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Do onshore and offshore wind farm development patterns differ?

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ABSTRACT

When developers are building wind farms offshore or onshore, are there notable characteristics that differentiate these projects? If so, what does this tell us about the nature of wind power development patterns? This study makes use of industry data from 44 wind farms, including 11 offshore wind farms, 19 onshore wind farms located in farmland and 14 wind farms located in forested areas with a total capacity of 1190 MW installed actual wind farms to test four hypotheses based on preconceptions identified in a literature review. Testing the validity of these preconceptions is important because if policymakers are to design policy to facilitate specific development patterns in a given nation, they need to be clear on what is working in the market. Our data suggest that, contrary to popular belief, offshore wind farms do not produce more energy per installed MW when compared to onshore wind farms. However, our data confirm that offshore wind farms produce more energy than onshore wind farms. We contend that this has less to do with superior wind quality in offshore sites than with scale differences. It appears that developers construct far larger offshore wind farms in order to presumably counteract the proportionally higher development costs associated with marine environments. One other remarkable finding associated with this study is that onshore wind turbines that are located in forested areas might be capable of matching the power production of offshore wind farms without incurring the additional costs associated with offshore projects.

Introduction

The sight of a wind turbine on the horizon has come to encapsulate what many perceive to be the initial stages of a transition to low carbon energy. There is good reason for this. Global wind power potential is enormous. In a 2005 study, Archer and Jacobson (2005) determined that capturing only 20% of technical potential using existing turbine technology "could satisfy 100% of the world's energy demand for all purposes (6995–10,177 Mtoe) and over seven times the world's electricity needs (1.6–1.8 TW)". Another team of researchers from Harvard University and the VTT Technical Research Center in Finland estimated in 2009 that "a network of land-based 2.5-megawatt (MW) turbines restricted to non-forested, ice-free, nonurban areas operating at as little as 20% of their rated capacity could supply more than 40 times current worldwide consumption of electricity" and more than "5 times total global use of energy in all forms" (Lu et al., 2009).

During the past two decades, companies worldwide have begun to harness this untapped potential. Installed wind energy capacity has increased from less than 8000 MW in 1997 to more than 432,000 MW by the end of 2015 (IRENA, 2016). Moreover, the sector has established itself as a major source of new employment, topping 1 million workers in the sector for the first time in 2014 (IRENA, 2015) with an expected doubling to 2 million by 2030. Indeed, on a kilowatt hour basis, it has been estimated that wind power produces 55% more jobs than coal-fired power and natural gas-fired power; and 21% more jobs than nuclear power (WRI, 2010).

To date, the majority of wind power projects have been constructed onshore. As of the end of 2015, of the 432,000 MW of installed wind power capacity, 420,000 MW exists onshore (IRENA, 2016). The first onshore multi-megawatt wind turbines were installed in 1978 in Denmark (Gipe, 1995) and were primarily installed in farmlands – which permitted joint use projects that lower costs – and in close proximity the sea, to take advantage of stronger coastal wind profiles (Manwell et al., 2009; Troen and Petersen, 1989). However, as wind power projects have grown in concentration, so has social opposition with not-in-my-backyard (NIMBY) sentiments clearly on the rise (Valentine, 2011).

In response, many nations are adjusting policies to encourage offshore wind power development (Valentine, 2014). For almost a decade, planners have seen great potential in offshore wind energy and lauded such developments as a way to avoid both the high cost of acquiring onshore tracts of land and social opposition to further onshore

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development (Ladenburg, 2009). Recent innovations in offshore foundations have made it possible to deploy wind turbines in deeper waters, enhancing global offshore wind potential (Adelaja et al., 2012). Consequently, offshore wind power capacity is on the rise, reaching 12,000 MW by the end of 2015 (IRENA, 2016). Offshore capacity is expected to increase rapidly in the coming years, especially in Europe (Young, 2015).

The pace of offshore development is highly contingent on the economics of any given offshore wind power project. Some research suggests that offshore wind farms exhibit cost advantages through less costly wind turbine materials because towers can be constructed at lower heights. However, most studies counter that offshore wind farms are more expensive to construct and maintain, due to the demand for larger fortified foundation structures, submarine cables and special vessels for transportation and installation (Bilgili et al., 2011). The general consensus is that offshore wind farms are still more costly than onshore options for generating energy. Yet, as perhaps a testament to market sentiments that offshore wind power projects present greater appeal due to lower risk of social opposition, one influential market report predicting low, central and high scenarios for installed wind energy in the EU in 2020, contends that offshore wind power will exhibit higher annual growth (%) than onshore wind power (EWEA, 2014).

The difficulties of earmarking suitable tracts of open land for onshore wind farms and the depressed rates of return for offshore wind projects have encouraged some wind project developers to search for non-traditional sites onshore. The increased tower heights of multi-megawatt wind turbines (Leung & Yang, 2012; Manwell et al., 2009) have made it possible to deploy wind farms in forested areas where land acquisition is cheaper and investment risks are lower because social opposition is expected to be lower due to increased distance to neighbors (Enevoldsen and Sovacool, 2016).

The reason why onshore wind farm development in forests merits special attention is because siting profiles differ markedly. The land use spectra for wind turbines in forested areas are different (Perks, 2010; Dai et al., 2015). Moreover, altered surface patterns cause shifts in wind profiles (Arnqvist, 2013; Dellwik et al., 2014), increasing turbulence and wind shear. Yet, from the existing literature there are indications that wind turbines deployed in forested areas are more likely to produce less electricity and have a shorter life span than other onshore wind farms (Enevoldsen, 2016). Nevertheless, studying onshore wind farms in forested areas is important because in some of the countries with high amounts of installed wind capacity, wind farms are increasingly being deployed in areas of managed forests, where owners are looking for extra income on land that cannot be used for food production (Enevoldsen, 2016).

Amidst this market flux with developments occurring within traditional onshore locations, in forested areas and in offshore sites, it merits investigating whether there any differences in development patterns. When developers are building wind farms offshore or onshore, are there notable characteristics that differentiate these projects? If so, what does this tell us about the nature of wind power development patterns? There are a number of preconceived notions. For example, a prominent assumption is that offshore wind farms will generate more energy per installed MW than onshore farms. But does this assumption hold true when one compares data from actual wind power developments? Testing the validity of these preconceptions is important because if policymakers are to design policy to support specific development strategies in a given nation, they need to be clear on what is working in the market.

