as this figure reflects a significant number of exports for most companies in the sample.

Therefore, the selected indicators to measure the speed of the internationalization of wind turbine firms are the following:

- The average number of new markets entered per year since the firm's first international expansion
- The number of years between the first year of the internationalization of the firm to the year when it reached the milestone of 20% of its final number of foreign markets; thus, for example, if a firm had exported to a total of 30 countries by the end of 2017, the figure in this indicator would be the years until it reached six foreign markets.
- Internationalization intensity over time

3. Results

The results indicate that some of the companies in the sector have had an international focus almost since their inception, while others have based their growth on meeting the needs of their home country. Fig. 2 depicts the 2017 market shares of the world's 15 leading wind turbine manufacturers, in which European companies continue to retain a significant quota: Vestas, SGRE, Enercon, Nordex and Senvion accounted for 56% of the 2017 market share of the 15 largest companies. Chinese companies reached a 30% share of the top 15, due to the strong momentum of wind power in their home country and the nature of a state-managed economy that favors national champions and state-owned companies [46]. In total, those 15 leading companies installed 45.5 GW in 2017, with a minimum contribution from Sinovel and XEMC.

3.1. Internationalization intensity

Table 1 summarizes the results of some indicators of the degree of internationalization as discussed in Section 2. First, it should be highlighted that the international activity of wind turbine companies has accounted for as much as 51% of the total installed capacity worldwide until 2017: 235,800 MW of 458,500 MW. Moreover, the first four companies reach 63% of the total installed capacity and 85% of the foreign installed capacity.

The I_{firm} indicator relates the installed capacity abroad to the total capacity installed by the firm, according to the formula of Equation (1). The indicator reveals that European companies have carried out most of their business in the international field throughout the history of the wind sector. Furthermore, Fig. 3 graphically illustrates these results: two companies, Vestas and SGRE, have captured most of the international wind energy business. However, Fig. 4 shows that Vestas and SGRE reached that position in very different way: Vestas was very international from the beginning whereas SGRE reached Vestas in 2011 and between this year and 2017 both accounted for roughly equal share of international sales, 47 GW Vestas vs. 45 GW SGRE. Table 1 indicates that these two companies have accounted for an overall 64% of the installed capacity abroad.

The results of the index $\bar{I}_{firm}$ offer a historical perspective of the international activity of the companies, since the average of the annual index I_{firm} was calculated. Vestas appears to be the only

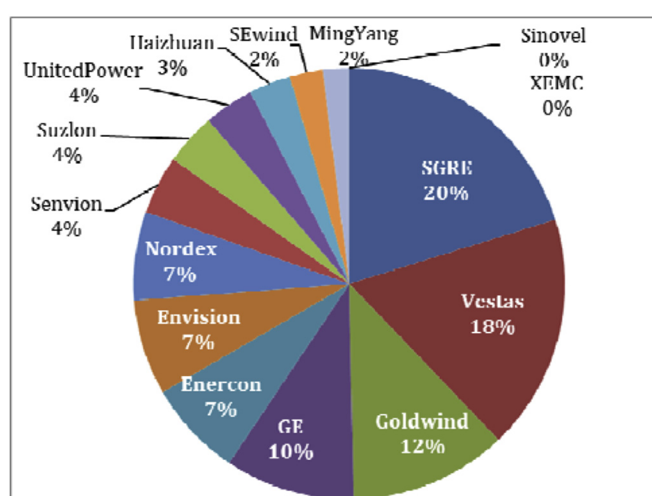

Fig. 2. Wind turbine market share in 2017 of the 15 leading OEMs in this study. Installations by other OEMs have been disregarded. Source: MAKE database [33].

Table 1
Results of the indicators of intensity of the degree of internationalization.

Company	Total installed capacity		Foreign installed capacity		Intensity	
	MW	%	MW	%	I_{firm} (MW foreign/MW total)	$\bar{I}_{firm}$ Annual average
Vestas	91,168	19.9%	87,521	37.1%	96%	70%
SGRE	82,922	18.1%	62,460	26.5%	75%	42%
GE	63,180	13.8%	22,189	9.4%	35%	18%
Enercon	49,038	10.7%	27,170	11.5%	55%	35%
Goldwind	32,643	7.1%	1,310	0.6%	4%	2%
Nordex	23,896	5.2%	17,112	7.3%	72%	33%
United Power	18,082	3.9%	254	0.1%	1%	0%
Suzlon	17,634	3.8%	5,907	2.5%	33%	9%
Senvion	17,108	3.7%	11,120	4.7%	65%	32%
Sinovel	16,739	3.7%	350	0.1%	2%	3%
Envision	11,940	2.6%	30	0.0%	0%	0%
Ming Yang	11,501	2.5%	180	0.1%	2%	1%
SEwind	9,937	2.2%	0	0.0%	0%	0%
XEMC	6,616	1.4%	4	0.0%	0%	0%
Haizhuan	6,132	1.3%	32	0.0%	1%	1%
	458,536	**100%**	**235,637**	**100%**		

Table 2
Results of the indicators of geographic extensity.

	Geographic extensity	
FIRM	No. countries	NSI_{firm}
Vestas	73	1.00
SGRE	70	0.96
GE	40	0.55
Enercon	47	0.64
Goldwind	13	0.18
Nordex	41	0.56
United Power	2	0.03
Suzlon	16	0.22
Senvion	26	0.36
Sinovel	8	0.11
Envision	2	0.03
Ming Yang	3	0.04
SEwind	0	0.00
XEMC	1	0.01
Haizhuan	1	0.01

company maintaining international business activity superior to the domestic business activity on an annual average, while the rest of the European companies reached desirable rates of foreign business of between 32% and 42% over time. The American company GE presents a lower $\bar{I}_{firm}$ of 18%, whereas Chinese companies have hardly developed an international business.

Fig. 4 represents the installed capacity in foreign countries by each company and helps with understanding their historical evolution. In addition, a dashed line in the figure indicates the sum of the domestic installations up to 2008, which puts the foreign business into perspective.

Vestas, SGRE, GE and Nordex display continuous growth, while Enercon's international business has been in decline since 2012. It is also interesting to note that Vestas first started a significant international expansion around 1995, while other companies did not start until the 21st century. However, during recent years and after the merge of Siemens and Gamesa, SGRE has caught up with Vestas in the international arena.

The figure reveals an interesting feature in 2012–2013: a general drop in foreign installations that is pronounced in the case of Siemens and Gamesa (SGRE). This drop is due to the fall of the U.S.

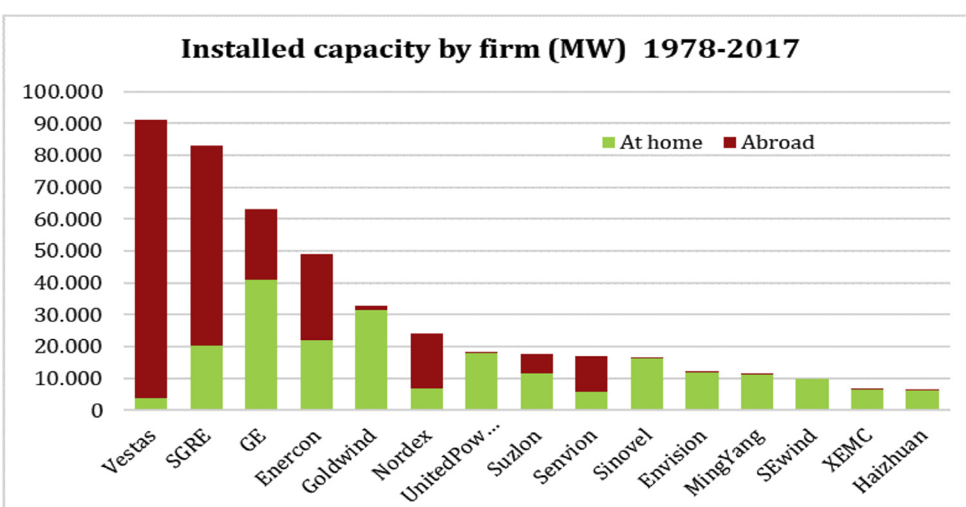

Fig. 3. The installed capacity by wind turbine manufacturers from 1978 to 2017, with a distinction of the capacity installed at home and abroad. Source: MAKE database [33].

