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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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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.

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.

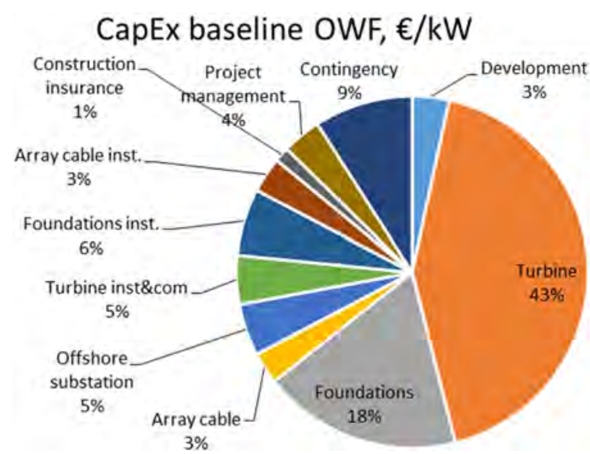

Fig. 1. Estimated breakdown of the capital expenditure of a baseline offshore wind farm in 2015. Source: [9].

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

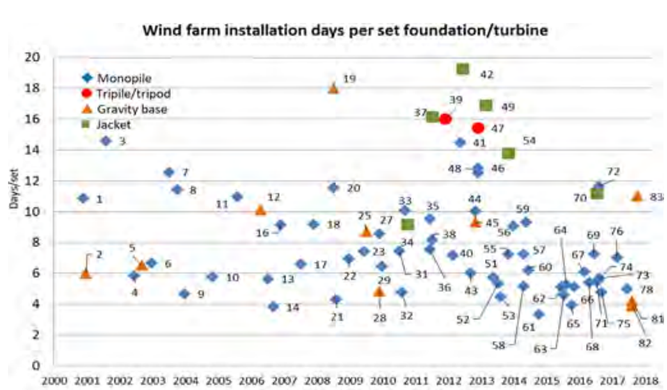

Fig. 2. Overall picture of installation (vessel-) days per each set of one turbine plus its corresponding foundation, with breakdown according to type of foundation. Source: own data. Notes: wind farms that were installed as a single entity (e.g. Lynn and Inner Dowsing) were counted as a single project; 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).

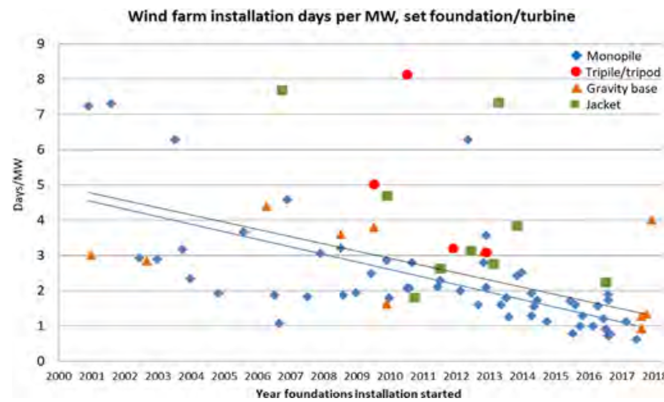

Fig. 3. Wind farm installation days per megawatt of installed capacity, for the set turbine + foundations, with breakdown according to type of foundation. Source: own data.

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.

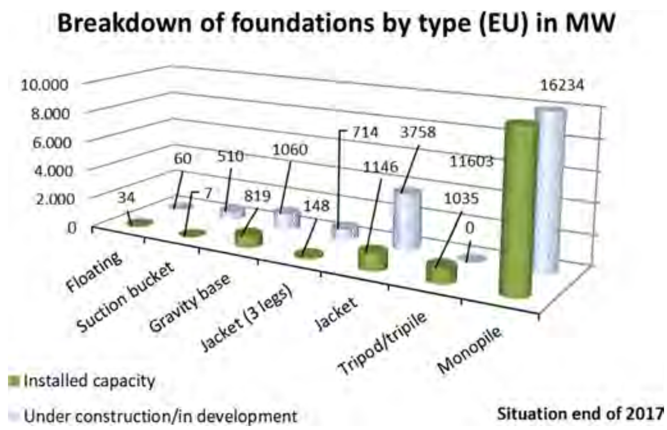

Fig. 4. Breakdown of offshore wind capacity per foundation type, for European OWF, both operational by the end of 2017 and under construction, or in development at the end of 2017 with expected commissioning by 2024. Source: own data. Remarks: 55% of the 22 GW in development have decided the foundation 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.