This study makes use of data from actual wind farms to test four hypotheses based on preconceptions arising from a literature review. The data used for this study is based on 44 different wind farms, including 11 offshore wind farms with a total installed capacity of 3589 MW, 19 onshore wind farms located in farmland with a total installed capacity of 1395 MW and 14 wind farms located in forested areas with a total capacity of 1190 MW installed.

Research design, hypotheses and methodology

Research design

The methodology adopted for this study centers around access to data from operational wind farms. For this reason alone, this study represents an uncommon opportunity to gain insight into what is actually transpiring in the wind power market. As mentioned above, the data used in this study comes from 44 different wind farms: 11 offshore wind farms, 19 onshore wind farms located in farmland and 14 wind farms located in forested areas.

The offshore wind projects are mainly located in the European region, which is due to the fact that Europe is the continent with the most installed offshore wind power (GWEC, 2016). The onshore projects are spread all over the world and the wind projects in forested areas are mainly located in Northern Europe, as some of the leading countries in wind energy development has been forced to locate newer wind projects in such areas. There is a concern that our sample is subject to geographical bias due to the heavy representation of European wind farms; however, we contend that the global diffusion of wind power has resulted in development cost convergence, attenuating such concerns.

To make the sample of wind projects as robust as possible, no data were excluded. We used what we had accessed to. The name and exact location of the wind farms have been anonymized due to our confidentiality agreement with the data provider.

A literature study was undertaken to inform the development of four hypotheses. This involved a search of online academic databases. The search was directed through the following keywords: “Wind Energy,” “Wind”, “Onshore”, “Offshore” and “Wind Power” in combination with “Cost of energy”, ”Onshore”, “Forest”, “Offshore” and “Energy production”. The search produced an enormous amount of literature, which was further filtered to exclude irrelevant papers with little or no focus on the topic. In the end, we stopped our analysis after reading through 41 papers because these papers revealed four preconceptions related to development patterns of onshore and offshore wind farms that we felt merited analysis.

An important tenet of policymaking is that robust policy cannot be developed until the policy context and the needs of central stakeholders are well understood (Bardach, 2011). This is especially true when it comes to development policy which relies on market incentives to catalyze private sector investment. In development policy, robust policy anticipates industry needs and engenders an environment that resolves barriers to voluntary investment activity (Valentine, 2012). This study embraces the principle that understanding differences in wind farm development patterns yield insights into industry investment patterns which can influence investment activity. Simply put, by understanding how developers are currently structuring wind farm sites – both onshore and offshore – policymakers can then begin to understand what carrots, sticks or sermons are needed to achieve wind power diffusion (Bemelmans-Videc et al., 2003).

Four preconceptions and four hypotheses

Based on the literature review, we identified four preconceptions implied in the articles studied, which help to shed light on development patterns for different types of wind farms (onshore, offshore and onshore in forested areas). Verifying these preconceptions will hopefully help us to better understand wind power development patterns preferred by industry, or indeed in some cases patterns colored by policy.

The preconceptions and hypotheses are further introduced in Table 1.

Preconception 1: Stronger and more stable offshore winds enable more wind power production.

The rationale for this preconception is grounded in geophysics. First, comparatively strong coastal breezes are created by thermal variations caused by differences in rates of thermal retention between land and sea. Second, onshore winds are more turbulent than offshore winds because onshore winds are influenced by natural (i.e. mountains and forests) and manmade (i.e. buildings) barriers (Wizelius, 2007). Consequently, there is a preconception that better wind conditions offshore, enable the construction of turbines with high wind capture capacities (Bilgili et al., 2011; Troen and Petersen, 1989).

Validating this preconceived notion is important for policymakers because in many advanced wind nations, the superior wind power potential of offshore environments often provides the justification for setting higher offshore development incentives. To test this:

Hypothesis 1. Offshore wind farms will produce more energy per installed MW compared to onshore configurations.

Preconception 2: Offshore projects must be larger to offset higher investment costs.

Most comparative studies acknowledge that offshore projects are currently more expensive on a per kilowatt hour scale than onshore projects. Offshore turbine foundations are far more expensive than onshore counterparts, transmission of collected energy is more expensive due to higher cable costs and the costs of constructing turbines in a marine environment are much higher due to the specialized equipment and unstable construction environment. As a result, Perveen et al. (2014) suggest that offshore wind farms should be constructed with a capacity above 1 GW to minimize the capital expenditures per installed MW. This then suggests that offshore wind power projects will be generally larger than onshore counterparts in order to generate the added revenue to cover higher fixed costs of construction.

Validating this preconceived notion is important for policymakers because if this is true, national wind power planning initiatives should seek to identify offshore sites that will allow developers to offset these higher investment costs. To test this:

Hypothesis 2. Offshore wind farms will produce more energy in aggregate compared to onshore configurations.

Preconception 3: Capacious oceans enable optimized spacing of offshore wind turbines, yielding more homogenous energy production from the installed wind turbines.

For developers, the success of a wind farm depends on maximizing profits per km^2 of a given site. This in turn depends on three factors: i) the price at which wind power can be sold, ii) the cost of the turbines and iii) the energy that each turbine can capture. Onshore, the ever-larger wind turbine blades combined with increasing costs and competition for acquiring land have forced the wind industry to decrease spacing between wind turbines, challenging developers to find an optimal balance between maximizing the number of wind turbines while limiting energy losses from wake impediments. Research suggests that wake losses cause substantial energy losses for wind farms (Subramanian et al., 2015). In response, a range of studies have recently been examining approaches to avoid such loss (Göçmen et al., 2016; Son et al., 2014). Despite the importance of this topic, no studies have examined if spacing differences actually occur in practice for wind farm configurations. The logical preconception is that offshore wind farms will exhibit more spacing between wind turbines, due to fewer complications with land acquisition. However, work done by Paul Gipe seemingly contests this notion. Gipe (1995) argues that successful onshore wind farms attenuate NIMBY opposition through planning that emphasizes esthetic uniformity and harmonized structures. This seems to suggest that onshore wind farms might actually be planned in a more spatially effective fashion.

Validating the preconception that offshore wind turbines will exhibit greater spatial distance will potentially allow policy makers to better understand the practical spatial challenges that wind power developers face when planning wind power projects. To test this:

Table 1
Four Hypotheses on estimated versus actual operational performance from three wind farm configurations.