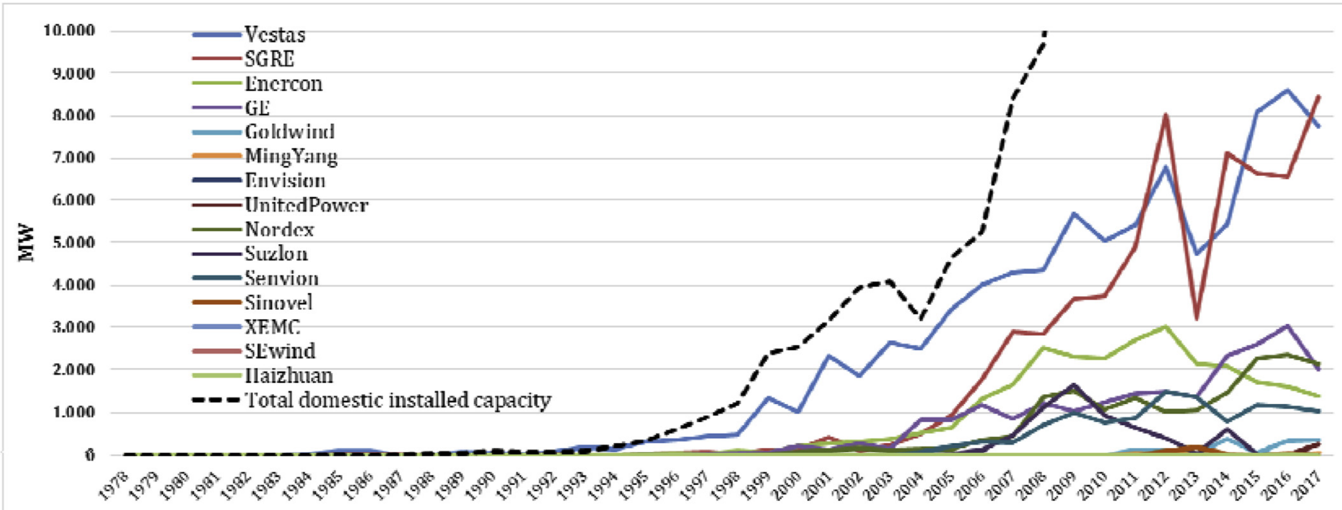

Fig. 4. The annual evolution of installed capacity abroad by firm and the total aggregate domestic installed capacity by all firms from 1978 to 2017. Source: MAKE database [33].

market, during which installing 13,124 MW in 2012 reduced to 1,084 MW in 2013 [47]. The data indicates that Siemens and Gamesa, two separate companies at that time, installed 3,875 MW in the US in 2012 and only 87 MW in 2013. Other companies suffered from the U.S. drop as well, primarily GE. However, the case of GE is not depicted in Fig. 4 because the US is GE's domestic market. The figure illustrates the lack of contribution from Chinese OEMs to internationalization as well as the retreat from foreign markets of Suzlon in 2012–2017.

3.2. Geographic extensity

The geographic scope, or extensity, of the wind turbine manufacturers is here assessed by means of the number of countries where they have expanded their businesses, depicted in Table 2 and Fig. 5. This information is accompanied by the calculation of the NSI, which allows a relative classification. Fig. 6 provides additional information on the historical evolution of the number of foreign markets per firm.

When comparing the trends displayed in Figs. 4 and 6, it is interesting to note how the world leaders, Vestas and SGRE, are also the manufacturers that have been present in many countries. However, their evolution was different: Vestas was consistently leading in both the number of countries and the installed capacity abroad, while SGRE lagged behind in both indicators until it reached Vestas around 2011. Since that year, Vestas installed in an average 33 countries per year and SGRE in 27.

Table 2 lists the high number of countries where Enercon, GE and Nordex have been present (47, 40 and 41, respectively). However, the share of those companies in the total foreign installed capacity (see Table 1: 12%, 9% and 7%) has not achieved a similar high level. In this regard, GE's and Nordex's NSI values are 0.55–0.56, lower than Enercon's 0.64. Senvion, Suzlon and Goldwind have been present in 26, 16 and 13 countries, respectively, but the volume of their activity abroad (Table 1) is different at 4.7%, 2.5% and 0.6% of the total foreign installed capacity.

Equally interesting a finding, the figures for Goldwind and other Chinese companies do not support the theory proposed by Porter in

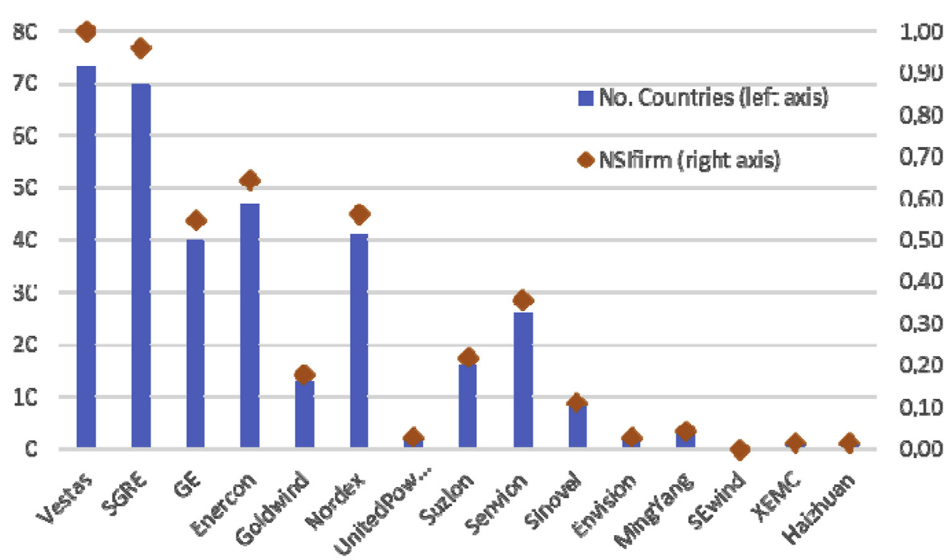

Fig. 5. Graphical representation of Table 2.

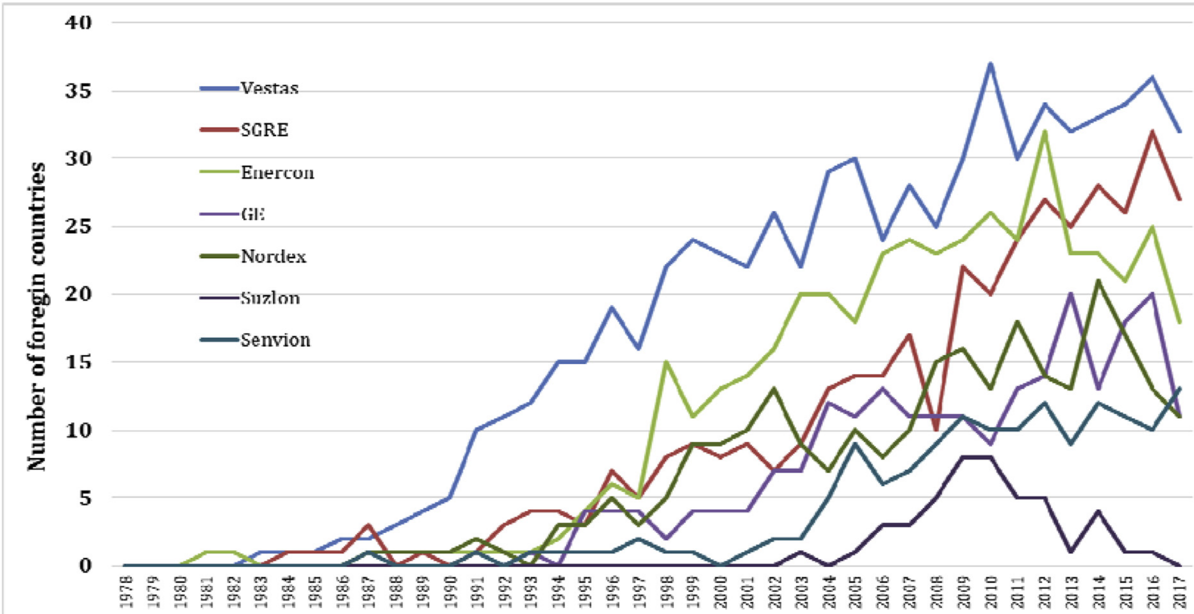

Fig. 6. Annual evolution of number of exported countries from 1978 to 2017 by firm (excluding Chinese companies). Source: MAKE database [33].

1990 that strong domestic pressure from rivals provides a competitive advantage for internationalization [48]. We think that this strong pressure is more theoretical than real in the Chinese case. With China as the leading country (189 GW installed by the end of 2017), the most international of the Chinese OEMs, Goldwind, has only installed between 3% and 4% of its business abroad, even though Goldwind has surpassed every other leading Chinese OEM in this respect.

3.3. Geographic diversification of companies

It was discussed previously that internationalization is different when it is balanced among countries rather than when one country (or a small handful of them) weighs heavily in the business portfolio of the company. In other words, the international diversification of each company is to be measured in relation to the size of its presence in each country, not only according to the number of countries where it is present. This indicator can be obtained by relating it to diversification indices based on the Herfindahl-Hirschman market concentration index.

Section 3.1 clarified that internationalization in the wind industry started, in practice, by 2000. For this reason, this indicator was applied to the period from 2000. Table 3 presents the average value $\overline{GD}_{firm}$ of the annual GD_{firm} index between 2000 and 2017. This indicator reveals once more that Vestas has the most diversified international activity with a $\overline{GD}_{firm}$ value of 1,334. On the other hand, the $\overline{GD}_{firm}$ index of Chinese companies takes a value close to 10,000 in all cases, thus indicating that they have virtually not expanded their activity outside their country. Fig. 7 depicts the annual values of the GD_{firm} for companies in the wind sector, excluding Chinese companies.