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

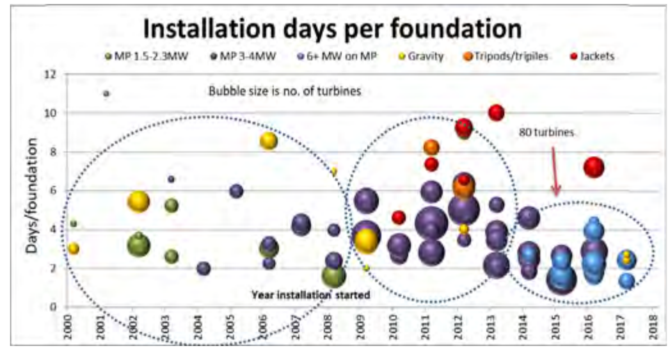

Fig. 5. Overall picture of the time taken to install one foundation (without the turbine) for each OWF that has finished foundations installation. Source: own data.

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

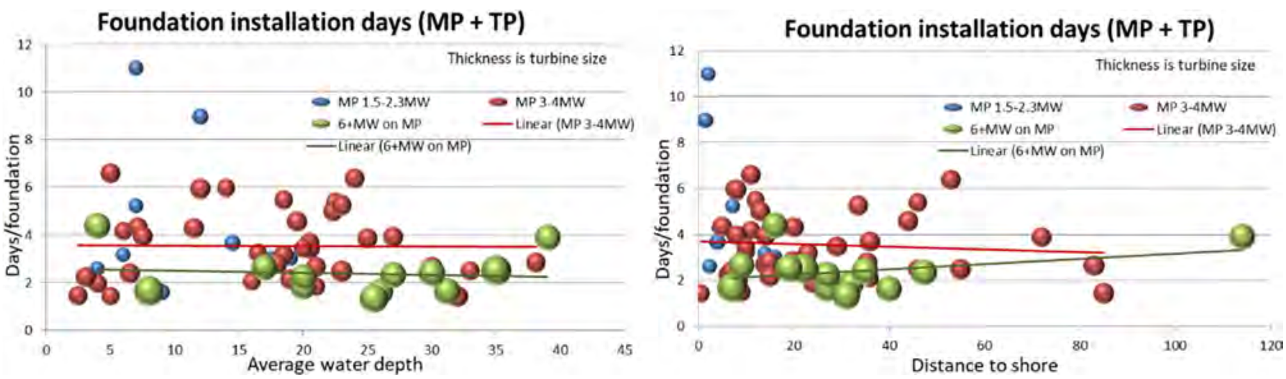

Fig. 6. Relationship between installation time and average water depth and distance to shore. Source: own data, 4COffshore.

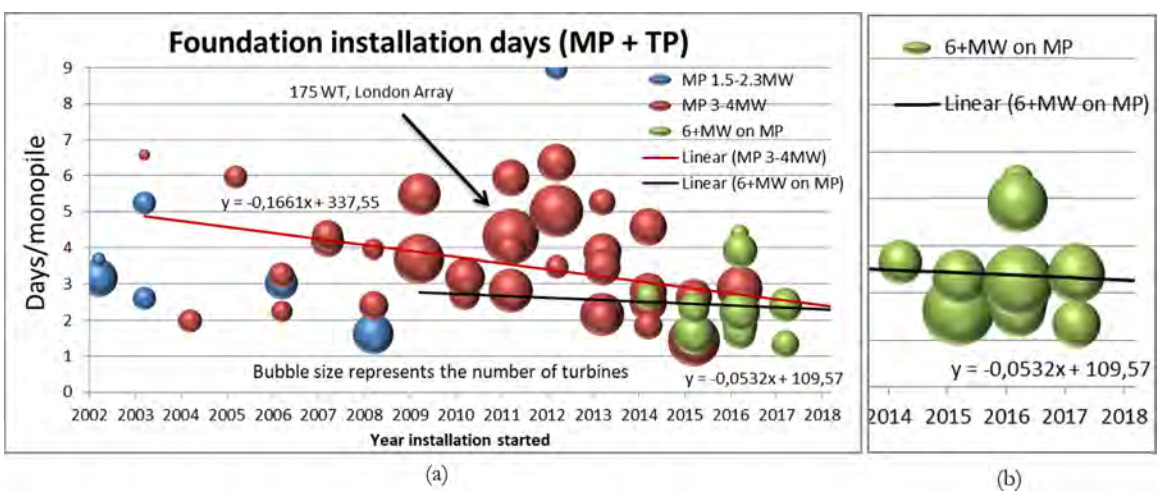

Fig. 7. (a) Evolution of foundation installation days related to wind farm size; (b) enhanced view of the 6 + MW set.