Preconception	Hypothesis
Stronger and more stable offshore winds enable more wind power production at offshore sites, in comparison to onshore wind farms	Offshore wind farms will produce more energy per installed MW compared to onshore configurations
Offshore projects must be larger than onshore projects to offset higher investment costs	Offshore wind farms will produce more energy in aggregate compared to onshore configurations
Capacious oceans enable increased spacing of offshore wind farms, engendering more consistent energy production for the installed wind turbines	Offshore wind farms will have more spacing between wind turbines; and therefore, record less variance in energy production from its wind turbines
Technological progress and learning effects are engendering more efficient wind farms	New wind farms will generate more energy per turbine than older wind farms

Hypothesis 3. Offshore wind farms will exhibit more spacing between wind turbines, and therefore record less variance in energy production from its wind turbines.

Preconception 4: Technological progress and learning effects are engendering more efficient wind farms.

Much has been written on the progressive technological advances being made in wind turbine technology. Between 1994 and 2013, wind turbine generation capacity increased eightfold from under 1 MW to over 8 MW (DONG Energy, 2008). To add to this, improved efficiencies through experience have had a noted effect on bringing down the cost of wind power production (Lindman and Söderholm, 2012). Yet, there is no data on how impactful these trends have been in terms of making wind farms more efficient.

Validating this preconceived notion is important for policymakers because the case for supporting wind power R&D rests largely on the capacity of such investment to enhance the economics of wind power production. Simply put, are technological enhancements and experience truly engendering better wind power developments. To test this:

Hypothesis 4. New wind farms will generate more energy per installed MW than older wind farms.

Analytical methodology

In order to process our data, the robustness of the results for the hypotheses will be tested using descriptive statistical analyses in order to test the hypotheses. The descriptive statistical analyses reveal basic measures, such as mean, median, minimum and max values, which make it possible to compare the configurations for each hypothesis. As advocated by Cohen (1988), graphs and diagrams are also used in the analysis to yield visual insights underpinning the statistics.

In comparing offshore and onshore wind power farms, a decision was made to further analyze onshore farms by delineating them into two configurations – onshore rural sites (i.e. farmlands) and onshore forested sites. This is because it is suspected that the recent trend of developing wind farms in forested areas exhibits development patterns that might be substantially different from onshore rural locations. There is a concern that in aggregating the onshore data, the new forested developments will confound the results. Therefore, we have elected to address this threat to internal validity by separating the onshore datasets.

Understanding how different variables influence the configuration of wind farms is important from both commercial and public policy perspectives. From the commercial side, smaller wind farm developers would benefit from a more informed understanding of what configurations might work best under various siting options. For policymakers, understanding how projects are currently configured in response to various siting scenarios is a critical first step to designing policy to induce targeted development. In response, we have attempted to conclude the study with an analysis of what our findings mean for policymakers.

Results and discussion

The graph in Fig. 1a presents the total number of wind farms, 44, and their annual production (MWh) per installed MW in 2015. The highest production from a wind farm was 4856 MWh per installed MW per year, and the lowest production was 1867 MWh per installed MW per year.

Fig. 1b summarizes the average wind farm size for each of the configurations studied in this article. The offshore wind farms are, on average, the largest with an average of 326 MW installed (and a median of 288 MW), far eclipsing the mean size of onshore wind farms of 70 MW (and median 43.5 MW). This reflects a global trend that sees offshore wind farm sizes continuing to outpace onshore counterparts (CarbonBrief, 2015). The wind farms deployed in forests have a mean size of 91 MW, yet, this is due to one large project of nearly 500 MW, which also is highlighted by a mean value of 36 MW. After describing the results, Discussion on findings section will highlight the more significant findings and discuss their implications.

Hypothesis 1: offshore wind farms will produce more energy per installed MW compared to onshore configurations

The first hypothesis tests a well-traveled assumption related to wind quality. We postulate that offshore wind farms will have a higher annual energy production per installed MW than onshore configurations. The rationale is that offshore wind farms are presumed to be strategically sited in locations with higher and more consistent wind quality (Archer and Jacobson, 2005; Perveen et al., 2014). Additionally, it is believed that offshore projects are typified by turbines that are separated by greater rotor distance ensuring a lower wake loss.

In undertaking our analysis, the two predominant onshore developments (onshore rural and onshore forested) have been disaggregated and compared to the offshore wind farms. When comparing onshore sites, wind projects located in farmlands are expected to record higher annual energy production per installed MW compared to the onshore wind projects in forested areas, due to the impact from the forest on the wind conditions, which in most cases would decrease the mean wind speed in the wind turbine's swept area and increase the turbulence level (Enevoldsen, 2016; Bergström et al., 2013).

The descriptive statistical analysis performed in Table 2 presents the results from the dataset, which suggests that offshore wind farms have a mean higher energy production per installed MW compared to the means from onshore wind farms and onshore wind farms in forests. The mean energy production per installed MW for offshore sites was 3234 MWh in 2015, for onshore rural sites the number was 2890 MWh, and for onshore forested sites, the production per installed MW was 2918 MWh.

However, closer analysis of Table 2 reveals that the difference might not be statistically significant. As the table indicates, offshore wind farms included in the study posted a standard deviation of 525 MWh, while onshore rural sites in the study exhibited a standard deviation of 904 MWh. The inference here is that some onshore rural sites might outperform some offshore sites by a significant margin. Therefore, the result cannot be generalized to an extent to allow us to confirm the hypothesis. Indeed, upon analysis of the data from individual wind farms included in the data set, some onshore rural were indeed producing far more power than some other onshore sites, as depicted in Fig. 2. The three projects with the highest energy production (MWh) per installed MW are onshore projects. It also merits noting that contrary to our expectations, onshore forested sites produced, on average, more energy per installed MW and exhibited far lower variance in power output.