The comparison between the results of two companies illustrates the contribution of this index to assessing the different character of internationalization from a country diversification point of view. Firms can be present in a similar number of countries yet have different structures of diversification. Both GE and Nordex are present in a similar number of foreign countries (40 and 41, respectively; see Table 2). However, the $\overline{GD}_{firm}$ index reveals that Nordex ($\overline{GD}_{firm} = 2{,}156$) has more geographically diverse business, while GE ($\overline{GD}_{firm} = 4{,}123$) concentrates its business more in some countries, led by its home market, the US.

The $\overline{GD}_{firm}$ figures include the respective acquisitions of Acciona by Nordex and Alstom by GE in 2016. Interestingly, these acquisitions were presented as complementary in terms of country diversification by both acquiring OEMs. For example, in the case of Nordex-Acciona, the press release noted that "the two wind turbine manufacturers have complementary technologies and market footprints, with Nordex's strong presence in Europe a good match for ACCIONA Windpower's established position in North and South

Table 3
Results of the indicator of geographic diversification $\overline{GD}_{firm}$.

Geographic diversification			
Firm	$\overline{GD}_{firm}$ (>YR 2000)	**Firm**	$\overline{GD}_{firm}$ (>YR 2000)
Vestas	1,334	**Senvion**	4,042
SGRE	2,420	**Sinovel**	9,556
GE	4,123	**Envision**	9,955
Enercon	3,021	**Ming Yang**	9,630
Goldwind	9,276	**SEwind**	10,000
Nordex	2,156	**XEMC**	9,991
United Power	9,745	**Haizhuan**	9,520
Suzlon	7,234		

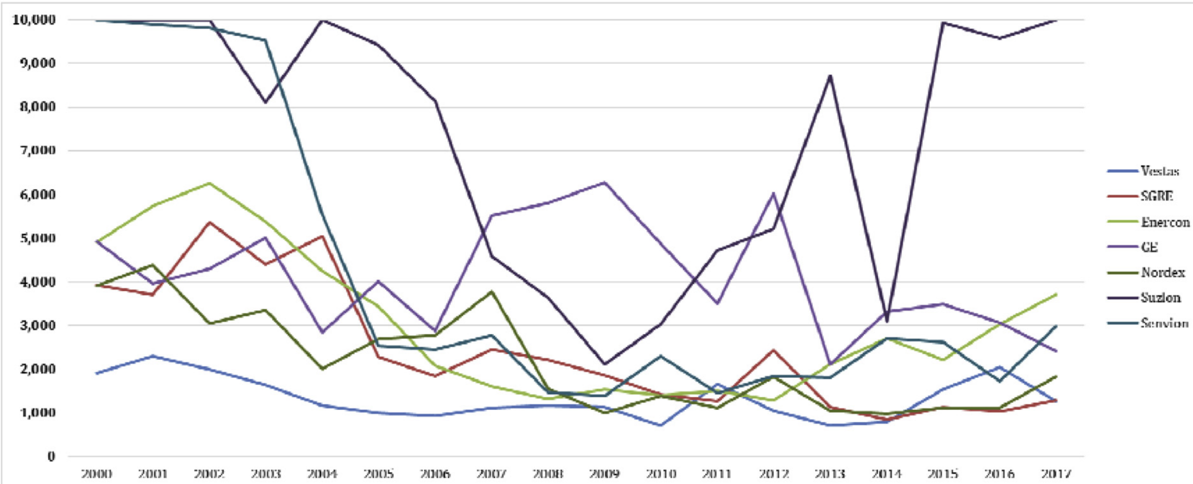

Fig. 7. Geographic diversification index GD_{firm} from 2000 to 2017 by firm excluding Chinese companies.

Table 4
Wind turbine installations of Acciona and Nordex for the period up to 2015, main markets.

Country	Nordex	Acciona	Country	Nordex	Acciona
Australia	1	239	Italy	626	65
Belgium	39		Japan	70	
Brazil		303	Lithuania	70	
Canada	26	177	Mexico		607
Chile		105	Netherlands	252	
China	724		Norway	148	
Colombia	20		Pakistan	150	
Costa Rica		50	Poland	271	183
Croatia		30	Portugal	411	
Czech Republic	13		Romania	100	
Denmark	135		South Africa	182	138
Egypt	63		South Korea		65
Estonia	18		Spain	203	1,730
Finland	247		Sweden	435	
France	1,402	39	Turkey	1,122	59
Germany	3,204		United Kingdom	1,122	36
Greece	111	6	United States	902	1,373
India	54		Uruguay	167	
Ireland	391		**Total**	**12,696**	**5,202**

Table 5
Onshore wind installations, in MW, which boomed in Germany between 2010 and 2017 and contributions by Enercon. Global installations by Enercon. Sources: German Wind Energy Association, MAKE database [33]. Note that Enercon does not make offshore wind turbines, thus only onshore figures are relevant here.

Year	2010	2011	2012	2013	2014	2015	2016	2017
Germany (DE)	1,453	2,012	2,217	2,786	4,571	3,731	5,002	5,334
Enercon DE	926	1,213	1,304	1,496	2,043	1,329	1,782	1,915
Enercon global	3,197	3,920	4,310	3,636	4,107	3,023	3,343	3,264

America" [49].

This statement matches data in the MAKE database, as presented in Table 4. Only in the US, Poland and South Africa were both companies about equally active in the number of installations, whereas in 28 of the 37 countries, only one of them was present or both were present but one had only a symbolic presence of less than 10 MW.

Fig. 7 reveals that the overall trend of the index $\overline{GD}_{firm}$ between 2000 and 2017 is slightly decreasing, which indicates greater diversification of the sector international activity. The trend can possibly be split into two clearer periods: from 2000 to 2011, all companies experienced an increase in diversification, whereas the period 2012–2017 introduced a slight reversing trend that was more severe in the cases of Suzlon and Enercon. Suzlon has experienced a deep crisis since 2011 that caused it to retreat to its home market of India after about seven years of significant international expansion. Enercon's evolution since 2012 was likely influenced by the boom of its home market, Germany, where it is the leading OEM (see figures in Table 5).

An even finer focus on the two more diversified companies, Vestas and SGRE for recent years (2014–2017) shows that SGRE became the most diversified company during that period, with an average $\overline{GD}_{firm}$ for the period of 1,068 vs. 1,407 Vestas. Even, during this period, Nordex with a $\overline{GD}_{firm}$ of 1,254 performed better than Vestas.

3.4. Speed of internationalization

Three indicators were used in this research to study the pace at which companies have expanded their operations abroad: the mean number of new markets entered per year since internationalization, the years passed from the first year of internationalization until reaching 20% of the total number of countries exported and the relationship between the exports and total sales over time.

Table 6 presents key figures used for the calculation and the results obtained for the first two indicators. In general, companies had an early internationalization led by Vestas and SGRE in the 1980s, and they were soon followed by the European companies Nordex, Enercon and Senvion and GE of the US. Chinese companies have not been included here because they have barely developed international activity.

The average number of new markets per year since the firm's first international foray is also presented in Table 6. This indicator reveals how the speed of internationalization of SGRE and Vestas has been faster than the rest of the companies, whereas Suzlon and Senvion have significantly lower ratios that make them lag behind the others.

As mentioned in Section 2 and according to the literature, it is worth calculating the number of years between the start of internationalization until the year when a firm achieved 20% of the final number of foreign countries exported. The companies that have the best ratios here are Suzlon, GE, Enercon, Senvion and Nordex. Conversely, SGRE and Vestas did not reach 20% of sales abroad until

Table 6
Results of the speed of internationalization indicators (excluding Chinese companies).

Firm	Company funding year	Start internationalization	Year > 20% countries exp.	Firm age (years)	Firm exp. age (years)	No. countries	Mean no. new markets entered per year since internationalization	No. years until 20% countries exp.
Vestas	1978	1981	1993	39	36	73	1.97	12
SGRE	1978	1984	1996	39	33	70	2.12	12
Enercon	1984	1992	1997	33	25	40	1.77	5
GE	1983	1993	1997	34	24	47	1.64	4
Nordex	1987	1991	1998	30	26	41	1.59	7
Suzlon	1996	2003	2006	21	14	16	1.07	3
Senvion	1988	1993	1999	29	24	26	1.00	6

12 years after starting exports.

Thus, Vestas and SGRE took longer to reach the 20% milestone, but they were also the first companies both founded and initiating exports; they were the pioneers and their work facilitated faster development of the global market. The data indicates that late entrants such as Suzlon were faster to reach the milestone, which was due to the greater maturity of the markets.

The third indicator selected to measure the speed of internationalization was the relationship between the exports and total sales over time. Fig. 8 represents the percentage of foreign versus total installed capacity by selected companies from 2000 to 2017 for clearer visualization of the historical data. The difference between some companies that began their international development early (Vestas and SGRE in 1981–1984) compared to others that have accelerated in recent years is relevant. Suzlon has not been considered in this figure because the effect of its deep crisis would introduce noise into the analysis.