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 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

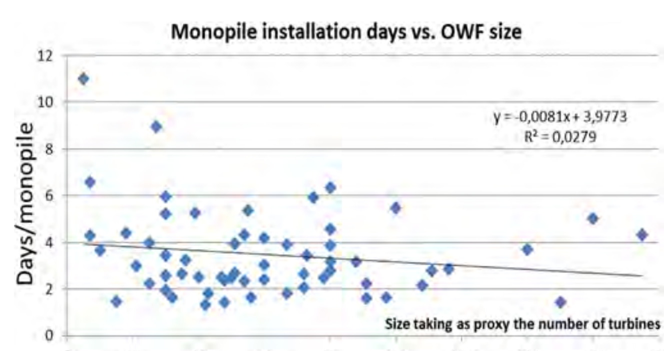

Fig. 8. Relationship between monopile installation time and wind farm size as reflected by the number of foundations.

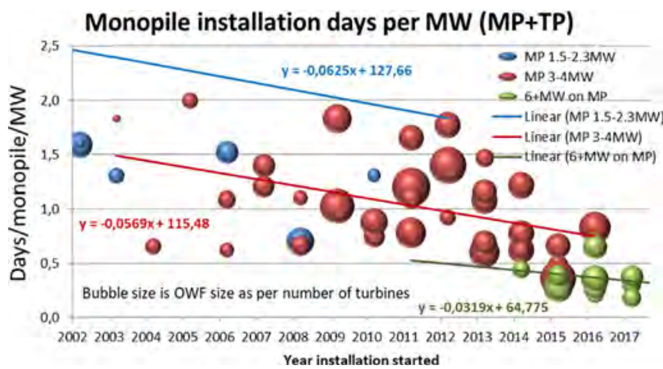

Fig. 9. Monopile installation days per MW terms.

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…

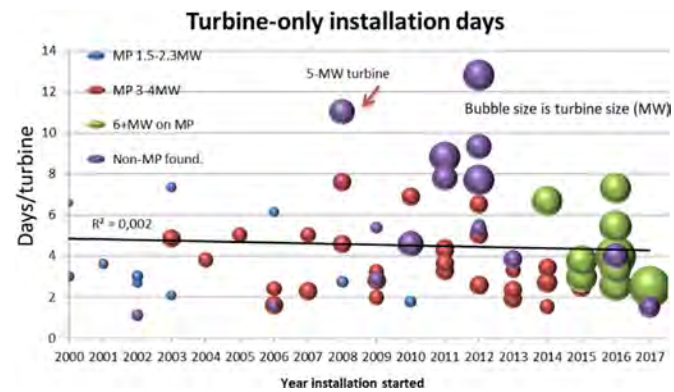

Fig. 10. Evolution of the turbine-only installation days and turbine size for monopile-based installations with turbines between 1.5 and 2.3 MW (blue) between 3 and 4 MW (red), and larger than 6 MW (green), as well as non-monopile-based installations of any turbine rating (purple). Source: own database. (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.

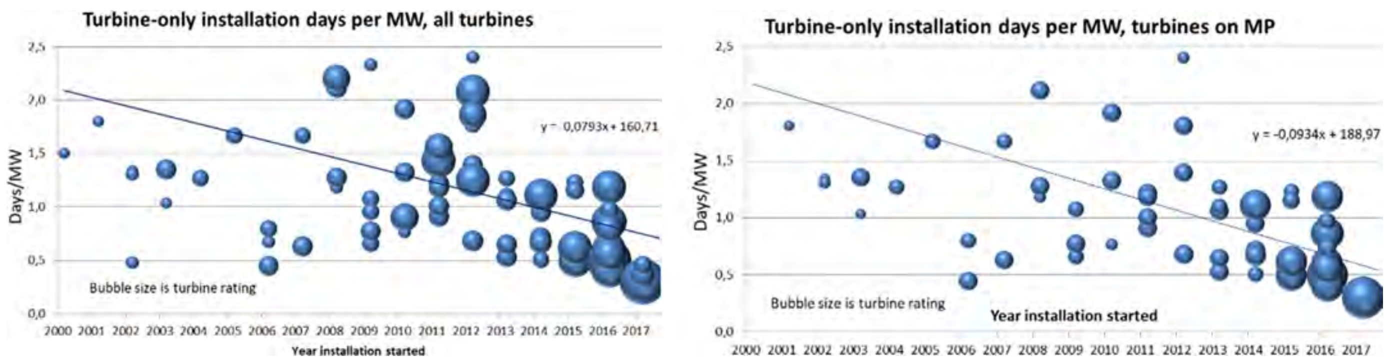

Fig. 11. Turbine-only installation days per MW under two scenarios: all turbines (left) and only turbines on monopiles (right). The installation year corresponds to the start of installation.