One of the possible interpretations of the data presented in Table 2 is that the varied size of projects might skew the results because larger onshore sites might have been sited in areas of preferred wind conditions. Conversely an alternative and contradictory perspective might also be true – offshore sites are comparatively more expensive so offshore projects are not selected only on the basis of wind quality, they are also

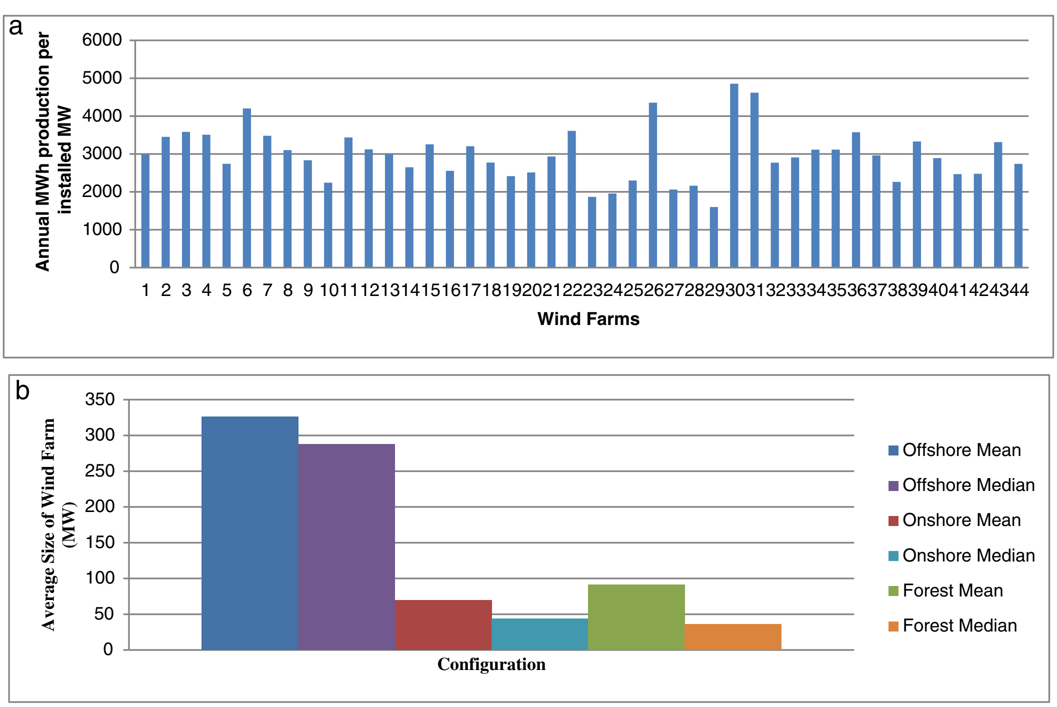

Fig. 1. a and b. The combined dataset.

Table 2
Descriptive statistical analysis of Hypothesis 1.

Offshore MWh per installed MW	
Mean	3234
Median	3437
Standard deviation	524
Minimum	2243
Maximum	4203
Onshore MWh per installed MW	
Mean	2890
Median	2712
Standard deviation	903
Minimum	1599
Maximum	4856
Onshore in forest MWh per installed MW	
Mean	2918
Median	2908
Standard deviation	378
Minimum	2264
Maximum	3576

selected according to lower siting and transmission & distribution costs. In order to test the theory that scale might influence the amount of energy produced per installed MW, we analyzed statistics to test the correlation between wind farm size and produced energy per installed MW. As the data depicted in Fig. 2, there appears to be no statistically significant relationship between wind farm size and produced energy per installed MW, amidst the wind farms included in our dataset.

The results of our analysis contradict conventional belief. The difference between energy produced by offshore and onshore turbines has previously been assumed to be up to 150% in the favor of offshore wind farms (IEA, 2008). Yet, our analysis appears to indicate that if any difference does exist, it is negligible. The reason for a smaller energy production gap might stem from the fact that service and maintenance offshore requires more downtime than for onshore wind projects, due to the challenges of transportation at sea (Koch, 2014).

Nevertheless, these findings are significant in light of a recent report from the U.S. Energy Information Administration (EIA, 2016) which predicted the 2022 levelized cost of different energy technologies. The report suggests that the average cost per produced MWh from offshore would be $196.9 – far higher than the $73.6 predicted for onshore wind energy. This suggests that offshore wind energy will be 2.67 times more expensive than onshore wind energy. Therefore, combined with the apparent risks of cost overruns and the higher installation costs, one is compelled to ask whether the extra energy production justifies the added investment. Of course, energy produced per turbine represents just part of the investment rationale for preferring offshore projects to onshore projects. Another influential factor is aggregate energy production. After all, if a wind farm produces slightly less energy per turbine but far more aggregate energy, the contribution to fixed development costs could be greater, thereby, justifying the project.

Hypothesis 2: offshore wind farms will produce more energy in aggregate compared to onshore configurations

In order to test the proposition that wind farm size is what drives offshore investment, we performed an analysis aimed at addressing the hypothesis that aggregate energy production from offshore wind farms will be greater than from the two onshore configurations. This is based on the preconception that offshore wind farms are not as spatially constrained as their onshore counterparts and offshore projects must have a larger critical mass to cover the extensive fixed costs associated with connecting offshore projects to onshore grids. Fig. 2 implies that this is the case, but we wanted to evaluate this in greater detail because confirming such a hypothesis supplements the wind quality findings of Hypothesis 1 with a finding that offshore farms are of greater scale. In short, these two findings would confirm that developers prefer larger scale offshore wind farms to offset the higher investment costs. The descriptive statistical analysis performed in Table 3 presents the results from the analysis.

The descriptive analysis in Table 3 confirms that the offshore wind farms in our dataset produce far higher aggregate energy production (MWh). The offshore wind farms produce over four times the mean aggregate production from onshore sites. Moreover, a comparison of the standard deviations associated with these three configurations suggests that aggregate wind power production associated with offshore wind farms is far more consistent than the two onshore configurations. For offshore wind farms the standard deviation is 56% of the mean; however, for onshore rural wind farms the standard deviation is a remarkable 106% of the mean and for onshore forested area wind farms the standard deviation is even higher – 140% of the mean. From this analysis, we can confidently conclude that there is strong evidence which supports our hypothesis that offshore wind farms produce more energy in aggregate that onshore wind farms do.