4. Discussion

The indicators proposed in this research to assess the internationalization of the wind industry reveal the different levels of success of the firms' foreign expansion as well as the evolution that allows the understanding of the current market situation. Thus, by comparing the results of the top 15 companies in Figs. 2 and 3, it is observed that Vestas and SGRE have led the market during the past 40 years and still maintain their leading positions.

These two companies also present the best results for internationalization. Table 7 lists the summary of the internationalization indicators obtained in this research, in which it is observed that Vestas and SGRE achieved the highest values both in the intensity of internationalization and in the geographic spread of their activity. When the $\bar{I}_{firm}$ index is considered, which presents the average value of the evolution of the international activity of the companies, a ranking similar to that of the I_{firm} index is observed for all companies except for Suzlon, which drastically drops from $I_{firm} = 33\%$ to $\bar{I}_{firm} = 9\%$. This reduction means that Suzlon's international activity has been prominent but also concentrated in a few years. These results justify deepening the study of the historical evolution of the overseas expansion of the companies and of the speed of that process.

Significant internationalization of the wind industry did not start until the beginning of the 21st century, except in the case of Vestas, which began its noteworthy activity abroad around 1993 (see Fig. 4 and Table 3). Among the companies that started to expand their business abroad later, SGRE has stood out in recent years, even at times surpassing the annual volume of Vestas's international activity.

Other than Vestas, the information in Fig. 4 allows companies to be classified into three groups:

- Enercon, SGRE and GE began to gain significant foreign sales volume in 2004, after the three companies had already reached an international presence in at least 20% of the countries exported to around 1997 (Table 6).
- Another group of companies (Nordex, Senvion and Suzlon) have accelerated their international activity since 2007, but these companies have subsequently experienced a different evolution. Nordex has consolidated its internationalization more than Senvion, whereas Suzlon has seen its internationalization shrank to nearly zero.
- Chinese companies have barely developed activity abroad, as can also be seen in the results summarized in Table 7. Among

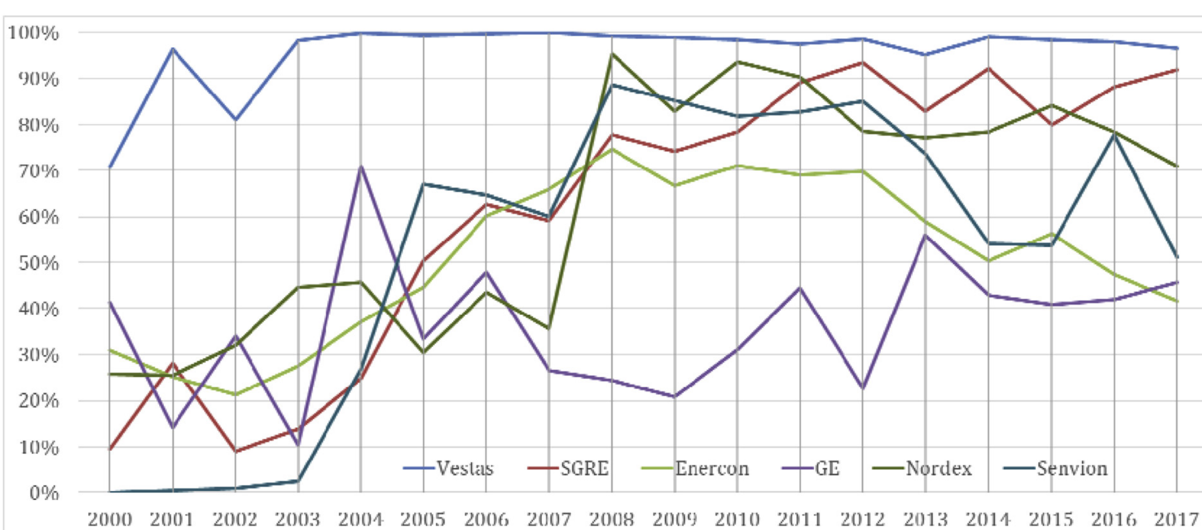

Fig. 8. The relationship between foreign and total installed capacity from 2000 to 2017 by firm, excluding Chinese companies and Suzlon.

Table 7
The results of the indicators of the degree of internationalization.

Company	Total installed capacity		Foreign installed capacity		Intensity		Geographic extensity		Geographic concentration
	MW	%	MW	%	I_{firm}(MW foreign/MW total)	$\bar{I}_{firm}$ Annual average	**No. countries**	NSI_{firm}	GD_{firm} (>yr 2000)
Vestas	91,168	19.9%	87,521	37.1%	96%	70%	73	1.00	1,334
SGRE	82,922	18.1%	62,460	26.5%	75%	42%	70	0.96	2,420
GE	63,180	13.8%	22,189	9.4%	35%	18%	40	0.55	4,123
Enercon	49,038	10.7%	27,170	11.5%	55%	35%	47	0.64	3,021
Goldwind	32,643	7.1%	1,310	0.6%	4%	2%	13	0.18	9,276
Nordex	23,896	5.2%	17,112	7.3%	72%	33%	41	0.56	2,156
United Power	18,082	3.9%	254	0.1%	1%	0%	2	0.03	9,745
Suzlon	17,634	3.8%	5,907	2.5%	33%	9%	16	0.22	7,234
Senvion	17,108	3.7%	11,120	4.7%	65%	32%	26	0.36	4,042
Sinovel	16,739	3.7%	350	0.1%	2%	3%	8	0.11	9,556
Envision	11,940	2.6%	30	0.0%	0%	0%	2	0.03	9,955
Ming Yang	11,501	2.5%	180	0.1%	2%	1%	3	0.04	9,630
SEwind	9,937	2.2%	0	0.0%	0%	0%	0	0.00	10,000
XEMC	6,616	1.4%	4	0.0%	0%	0%	1	0.01	9,991
Haizhuan	6,132	1.3%	32	0.0%	1%	1%	1	0.01	9,520
	458,536	**100%**	**235,637**	**100%**					

them, Goldwind and Sinovel have been present in 13 and eight foreign markets, respectively.

The indicators represent the relationship between the number of countries where companies have expanded their activity and the volume of their international business. By jointly analyzing the results of the indicators $\bar{I}_{firm}$ and $\overline{GD}_{firm}$ in Table 7, it is confirmed that Vestas is the company that has historically extended its international activity more, demonstrating the highest intensity values of the degree of internationalization, $I_{firm} = 96\%$ and $\bar{I}_{firm} = 70\%$. In addition, Vestas is the company that has the most balanced international business between countries, with the lowest value of $\overline{GD}_{firm} = 1{,}334$; all the other companies present a higher concentration of their foreign business in a smaller number of markets.

Considering the historical evolution in Figs. 6 and 7, since 2009, the global wind energy market has increased remarkably, and companies are diversifying, except for GE, which has been significantly focused on meeting the high demand in its home country. Two companies, Enercon and Senvion, have reduced their diversification since 2013 (see Fig. 7), although Senvion maintains a presence in a relatively high number of countries but concentrates its activity in a few of them. Finally, it is interesting to observe how most companies evolved in 2017, decreasing their presence in some countries (Fig. 6) and concentrating their business more (Fig. 7), a situation that reveals the maturity of some markets and pressures companies toward higher market diversification.

One of the main results of this research is the inclusion of some measures of the speed of internationalization in the assessment of company effectiveness. When analyzing the indicator of the average number of new markets exported per year since the firm's first international expansion (Table 7), it is possible to group the companies into three different sets:

- Vestas and SGRE present the highest value, near or above 2
- Enercon, GE and Nordex present values between 1.59 and 1.77
- Suzlon and Senvion present values at or just above 1.

These numerical values reflect the different paces of expansion of the international activity of these companies, highlighting Vestas and SGRE as more global companies, followed by GE, Enercon and Nordex.

The result of the individual indicators offers the opportunity to rank companies' internationalization, and this ranking is listed in Table 8. Overall, Vestas is leading in nearly all indicators, while SGRE follows, then a group of four Western companies ahead of the Asian companies, which are headed by Suzlon.

5. Conclusions

The wind energy technology manufacturing industry, as best

Table 8
Internationalization ranking of wind turbine manufacturers.

Ranking/indicator	Intensity	Geographic diversification	Geographic extensity	Speed (Avg. markets/yr)	Overall ranking
Vestas	1	1	1	2	**1**
SGRE	2	3	2	1	**2**
Enercon	3	4	3	3	**3**
Nordex	4	2	4	5	**4**
GE	6	6	5	4	**5**
Senvion	5	5	6	8	**6**
Suzlon	7	7	7	7	**7**
Goldwind	9	8	8	6	**8**
Sinovel	8	10	9	9	**9**
Ming Yang	11	11	10	10	**10**
United Power	12	12	11	10	**11**
Haizhuan	10	9	13	14	**12**
Envision	13	13	11	10	**13**
XEMC	14	14	13	13	**14**
SEwind	15	15	15	15	**15**

represented by wind turbine manufacturers, is an industry with a very limited number of key players: the top 15 manufacturers accounted for more than 85% of worldwide installed capacity by the end of 2018. This level of concentration enabled the researchers to perform a very thorough assessment of the different business internationalization models.