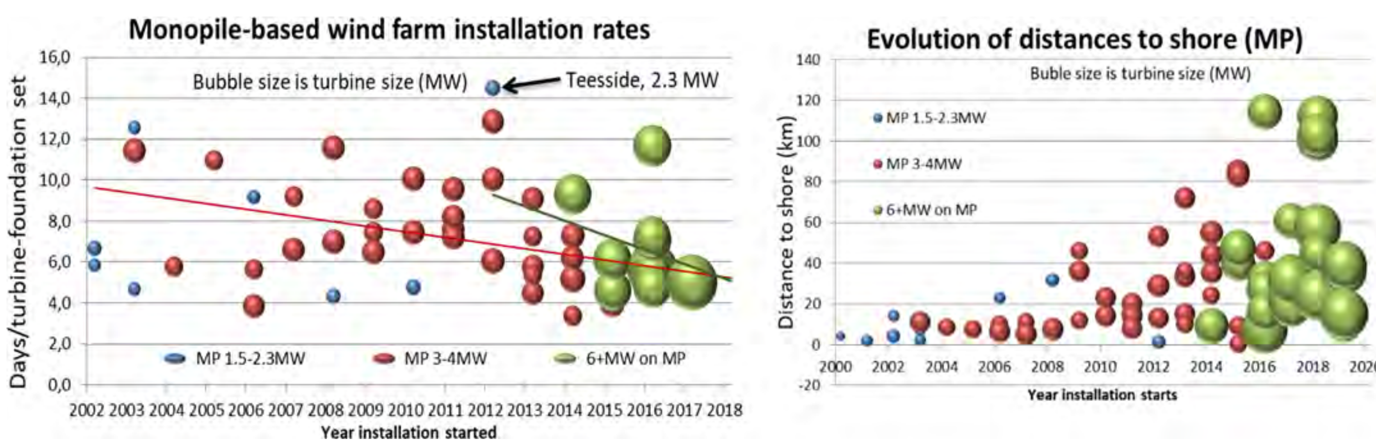

Fig. 12. Monopile-based, full-set installation times and distances to shore.

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

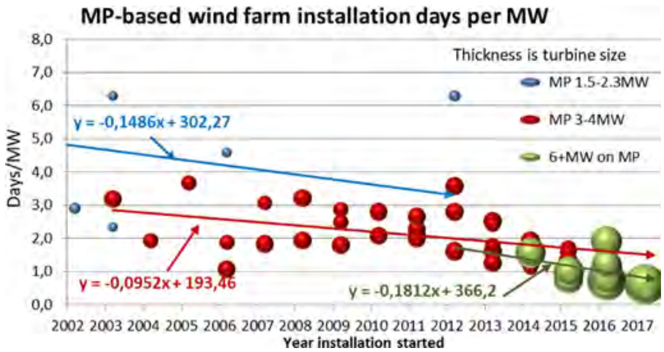

Fig. 13. Evolution installation rates per MW of installed capacity in wind farms with monopile foundations.

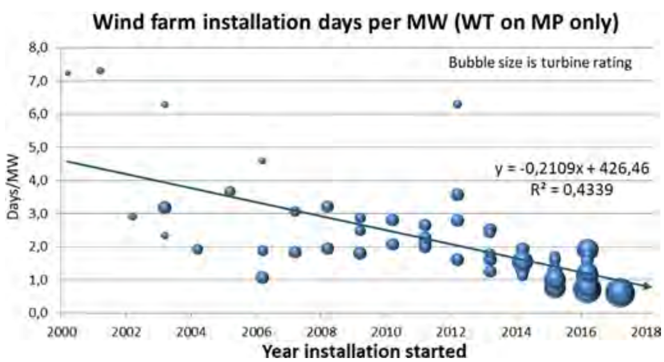

Fig. 14. Evolution of the installation rate for turbines mounted on monopiles, all turbine ratings in a single data series.

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.

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.

Appendix A

See Table A1.

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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