We wanted to test this hypothesis with added rigor and so decided to also evaluate the strength of the relationship between aggregate energy production and wind farm size. Doing so would help us attenuate any threat that differing wind quality patterns were acting as a

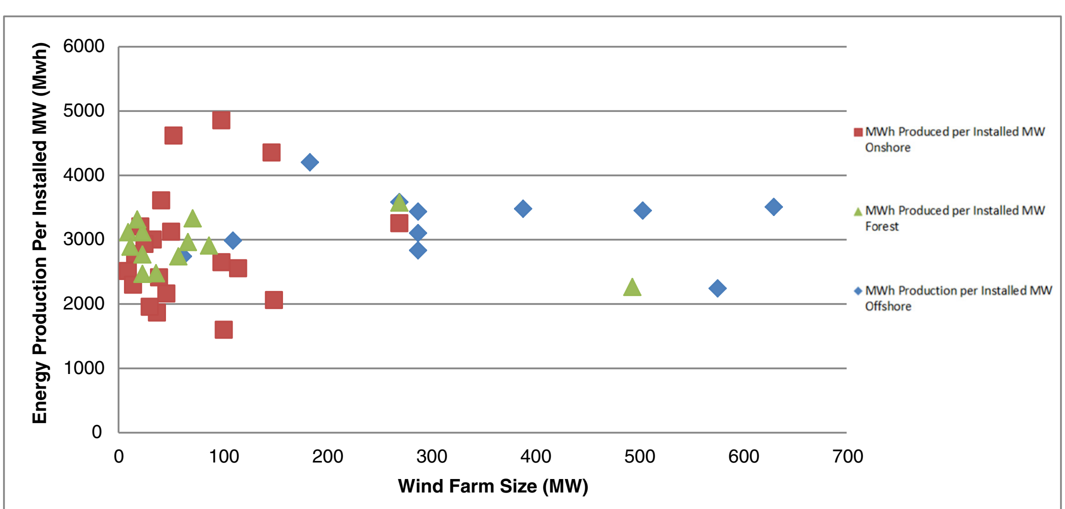

Fig. 2. Comparing annual energy production from three configurations.

Table 3
Descriptive analysis of aggregate energy production.

Offshore cumulative wind farm production (MWh)	
Mean	1,048,835
Median	967,971
Standard deviation	586,159
Minimum	169,975
Maximum	2,210,852
Onshore cumulative wind farm production (MWh)	
Mean	211,887
Median	123,788
Standard deviation	223,609
Minimum	22,614
Maximum	879,221
Onshore in forest cumulative wind farm production (MWh)	
Mean	256,386
Median	89,211
Standard deviation	358,199
Minimum	28,661
Maximum	1,118,820

confounding factor in our analysis. Fig. 3 presents the relationship between installed MW and energy production (MWh) for the 44 wind farms.

Fig. 3 reveals that a strong correlation exists between installed wind power capacity and aggregate energy production. Therefore, we feel justified in concluding that forces catalyzing the development of comparatively large offshore wind farms are not as much based on superior wind quality (refuted through Hypothesis 1) but rather is likely due to a need to recoup higher fixed investment costs associated with offshore projects.

However, the higher standard deviations associated with onshore projects outlined in Table 3 give rise to a new conundrum: Is the enhanced reliability of aggregate wind power production in offshore environments attributed to more stable wind flow patterns or does the marine environment allow for more dispersed spacing, thereby enhancing wind quality by reducing wind shear? To answer this question, we turn to hypothesis three.

Hypothesis 3: offshore wind farms will have more spacing between wind turbines, and therefore exhibit less difference in energy production from its wind turbines

The third hypothesis evaluates the preconception that offshore wind farm turbines are spatially less concentrated than onshore wind farms. Consequently, offshore turbines will be less susceptible to wake effects that degrade wind quality. In other words, this hypothesis, if true, explains in part why the standard deviation of power production for the offshore wind farms including in our dataset is lower (as a percentage of the mean output) than the standard deviation of power production for the onshore wind farms.

In order to test this hypothesis, we first needed to collect data on turbine spacing within wind farms. However, a complicating factor emerged – for all wind farms in our dataset, the spacing between turbines was not uniform. Therefore, to derive a standard measure for comparison, the median difference for the highest and lowest spacing for all the wind turbines within each wind farm was calculated. Another complicating factor was that the turbines varied by rotor diameter and this difference had the potential to confound the results because offshore wind turbines that are typically of higher installed capacity would automatically require greater spacing. In order to adjust for this factor, distance was calculated as a factor of the rotor diameter.

Fig. 4 graphically depicts the relationship between the mean energy output (MWh) per wind turbine and the mean spacing (adjusted for rotor size) for the wind turbines of the wind farms. It merits noting that due to insufficient information on the wind turbine coordinates, only 28 wind farms have been analyzed for testing this relationship. The mean spacing describes the horizontal distance between wind turbines in a wind farm measured in the wind turbine's rotor diameter.

The data presented in Table 4 verifies the first part of Hypothesis 3 - the spatial separation between offshore wind turbines is less variable but higher, when compared to the onshore configurations. Next, we turned to the question of whether or not the greater spatial spread of offshore wind turbines gives rise to more consistent power production.

Previously, we produced results of power production in Table 2. In Table 5, we have reproduced this data along with the data on wind farm spacing to get a feel for whether or not increased spacing of turbines is correlated to reduce energy production variance. As Table 5 suggests, if we were to take the average of the minimum and maximum spacing means of the wind farms, offshore turbines in our dataset can be said to exhibit greater spatial distance than either of the onshore configurations. As the power variation column indicates, energy production variation at onshore rural locations is significantly higher than the power variation at offshore farms. Therefore, there is evidence that our hypothesis might be valid when comparing onshore rural sites to offshore sites. However, when onshore forested sites are evaluated on the same metrics, it is apparent that the forested onshore sites included in our dataset actually exhibit less power variation than offshore sites, despite having turbines that are, on average, approximately 36% more concentrated in terms of spatial placement. These contradictory findings lead us to question the validity of our hypothesis and seek more definition in our statistical analysis.

When examining Table 5, it becomes clear that there is no correlation between power variation and turbine spacing.

An obvious question that should arise from the data presented in Table 5 is what causes the stark contrasts? If we tested offshore farms versus onshore rural farms only, we might conclude that greater turbine spacing does indeed contribute to attenuating energy production

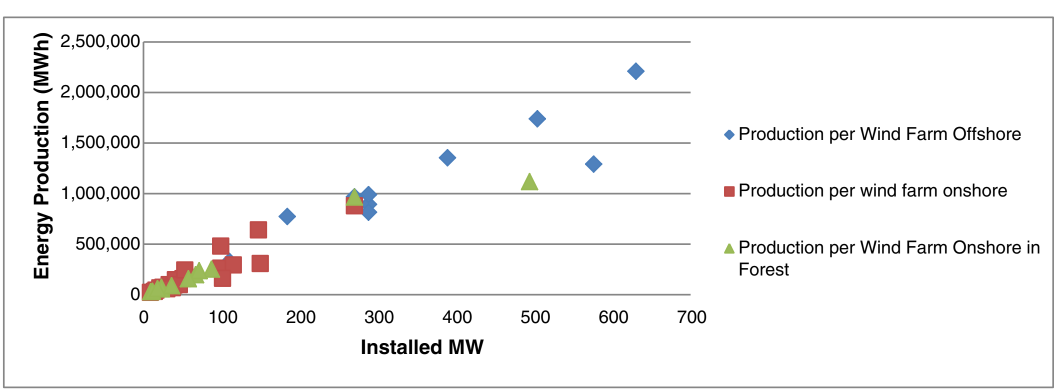

Fig. 3. The relationship between wind farm size and energy production.