For the first time, this research has applied business internationalization indicators to analyze the internationalization effectiveness of the wind energy technology industry. Moreover, with the novelty of including an indicator of speed, this research combined four indicators in a way to shed additional light on the process.

An intensity indicator provided evidence of how much the different companies have internationalized related to their total activity and the evolution of each firm's international business relative to each other's and to the global domestic business. The geographic extensity indicator revealed the range of countries that the companies expanded to and how apparently similar firms (in terms of depth of internationalization) focus the range of their international business differently. The geographic diversification index exposed the quality of internationalization and demonstrated that some firms narrowly focus their business on a limited number of countries, whereas the market leaders have a more balanced portfolio of sales per country. Finally, the speed indicator proved that first movers were slow in internationalizing, but they paved the way for other companies to internationalize at a much faster pace.

One company, Vestas, has led the internationalization of this industry since the beginning, both in terms of depth (96% of sales abroad, as measured by the intensity indicator $\boldsymbol{I_{firm}}$) and width (73 countries entered). Vestas has also led in the quality of internationalization, as it is the company with the lowest dependency on a small number of markets, as presented by the geographic diversification index with a $\overline{GD}_{firm}$ value of 1,334. Close to Vestas, SGRE, the company resulting from the merge of Siemens Wind Power and Gamesa, currently presents similar figures in all these indicators (75% intensity, 70 countries and $\overline{GD}_{firm} = 2{,}420$) after trailing behind during most of the growth period of the industry. Moreover, since 2011, SGRE has reached Vestas in the depth of internationalization (sales of 45 GW vs. 47 GW respectively) but not in the annual number of countries, with 27 and 33 countries respectively. Since 2014, SGRE has presented best-in-industry quality of internationalization with an average $\overline{GD}_{firm} = 1{,}068$, closely followed by Nordex (1,254) and Vestas (1,407).

Chinese companies, relative newcomers, are yet to enter foreign markets, although they are starting to do this and are led by Goldwind ($\overline{GD}_{firm}$ 7,334 in the 2014–2017 period). These companies demonstrate that, in the wind energy sector at least, a strong rivalry pressure in the domestic market is not a guarantee for the international competitiveness of its highest performing firms. The findings suggest that other elements different from competitive forces highly influence the Chinese domestic market.

The openness of the wind energy sector, in terms of international reach, suggests that one of the important questions for future research is whether the arrival of foreign companies in a country with incumbents increases competition and how it occurs.

Disclaimer

The views expressed in this paper are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission. The authors declare not to have any significant competing financial, professional or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

Declaration of competing interest

None.

CRediT authorship contribution statement

Jose M. Yusta: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Roberto Lacal-Arántegui:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

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Abbreviations

GE: General Electric
GW: gigawatt (= 1 billion Watts)
HHI: Herfindahl-Hirschman index
IEAWind: International Energy Agency Wind Technology Collaboration
JRC: Joint Research Centre of the European Commission
MW: megawatt (= 1 million Watts)
NSI: network spread index
OEM: original equipment manufacturer, in this report OEM refers to the turbine manufacturer
SGRE: Siemens Gamesa Renewable Energy
TNI: transnationality index

4. Methodology, discussion and conclusions

This section presents and discussed the methodologies used in the different areas of research, discusses the four pieces of research and their respective results as well as the final conclusions of the PhD work.

4.1. Methodology

The nature of this research required methodologies to be adapted to the data available in each of the four main pieces of research. Data originated from very different sources as well as different models were used. Data sources have been described in the introduction, whereas models used ranged from purpose-built Visual-Basic for Applications (VBA) to popular regression analysis software.

All methodologies started by defining the system boundary and the objective under study. These were: assessing offshore wind farm installation time and its evolution [5]; technological and performance (in terms of energy production) changes due to wind turbine repowering independent from locational changes in wind resource [6]; elements of the globalisation of the wind industry and within it a focus on the contribution by European companies manufacturing turbines and developing wind farms, including some of the economic impacts of these companies at home and abroad [7]; and selecting and applying indices appropriate to the assessment of the globalisation of the main wind turbine manufacturers worldwide, their internationalisation effectiveness of these companies which is that eventually resulted in the global deployment of wind energy [8].

In general, all four pieces of research in this thesis required careful analysis of definitions used in scientific, official, and commercial literature. Some of the concepts were found not to have a universally-accepted definition, not even when sources are limited to scientific literature. In other cases, the subject was so new that there was not a definition, as for example the indicator ("vessel-day") used in the analysis of offshore wind installations (see section 3.1 in [5]). In another example from the same piece of research, the data were populated with a wide range of elements (vessels), sometimes with very different characteristics, and this led to questioning where to set the system boundary of vessel characteristics (op. cit.). But without doubt the need to establish definitions was more pressing when the methodology demanded the definition of indicators as in [8].

Another common element of the diverse methodologies was the need to define, or take decisions on, milestones. These included the first and last day vessel activity is counted as "installation": for example, the time for loading items in the harbour is included or not? [5].

Graphical representation was a methodological element included in all articles, based on the premise that graphs can help quickly (and better) communicate a situation, and it can show more interrelated facts – as well as enabling the reader to extract his/her own conclusions. Figure 3 includes an example from article [5], where figure 3 showed how installation days per MW were reduced from around 5 to below 1, and in combination with figure 12 right in the same article (which shows the increasing size of the turbines and distances to shore), gives the reader a good impression of how big the effort has been: new technology made that larger turbines much reduced installation time ***despite*** installations being much further away from the shore.

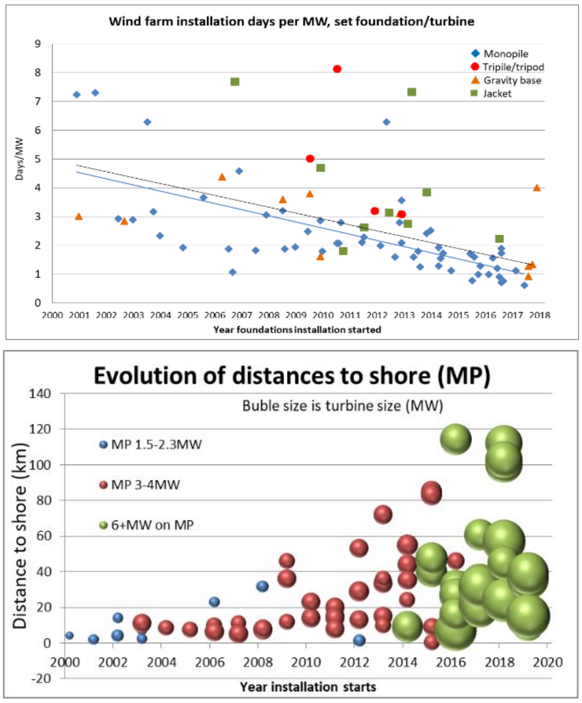

Figure 3. Figures 3 and 12 in article [5]

In another example from [6], research on the technological impact of repowering showed that both average power rating (figure 3 there) and rotor diameter (figure 5) increased throughout the period, but then figure 7 showed how both elements interacted with each other resulting in a clear downwards trend in turbine specific power.

The methodology in the analysis of offshore wind installations [5] was based on the time it took vessels to install the foundations and turbines (or their different components) for every offshore wind farm, and defined as unit the “vessel-day”. Thus, for example, if one vessel installs all the turbines, the number of vessel-days per turbine is:

$$Vd_t = \frac{d_{ie} - d_{is}}{N_t}$$

Where $\boldsymbol{Vd_t}$ is the number of vessel days per turbine installed; $\boldsymbol{d_{ie}}$ is the date turbine installation ends; $\boldsymbol{d_{is}}$ is the date turbine installation begins, and $\boldsymbol{N_t}$ is the number of turbines installed by the given vessel

In the cases when more than one vessel has installed the given item or set of items, it is necessary to take into account the period that each vessel has been installing, and the formula is modified to:

$$Vd_t = \frac{\sum_{i=1}^{n}(d_{ie} - d_{is})}{N_t}$$

Where ***n*** is the number of vessels installing any turbine items. For example, two vessels that installed the same item (e.g. turbines) during one week are counted as 14 vessel-days.

These aspects were later analysed in terms of days per megawatt installed.

The concept of "vessels" used for this analysis includes only large installation vessels able to install the heavy items (see below), such as purpose-built turbine installation vessels (e.g. Bold Tern [95] or Pacific Orca [96]); self-propelled jack-ups (e.g. Sea Installer [97] or Seajacks Leviathan [98]); jack-up barges which need tugs for propulsion (e.g. JB114 [99]); or heavy-lift vessels (e.g. Oleg Strashnov [100], Jumbo Javelin [101], or Svanen [102]).

Items whose installation is considered separately, when information is available, include: the complete turbine or any of its parts; monopile, transition piece, gravity foundation, jacket, tripile and anchor piles (for jackets and tripiles).