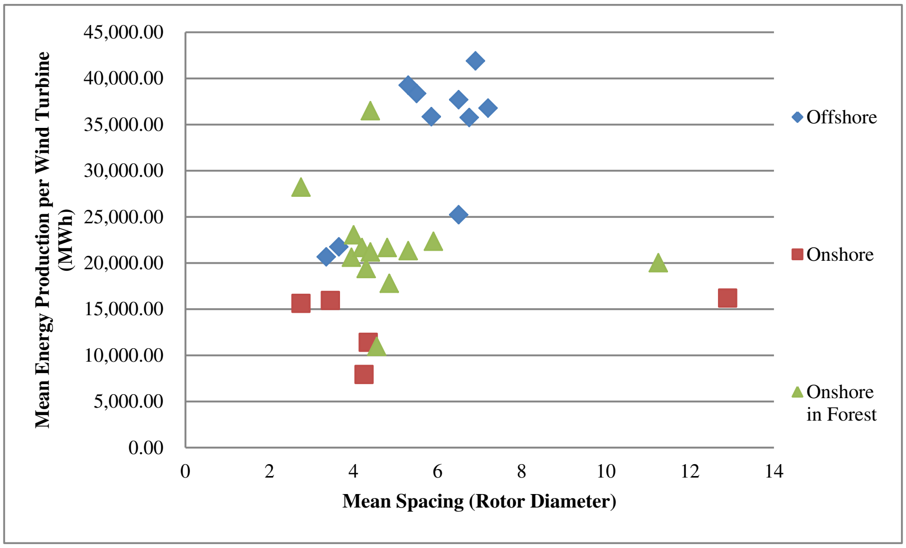

Fig. 4. The relationship between energy output (MWh) and spacing (rotor diameter).

variances. However, the onshore forested wind farm dataset contradicts this conclusion and forces us to consider why the two onshore configurations exhibit such a stark contract when it comes to power variation, despite exhibiting similar profiles when it comes to turbine spacing. Indeed, one would be tempted to conclude that the results in Table 5 for the onshore configurations contradict the popular conception that wind farms placed in forested areas suffer from poorer wind quality due to the turbulence engendered by the trees.

One possible explanation for this puzzling result is that the forested onshore wind farms are a relatively new phenomenon. Accordingly, these farms would likely be constructed using the most advanced wind power systems in preferred locations. As a result, the turbines within the wind farms in the forested areas will be more efficient at capturing better quality wind, when compared to the older turbines that one would likely find within the rural onshore wind farm locations. In explaining why the power variation in forested onshore locations is better than the power variation in offshore locations one might hypothesize that both configurations use newer and more efficient technology but the forested locations suffer from less downtime than do the turbines that are sited in marine environments. To evaluate this notion, we turn to hypothesis four.

Hypothesis 4: new wind farms will generate more energy per installed MW than older wind farms

The fourth hypothesis evaluates a preconception that is both intuitive and grounded in published literature – new wind farms will generate more energy per turbine than older wind farms will because of improved technology and learning by doing efficiencies. The arguments in support of this notion stem from the observed trend of wind turbines becoming more efficient due to increased knowledge of siting (Sahin, 2004), innovations to the control systems and generators, the increased height of the towers, and the increased size of the wind turbine blades

Table 4
Minimum and maximum turbine spacing.

	Median for minimum spacing (as a factor of rotor diameter) - meters	Median for maximum spacing (as a factor of rotor diameter) - meters
Offshore farms	5.15	6.80
Onshore farms - rural	3.3	5.4
Onshore farms - forested	3.6	5.2

(Manwell et al., 2009). According to popular consensus, these developments allow the modern wind turbine to produce more energy per installed MW than its predecessors. According to one study in 2009, a wind turbine produced in that year would generate 180 times more electricity when compared to 20 years before, at less than half the cost per produced MWh (Blanco, 2009). Compared to turbines manufactured just 25 years ago, modern turbines are four times larger. The maximum rotor diameter has increased to more than 100 m and the maximum hub height has grown to more than 70 m (Paulsen and Thüring, 2015). This change in wind power system size and know-how is considered to have increased the efficiency per installed MW, despite the fact that the generator size (MW) of the wind turbines have increased as well.

We began to test this hypothesis by conducting a statistical analysis than correlated energy production on an installed MW basis with the year that the wind farm was built. Fig. 5 graphically illustrates the distribution of the dataset, where the bubbles represent the cumulative energy production (MWh) per wind farm.

It might be apparent from the graphic depiction of the dataset in Fig. 6 that there is not a decisive trend that supports the hypothesis. Compared to the energy production from the wind farms that were established in 2007 (3000 MWh per installed MW), some turbines from subsequently sited wind farms are clearly producing more energy per installed MW, while other wind farms are less effective.

As Fig. 5 indicates, there appears to be little relationship between the year of installation and energy production from the wind farms in our dataset.

In evaluating this data, it was feared that configuration (onshore, onshore-rural, onshore-forested) might be a confounding factor. For example, if one configuration were dominant in early years and another configuration were dominant in later years, the results might be skewed due to selection bias (Cook and Campbell, 1979). Therefore, another statistical analysis was run whereby the data were segregated by configuration type. Fig. 6 provides a graphic depiction of the data. Once again, one can readily see that an upward trend that would indicate a positive innovation effect is not visually evident. To be empirically certain, we also ran a statistical analysis delineated by the three configuration types.

When separating the data based on the three configurations, it becomes clear that there might have been a slight selection bias in the data. The coefficient for offshore wind farms is negative suggesting a regression in turbine efficiency while the onshore configurations exhibited a positive correlation, suggesting improved turbine efficiency.

Table 5
Power variation vs. turbine spacing.

	Mean (MWh/installed MW)	Standard deviation (MWh)	Power variation (SD as % of Mean)	Mean of min/max spacing (as a factor of rotor diameter) - meters
Offshore farms	3234	525	16.2%	5.98
Onshore farms - rural	2891	903	31.2%	4.35
Onshore farms - forested	2918	378	13.0%	4.40

However, we cannot validate our hypothesis that newer wind farms produce energy more efficiently.

With that said, there are a couple of threats to validity that must be noted for this hypothesis test. First, we have used the year of wind farm establishment as a proxy for the age of the turbines. This might not be true as wind farm developers might not install the newest turbines. Although we contend that the global shortage of wind turbines has created market conditions whereby turbines that are manufactured go almost immediately into service, this cannot be ascertained with the data that we have; and therefore, the concern remains as a threat to construct validity. Second, it might very well be that the onshore-rural configuration is the only configuration that can be validly used to evaluate our hypothesis. This is because the offshore and onshore-rural configurations reflect relatively new siting options and the relatively low coefficients associated with these configurations might simply reflect project teething pains. In short, there has not been enough learning for a learning effect to be ascertainable. On the other hand, onshore rural wind farms are well established and mature. Therefore, these farms would be most likely to exhibit positive efficiency progress caused by learning by doing and improved technology.

Discussion on findings

The following section summarizes the results of the tests conducted for the four hypotheses. The results of examining the hypotheses have been summarized in Table 6 below and a brief discussion of the implications of these findings will follow.

The results presented in Table 6 show that only one of our hypotheses was supported by the data from our dataset. If our data is representative of the broader universe of wind farm data there are some interesting ramifications associated with these findings. However, before we turn to an analysis of the implications of our findings, it merits highlighting some of the potential threats to validity associated with our analysis.

Overall, there were a number of threats to validity that can be attributed to the study, all stemming from the unique nature of our data. In many quasi-experimental studies, threats to validity are attenuated through strategic research design. However, in this study, the analysis was entirely dependent on a dataset that was provided by the industry. We could not supplement this data with our own primary observations because of the geographic dispersal of the sites, budget constraints and site access limitations (because the sites were private property). Therefore, when it came to manipulation of the data, we tried to ensure that no data were excluded in order to avoid this form of selection bias (Cook and Campbell, 1979). Nevertheless, despite our best efforts, there are some threats to validity that simply could not be removed due to the nature of our data.

In terms of statistical conclusion validity, there were two basic concerns. First, the geographic settings of the wind farms are not homogeneous. The sites vary significantly in terms of terrain, physical impediments, surrounding environment, climactic patterns, and wind quality. Unfortunately, there was not enough data on the specific sites to avoid this threat known as *extraneous variance in experimental settings* (Cook and Campbell, 1979). Although we contend that the large number of windfarms (44) included in the dataset help to somewhat attenuate this threat, more data on the physical features of these sites would be necessary to fully alleviate this concern. Second, both within windfarms and between windfarms, the turbines that were used for generating the electricity were heterogeneous – differing in terms of nameplate power output and turbine features, such as variable gears or blade sizes. Because the technology differs, this introduces a threat to validity known as *heterogeneity of units* (Cook and Campbell, 1979). Again, it would be useful to validate the results through comparisons of wind farms employing similar turbine technology; however, in practice this is not feasible. Turbines are chosen specifically to optimize the unique characteristics of the sites. Once again, we contend that the analysis of numerous windfarms inject a degree of representative

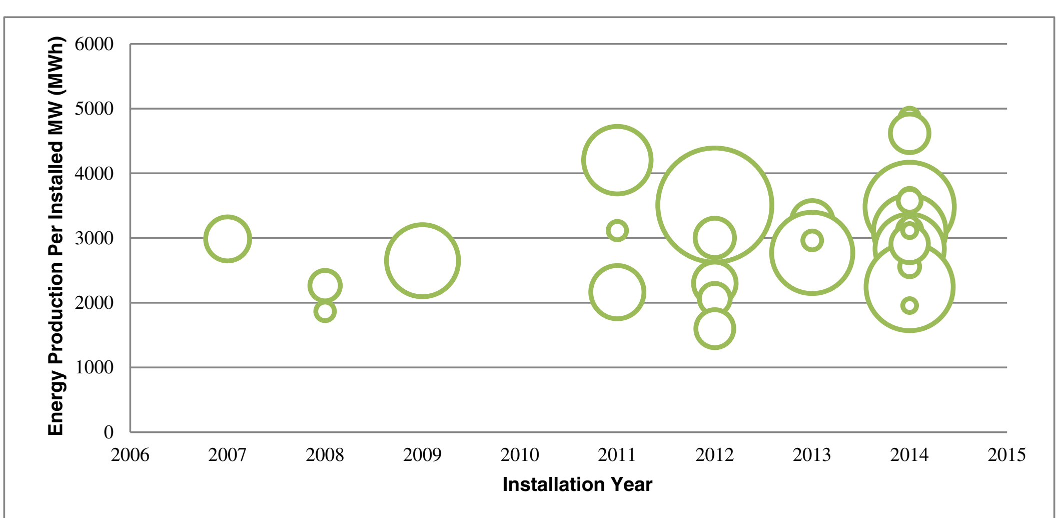

Fig. 5. The innovation effect.

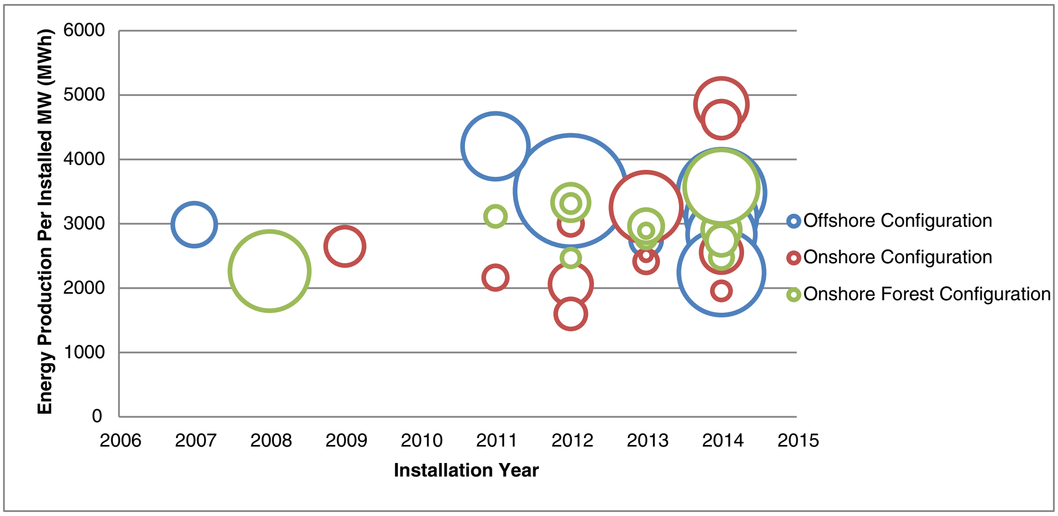

Fig. 6. Innovation effects for each configuration.

validation into the study, but the threat remains and cannot be attenuated.