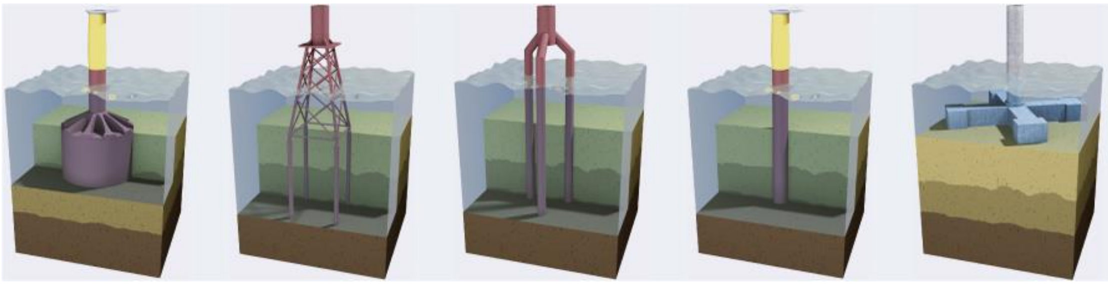

Figure 4. Foundation types suction bucket, jacket, tripile, monopile and gravity-based. Courtesy TRADYNA [112]

The research on repowering [6] required a different methodology. In this case, official data with technological details of old and new turbines and detailed annual production was obtained from [103] and [104]. A VBA macro for MS Excel was created to manage such enormous amount of data and to detect mistakes and gaps. Then, graphical analysis and parameters provided by Excel (e.g. R^2) were used. The last part of this research, which focused in changes in performance, required the use of regression modelling tool Minilab.

Regression analysis has been applied in the energy field e.g. by Lee & Yang [105], Fumo & Rafe Biswas [106] and Ma et al. [107]. In the wind energy field, Arias-Rosales and Osorio-Gómez [108] have applied regression analysis to wind turbines based on estimates of the cost of energy.

Among the statistical models commonly used, linear regression analysis has shown promising results because of the reasonable accuracy and relatively simple implementation when compared to other methods [106]. Under the multiple linear regression approach, the selection of the explanatory variables is a key issue because irrelevant variables have negative effects on the process [109]. To ensure that the multiple linear regression approach is the appropriate methodology, it has been tested so that the input variables selected are linear (i.e., all of them follow a normal distribution) and independent from each other.

The correlation between the technological changes brought about by repowering was explored (i.e., the increases with time in hub height, rotor diameter, and power rating) between the repowered and new turbines, and the increases in annual energy production (*AEP*) in each case. The regression analysis took *AEP increase* (*ΔAEP*) as the dependent variable and all other variables as independent variables. The reason for defining *AEP* as the dependent variable is that the final objective of repowering is increased production, which is also the natural consequence of the changes in technological variables.

The regression analysis with Minitab statistical software considered the following predictor variables:

ΔTR = Change in turbine rating (MW)

ΔHH = Change in hub height (m)

ΔSP = Change in specific power (W/m^2)

YR = Repowering year.

The first analysis trials quickly showed that two variables were not statistically significant (*ΔHH, YR*), as the p-value was above 0.05 for these predictor variables. The two remaining independent variables (*ΔTR, ΔSP*) were found to be of statistical significance for the regression model.

The coefficient of multiple determination, R^2, takes an acceptable value of 93.37%, and adjusted R^2 is 93.30%. A small Mallows' Cp value of 3.0 was obtained, indicating that the model is sufficiently precise. It was concluded that the model fitted the data well.

Other assumptions that are required for multiple regression analysis to give a valid result were checked as well. They are shown in Table 2 of the article [6] and summarised here:

- The independent variables are significant, as p-value is below 0.05 for both variables.
- The variance inflation factor (VIF) is 1.29 for the two independent variables of the regression model, indicating that the predictor variables are not correlated.
- The residuals show an approximate constant variance.
- The residuals are normally and randomly distributed.

It was noted that the ratio between turbine rating and swept area is a very important technical feature: it is a basic design parameter used by turbine manufacturers for products better suited for specific wind conditions. Because of this reason further analyses were carried out: the swept area (SA, m^2) was tried instead of specific power (W/m^2) in the regression analysis. Somehow, although R^2 reached 95%, the results showed a VIF value of 7.83 for both statistically significant variables *ΔTR* and *SA*, indicating a possible problem of multicollinearity.

Another analysis was based on the previous regression model result that change in hub height (*ΔHH)* was not significantly related to the increase in energy production. To explore this further, the data set was split into two subsets: from 2000 to 2005 and 2007 to 2015, to examine possible partial time correlation. However, the results of the analysis showed again that *ΔHH* remained a non-significant variable for the regression model.

Because the research on globalisation [7] attempted to present a global situation, its methodology focused on the two main sector activities: manufacturing wind turbines and development of wind farms. Rather than using complex modelling, the key methodological approach was the contrasting of different sets of data in order to surface and explain the realities of globalisation in the sector.

For example, the research compared installed capacity and energy produced and showed that wind electricity generation is more efficient in the US with a 33.9% capacity factor than in the EU (24.5%) and China (22.3%). The research further explored the reasons and proposed that grid limitations in China prevented the full exploitation of wind resources in the north, whereas the equivalent wind-rich area in the US, the Midwest, was well exploited.

Regarding wind turbine manufacture, a comparison of annual deployment from the Global Wind Energy Council and annual sales from industry intelligence showed that European companies have a global market share that nearly doubles the share of installations in the EU. For example, in 2016, European manufacturers installed around 44.4% of global installations whereas wind farms installed in Europe were only 22.9% of global installations. This is a success story. Further, the research compared and showed where income is produced and where employees are kept: European manufacturers obtain relatively little income in Europe but most of their staff is still in this continent.

Finally, the article on globalisation explored the little-know wind farm developer market through global figures and corporate events such as mergers, memorandum of understanding and other.

This research started a line of work that was later followed with the fourth article in this thesis: the internationalisation of turbine manufacturers. This was the result of data on where and when manufacturers had installed turbines, as shown in section 3.4 of [7].

The research on monitoring internationalisation required the definition of internationalisation indicators based on scientific literature in the area of economics, a personal challenge given my engineering-oriented background. In general, these can be classified as structural, performance-based and attitudinal [94], and composite indices have been created with the individual indicators [92], perhaps because there is not an individual indicator that satisfactorily measures the overall degree of the internationalisation of a firm [94]. The research proposed the use of several structural indices that help with assessment, lead to a useful analysis and together present a meaningful picture of the process. For a measure of the intensity of internationalisation, we focused on the ratio of the installed wind turbine capacity abroad ("exports") to the company's total installed capacity ("total sales"). This index is one of the three that constitute the more broadly-used transnationality index [25], and it is one for which the available data allows full research. This index can effectively measure the *depth* of the foreign expansion for each firm.

First, we calculated this index for each year in the sample, from 1978 to 2017. Then, the intensity index $\boldsymbol{I_{firm}}$ was obtained for the total amount of the installed capacity by each firm in all 112 countries and territories. In addition, a second indicator $\boldsymbol{\bar{I}_{firm}}$ was calculated, averaging the annual intensity index.

$$I_{firm} = \frac{\sum_{yr} \sum_{co \in foreign} P_{firm,co,yr}}{\sum_{yr} \sum_{co} P_{firm,co,yr}} \quad (1)$$

$$\bar{I}_{firm} = \frac{1}{40} \sum_{yr=1978}^{yr=2017} \frac{\sum_{co \in foreign} P_{firm,co,yr}}{\sum_{co} P_{firm,co,yr}} \quad (2)$$

Where $\boldsymbol{\sum_{yr} \sum_{co \in foreign} P_{firm,co,yr}}$ is the installed capacity abroad by each wind turbine *firm*, in each country ***co***, in each year ***yr***, while $\boldsymbol{\sum_{yr} \sum_{co} P_{firm,co,yr}}$ is the total installed capacity by each wind turbine ***firm***, in each country ***co,*** in each year ***yr,*** including the domestic and foreign capacity.

With regards geographic extensity, the number of foreign countries and territories in which each company has installed wind turbines is the relative worldwide spread of each firm [26].

This spread is directly related to what can be called the *width* of internationalisation of a company, which is measured by the network spread index (NSI), a ratio for each firm of the absolute number of foreign countries where the firm ever deployed wind turbines to the similar figure for the firm that installed turbines in more foreign countries [43].

$$NSI_{firm} = \frac{Ncountries_{firm}}{\max\limits_{1 \le firm \le 15}\left(Ncountries_{firm}\right)} \quad (3)$$

There $\boldsymbol{Ncountries_{firm}}$ is the absolute number of different foreign countries that a firm has ever done business with.

A firm whose foreign activity is diversified does business in each market in a balanced way. This balance protects the firm against the ups and downs of individual markets. This protection is unlike a firm whose business mostly depends on a few of its export markets. We propose the use of a geographic diversification index $\boldsymbol{GD_{firm}}$ to measure how the activity is split among those countries.

First, for every firm and year, we calculated the ratio of the installed capacity in each country ($\boldsymbol{P_{firm,co,yr}}$) to its total installed capacity. Second, we used the well-known Herfindahl-Hirschman index (HHI) [44] to obtain a measure of the diversification of the firm activity for each year $\boldsymbol{GD_{firm,yr}}$. Finally, we computed the mean of the annual HHI values to obtain an average value of the geographic diversification index of each company in the whole period $\boldsymbol{\overline{GD}_{firm}}$. This average index can also be calculated for a different number of years.

$$GD_{firm,yr} = \sum_{co=1}^{112}\left(\frac{P_{firm,co,yr}}{\sum_{co=1}^{112} P_{firm,co,yr}}\right)^2 \quad (4)$$

$$\overline{GD}_{firm} = \frac{1}{40}\sum_{yr=1978}^{yr=2017}\left[\sum_{co=1}^{112}\left(\frac{P_{firm,co,yr}}{\sum_{co=1}^{112} P_{firm,co,yr}}\right)^2\right] \quad (5)$$

The index varies between 0 and 10,000, where 10,000 indicates that the company concentrates its sales in a single country, while values closer to zero indicate greater international diversification.

Internationalisation studies using structural indicators do not usually include a measure of speed. However, this speed is an important issue and a key aspect of a firm's international strategy [7,10]. Hence, we discuss here a set of indicators based on proposals in the literature that quantify the average speed at which the company has expanded internationally.

Hilmersson et al. [19, 20] have suggested several possible indices to measure the speed of internationalisation: the mean number of markets exported per year since inception, the ratio of exports to total sales and the share of the firm's assets abroad. Concerning the first index, Mohr [21] has proposed a variation as the average number of foreign markets divided by the number of years since the firm's first international expansion. Using the date of the first international expansion fits better with the wind industry than the date of inception since sales abroad started after a long period of technology development.

The ratio of exports to total sales constitutes internationalisation intensity as defined in Section 2.1. How this element evolved over time can be a useful indicator for the assessment of the internationalisation dynamics of a firm. In the case of wind turbine manufacturers, the indicator is defined as the percentage of the foreign against the total rated capacity (in MW) of the turbines installed.

Speed could also refer to the length of time until a certain milestone is achieved. The literature suggests using for this indicator between 10% and 20% of the total number of countries and territories exported to [33,45,46]. After analysing the historical data series from the database, we proposed this milestone to be 20%, as this figure reflects a significant number of exports for most companies in the sample.

Therefore, the selected indicators to measure the speed of the internationalisation of wind turbine firms are the following:

- The average number of new markets entered per year since the firm's first international expansion
- The number of years between the first year of the internationalisation of the firm to the year when it reached the milestone of 20% of its final number of foreign markets; thus, for example, if a firm had exported to a total of 30 countries by the end of 2017, the figure in this indicator would be the years until it reached six foreign markets.
- Internationalisation intensity over time

The data about the installed capacity, in megawatts (MW), from each of the 15 primary wind turbine manufacturers in 112 countries and territories worldwide from 1978 to 2017 was used for the purpose of this study [34]. The database is nearly complete, as it includes a total of 517.7 GW of wind turbines installed or commissioned during this period, including old turbines that have already been decommissioned. This figure is 96 % of the most accurate estimate of the worldwide installed capacity, 539.6 GW, by the Global Wind Energy Council [35]. The main gaps in the database correspond with Chinese installations; for example, a total of 32.6 GW of installations were assigned to Goldwind of China, whereas its actual installations were 42.7 GW in China [36] plus 1.3 GW abroad. The installed capacity by the top 15 turbine manufacturers, also called original equipment manufacturers (OEMs), in the database was 458.5 GW, or about 85 % of the worldwide installed capacity by the end of 2018.

After having worked with wind installation databases from five different industrial intelligence suppliers since 2009, we found that the MAKE database is the most complete in terms of the number of installations (in MW) that are allocated to each turbine manufacturer. However, the database still retained some elements that had to be refined. This refining work consisted of screening the initial installations in the database against the company's history on either its website or wind energy-related books of the 1990s [37,38] and against some of the other databases from industrial intelligence suppliers [39–42].

The data therefore allows the assessment of certain structural measures of the internationalisation of these wind firms. The indicators aid in understanding the evolution of market dynamics, firm expansion and the influence of the domestic renewable policy on boosting a firm's global activity. Hence, we selected and applied the following structural indices to the analysis of wind turbine manufacturer internationalisation.

4.2. Discussion on techno-economic aspects of key cost-reduction issues

The research on offshore wind installation [5] presented an assessment of the learning-by-doing and technological improvements in installation of turbines and foundations of offshore wind farms achieved during the previous two decades. It showed that turbine plus foundation installation time decreased from 7.6 days in 2000–2003 to 5.9 days in 2016–2017 for monopile-based projects. Interestingly, this reduction in installation times occurs despite the increase in distances to shore.

It was demonstrated that the reduction in installation times was stronger when the effect of larger turbines was taken into account. Installation times for all wind farms with monopile foundations were reduced from just below 4 days per MW in 2000–2003 to 1.06 days per MW in 2016–2017, a 71% reduction. This reduction was mostly caused by improvements in the installation of the foundations. Foundation installation times per megawatt improved by 87%, significantly more than turbine installation per MW (55%). However, the biggest effect was achieved by the increase in the size of individual turbines (to 8.25MW at the offshore wind farm Walney 3) and the corresponding increase in foundations size and reduction in the number of foundations and turbines for the same given wind farm capacity.

This research found that the effect of economies of scale, measured based on wind farm size, was not significant in reducing the installation time for either foundations or turbines.

A limitation of this study was that the effect of waiting-on-weather days has not been discounted, and it was strongly recommended some follow-up work to analyse this effect. A second limitation was that some of the dates corresponding to the oldest wind farms lacked the accuracy of data available for the newest projects. It was suggested that this research could be a starting point for thorough quantification of key technological and non-technological elements behind the impressive offshore wind cost reductions of late. These include, e.g. other installation elements, mainly cable installation, or the impact of evolving financing rates and financing structures. The resulting research could be put together to fully understand how a technology that is subject to the strong force of nature has been able to manage and dominate it.

The research on the technology effects in repowering wind turbines [6] was as well pioneering in assessing the technological effects caused by a large set of real repowering projects and their impacts on energy production on a turbine-by-turbine level. The average repowering occurred has brought nearly a three-time increase in rotor diameter, or a nine-time increase in swept area, and a doubling of hub height. New turbines were between 6 and 11.6 times as powerful as decommissioned turbines, depending on how the average was taken. The results showed that repowering resulted in an increased capacity factor of 7.1% on per turbine basis, or 9.7% on a per production basis.

During the first years of repowering, new turbines had significantly higher specific power than the turbines they replaced, but this trend reversed in the 2014 to 2017 period. This was linked to changes to the financial support instrument being used at the time in Denmark, which from 2014 promoted turbines with low specific power.

New turbines have a higher annual energy production compared with the removed turbines. On a weighted average, per-turbine production as a result of repowering increased by 2.3 GWh between 2001 and 2003; by 6.7 GWh between 2008 and 2011; and by 7.7 GWh between 2013 and 2015. Because the annual electricity production remained relatively stable for the removed turbines, the increase in additional energy production was due to the sharp increase in performance of the new turbines. The average annual energy production achieved by new turbines was about 4.94 GWh, or 9.0 times the production of the removed turbines. Also, the study showed that specific energy production (per m^2 swept area) increased in 99% of the cases. On average, specific electricity production increased by 320 kWh/m2/yr.

A regression analysis was performed to assess the impact of the underlying changes in technology on energy output. It showed that the increase in energy production was directly related to the increase in turbine rating and the decrease in specific power of the new turbines. On average, every additional kilowatt of rated power added 3.22 MWh to the annual energy production, and each W/m^2 of lower specific power increased annual electricity production by 8.62 MWh.

Further, this study analysed the effects of repowering on a turbine-by-turbine level. This was done to mitigate the influence of local variations in the wind resource. Of course, it is unusual that a repowering project substitutes each turbine with a newer, larger one. Repowering projects most often concern whole wind farms where both turbine and power grid upgrades are performed and wind farm configuration is optimised for energy production and levelled cost of energy, often by reducing turbine counts but approximately maintaining power density. A follow-up to this study has been proposed to use empirical data to characterise the actual change in turbine density and energy production resulting from deployment of new modern turbines in place of older facilities at the end of their life. A further research question would also be to analyse the financial aspects of repowering: for example, was the repowering performed at the optimal time from a cost perspective?

From a societal view point, and considering the growing market for repowering in the coming years, it is important to understand if market-driven repowering projects will also deliver the socioeconomic benefits to society. In particular, will the wind resource be utilised optimally? What are indirect economic impacts (e.g., on the value of land) of repowering? These questions need answers in order to determine if repowering could be more efficient or steered by policy instruments to bring the additional value for the economy and the society.

4.3. Discussion on deployment aspects: globalisation and internationalisation

Globalisation [7] goes hand-by-hand with localisation. In order to compete in large markets (India, China, US, Brazil), EU companies have had to grow local manufacture and a supply chain. The US is somehow the exception and this could be due to its openness as a market. Smaller markets are supplied from the main production centres (whether the EU or factories in China) and do not require localisation.

Vestas, Gamesa, and other European companies to a lesser extent have been successful at localisation whereas Suzlon and Chinese companies are generally less able to localise supplies, perhaps due to the low-cost production achieved in their home countries.

OEMs in the EU contribute to the economy significantly thanks to their exports, but China is emerging as a manufacturing hub for them. Eventually, this could result in Chinese suppliers offering products of higher quality which risks increasing competition from Chinese OEMs using this modality of technology transfer. Whereas seven acquisitions of EU technology firms by US companies, and four acquisitions by Chinese companies were identified, no European company acquired a US or Chinese technology firm. This can be the result of the longer history of EU companies in the business, of the quality of their technology, of the successive crisis affecting the sector in Europe, of the availability of funding on the side of the American and Chinese, or a combination of these. Significantly as well, General Electric of the US has been the acquirer of all but one European technology companies bought by US firms.

The European wind industry is a success story of worldwide reach that attracts jobs and growth for Europe. In order to ensure that this will continue to be so in the mid- or long-term future, the industry may need the help of European and national policy makers with consented, well-targeted actions. Support programmes could help maintaining technological leadership through research, development and innovation programmes feeding on cross-industry knowledge and knowhow. They could support industrial leadership also in the manufacture of components. Instruments to financially and politically back the expansion of the industry to new and existing foreign markets may also be required.

Further reflection of policy makers with developers, turbine manufacturers and other key players may be needed so as to increase the impact of the sometimes already existing programmes (e.g. Horizon 2020) and make their implementation more comprehensive.

The wind energy technology manufacturing industry, as best represented by wind turbine manufacturers, is an industry with a very limited number of key players: the top 15 manufacturers accounted for more than 85% of worldwide installed capacity by the end of 2018. This level of concentration enabled the researchers to perform a very thorough assessment of the different business internationalisation models [8].

Business internationalisation indicators were applied to analyse the internationalisation effectiveness of the wind energy technology industry. Moreover, with the novelty of including an indicator of speed, this research combined four indicators in a way to shed additional light on the process.

An intensity indicator provided evidence of how much the different companies have internationalised related to their total activity and the evolution of each firm's international business relative to each other and to the global domestic business. The geographic extensity indicator revealed the range of countries that the companies expanded to and how apparently similar firms (in terms of depth of internationalisation) focus the range of their international business differently. The geographic diversification index exposed the quality of internationalisation and demonstrated that some firms narrowly focus their business on a limited number of countries, whereas the market leaders have a more balanced portfolio of sales per country. Finally, the speed indicator proved that first movers were slow in internationalising, but they paved the way for other companies to internationalise at a much faster pace.

One company, Vestas, has led the internationalisation of this industry since the beginning, both in terms of depth (96% of sales abroad, as measured by the intensity indicator $\boldsymbol{I_{firm}}$) and width (73 countries entered). Vestas also led in the quality of internationalisation, as it is the company with the lowest dependency on a small number of markets, as presented by the geographic diversification index with a $\overline{GD}_{firm}$ value of 1,334. Close to Vestas is SGRE, the company resulting from the merge of Siemens Wind Power and Gamesa, currently presents similar figures in all these indicators (75% intensity, 70 countries and ($\overline{GD}_{firm}$ = 2,420) after trailing behind during most of the growth period of the industry. Moreover, since 2011, SGRE has reached Vestas in the depth of internationalisation (sales of 45 GW vs. 47 GW respectively) but not in the annual number of countries, with 27 and 33 countries respectively. Since 2014, SGRE has presented best-in-industry quality of internationalisation with an average $\overline{GD}_{firm}$= 1,068, closely followed by Nordex (1,254) and Vestas (1,407).

Chinese companies, relative newcomers, are yet to enter foreign markets, although they are starting to do this and are led by Goldwind ($\overline{GD}_{firm}$7,334 in the 2014-2017 period). These companies demonstrate that, in the wind energy sector at least, a strong rivalry pressure in the domestic market is not a guarantee for the international competitiveness of its highest performing firms. The findings suggest that other elements different from competitive forces highly influence the Chinese domestic market.

The openness of the wind energy sector, in terms of international reach, suggests that one of the important questions for future research is whether the arrival of foreign companies in a country with incumbents increases competition and how it occurs.

4.4. Conclusions

The success story of wind energy is proven by its nearly-exponential expansion as an electricity generation technology, with installed capacity growing from 20 GW in 2000 [8] to 650 GW in 2019 [110]. This success has been possible due to the support of the society, with global environmental concerns as the very root of this support. This support pushed governments to create the regulatory context necessary for the technology to expand when cost of generating electricity was more expensive than fossil fuel- and nuclear-based generation. This growth enabled large-scale innovation that eventually resulted in technology (and financial, and other) improvements reducing the cost of energy from new wind farms to the point that the technology nowadays regularly undercuts conventional generation in auctions around the world.

This research has provided evidence and analysis of two key technological elements that have contributed, and will still contribute further, to reducing the cost of wind electricity. In the offshore subsector, the time necessary to install turbines and foundations was reduced very significantly, e.g. by 71% per MW in the case of monopile-based wind farms from 2000–2003 to 2016–2017 [5]. In the onshore subsector, the repowering of old wind farms resulted in new turbines generating nine times as much electricity as the old turbines and an impressive increase of capacity factor of 7.1% on a per-turbine basis, or 9.7% on a per-production basis [6].

The political support, the increase in deployment, innovations and the subsequent reductions in the cost of electricity transformed what was a very local sector into a global technological and industrial sector. Globalisation resulted in winners and losers: from an industrial point of view, small countries with small markets lack the market to develop its own industrial champions and even to attract manufacture from global champions. Large markets such as China, the US, India and the European Union have fostered local wind energy technology companies and promoted them to global champion status [7]. However, these large markets produced companies that play in the global arena in very different ways, some are large enough in their home country and do not want to (or cannot) internationalise, and some were born directly with an internationalisation soul [8].

The research has presented evidence of elements proper to a normal, healthy industrial sector. From an initial political support, thanks to it and to technological innovation, the sector now produces electricity at prices competitive with other technologies. The sector has internationalised, fostered mergers and acquisitions. All-in-all, those elements, along with the continuous need to de-carbonise electricity production, bode very well for the future of the wind energy sector.

Appendix

All articles that make up this thesis have been already published.

Journals details

The journals where the articles were published are listed below.

- "Offshore wind installation: Analysing the evidence behind improvements in installation time" *Renew. Sustain. Energy Rev.*, vol. 92, pp. 133–145, Sep. 2018. This journal JCR impact factor was 10.556 in 2018. Categories:
    - ENERGY & FUELS -- SCIE quartile 1
    - GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY – SCIE quartile 1
- "Technology effects in repowering wind turbines" *Wind Energy*, vol. 23, no. 3, pp. 660–675, 2020. This journal JCR impact factor was 3.125 in 2018 and 2.646 in 2019. Categories:
    - ENGINEERING, MECHANICAL – SCIE quartile 2 (2018) and 3 (2019);
    - ENERGY & FUELS – SCIE quartile 1 (2018) and 2 (2019)
- "Globalization in the wind energy industry: contribution and economic impact of European companies," *Renew. Energy*, vol. 134, pp. 612–628, Apr. 2019. This journal JCR impact factor was 6.274 in 2019. Categories:
    - ENERGY & FUELS – SCIE quartile 1;
    - GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY – SCIE quartile 1
- "Measuring the internationalization of the wind energy industry," *Renew. Energy*, no. 157, pp. 593–604, 2020. This journal JCR impact factor was 6.274 in 2019. Categories:
    - ENERGY & FUELS – SCIE quartile 1;
    - GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY – SCIE quartile 1

Contributions

The PhD candidate planned the research, carried out literature review, sought data, built and used models, led the discussions and extracted conclusions. In all cases, the PhD candidate led the research and was both main and corresponding author. Parts of the research were carried out in collaboration with other researchers, and therefore it is necessary to describe the respective contributions.

More specifically, in the article *Offshore wind installation: Analysing the evidence behind improvements in installation time* [5], Dr José M. Yusta Loyo and Dr José Antonio Domínguez Navarro advised on the strategy of the research, data and model limitations, whereas the PhD candidate had responsibility over the definition of the research project, data collection, data analysis, modelling, results and conclusions.

Regarding the research on *Technology effects in repowering wind turbines* [6], responsibilities were shared with Dr Andreas Uihlein and Dr José María Yusta Loyo. The former helped defining the research question as well as focused on German data and analysis; the latter set the regression model. The PhD candidate had exclusive responsibility over data collection and data analysis of the Danish part; setting the Visual Basic for Applications, Excel-based models.

The research leading to the article *Globalization in the wind energy industry - contribution and economic impact of European companies* [7] was full responsibility of the PhD candidate, as it is shown by his sole authorship.

Its detailed follow-up, the article *Measuring the internationalisation of the wind energy industry* [8] was a joint effort with thesis supervisor Dr José María Yusta Loyo. The PhD candidate took exclusive responsibility over data collection and shared responsibility on data analysis, modelling, results analysis and conclusions.

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