In regard to internal validity, there are two main concerns. First, although the data set included turbines from all around the world, the vast majority of the wind farms from the dataset are located in Europe, injecting a degree of geographic bias into the sample. Only further testing using wind turbines from different sample sets will mitigate this threat; therefore, this represents an avenue of future research. Second, there might be an *additive threat* associated with this analysis in that wind farm developers tend to upgrade their infrastructure over time. Turbines are refurbished, new transformers are added and improvements to the maintenance schedule are made. Therefore, these phenomenon are threats to our fourth hypothesis which postulates that new wind farms will generate more energy than older wind farms on a per megawatt basis. In order to attenuate this threat, data would be needed on maintenance schedules, part replacements and infrastructure upgrades. This is data that we did not have. However since this threat applied mainly to the fourth hypothesis, and would likely be of limited impact because of the number of wind farms included in this study, we simply conclude that analyzing the technical evolution of existing wind farms represents a promising area for further research.

In terms of construct validity, there is a concern that in testing the fourth hypostasis that our decision to use the age of the wind farms as a proxy for the age of the turbines on the wind farm will not be accurate. Older wind turbines might be purchased from suppliers or, as mentioned in the previous paragraph, existing turbines might be upgraded over time. These factors would skew our results and invalidate the proxy. In order to attenuate this threat to construct validity, we would need more detailed information on when each turbine was manufactured. This is information that we did not have and so we have absorbed some risk in our construct strategy. The fourth hypothesis was not supported. However, if the hypothesis was not supported because older wind farms were upgraded with newer turbines, then the results of our analysis have been confounded. Once again, this concern can be vetted in the future through follow-up studies using the manufacture date of turbines, if available.

Regardless of these extant threats to validity, we contend that this study still exhibits a high degree of predictive validity, particularly in regard to the first three hypotheses which would not be significantly impacted by any of these threats to validity because the relatively large sample size of wind farms would help to dampen any confounding threats. This study is the first of its kind and employs proprietary data in order to undertake the analysis. It is a unique situation where, as researchers, we do not have full control over our data collection strategy.

Table 6
Summarizing hypotheses results.

Hypothesis	Tested by	Hypothesis supported/ unsupported	Effect
Offshore wind farms will produce more energy per installed MW compared to onshore configurations.	Descriptive statistics analysis	Unsupported	The analyses revealed very low coefficients of determination, suggesting that the correlation between energy produced on a per MW basis and site configuration is not supported by the data.
Offshore wind farms will produce more energy in aggregate compared to onshore configurations.	Analyses of variance Descriptive statistics analysis	Supported	The preconception was validated, as offshore wind farms in the dataset produced far more energy than its onshore counterparts. The descriptive statistics analysis revealed that offshore wind farms are generally larger, which is the main catalyst behind greater energy production.
Offshore wind farms will have more spacing between wind turbines, and therefore less difference in energy production from its wind turbines.	Analyses of variance Descriptive statistics analysis	Unsupported with an exception	The precondition was not supported. Although offshore wind farm turbines did exhibit greater spacing between units, this did not translate into diminished power variation when compared to the onshore forested sites. There was however loose support for the claim that offshore wind turbine exhibit greater spacing and lower power variance than onshore rural turbines.
New wind farms will generate more energy per turbine than older wind farms.	Analyses of variance Descriptive statistics analysis	Unsupported	This preconception was also not supported by the data. The statistical analyses indicated that the correlation between turbine power generation and turbine age was not strong. Indeed, a negative trend was ascribed to offshore turbines.

Therefore, there are bound to be threats to statistical conclusion, internal and construct validity. Over time, as more data are made available to researchers, these findings can be supplemented and verified to a higher degree of certainty.

With these threats to validity in mind, we feel that we can now turn to a discussion of the findings that we feel represents externally valid conclusions.

The realities of offshore wind farm power production

Contrary to popular belief, our data set suggest that enhanced wind quality - commonly attributed to offshore wind farms - does not necessarily translate into improved power production per MW of installed capacity. This is a remarkable finding because the power of wind is proportional to the cube of the wind speed (Wizelius, 2007); and it has widely been assumed that offshore winds are both stronger and more consistent. Consequently, turbines at offshore wind power sites should produce significantly more energy on an installed megawatt basis.

In order to find out why this is the case, further research is needed. We posit that there are four possibilities that might explain why offshore wind power does not live up to its billing as a vastly superior wind force. First, although it is true that offshore winds might be less turbulent due to the absence of geographic figures that might cause additional wind drag, this difference might not make much of a difference with the modern variable gear turbines. Second, the strength of offshore winds tends to be heavily influenced by sea and land breezes caused by thermal retention variances between the ocean and bodies of land. Therefore, although offshore wind speeds might be higher than onshore wind speeds at times during the day, they might not be vastly superior over the duration of the day, and as a result, the impact might be negligible. Third, due to operating in a harsher marine environment, offshore wind turbines might experience more downtime than their onshore counterparts, and as a result, each turbine might produce less energy over the course of a year.

Regardless of the cause of this outcome, it is clear that given the higher construction costs associated with offshore wind farms, developers cannot count on preferred wind conditions to enhance the economic attractiveness of their offshore development projects. Instead, developers need to focus on offsetting the higher construction costs through larger wind farms. Indeed, our data set supports this conclusion. Although offshore wind farm turbines did not produce more energy on a per megawatt basis, the offshore wind farms produced far more energy in aggregate simply because they were so much bigger than their onshore counterparts.

There's a lesson here for policymakers as well. Since developers require larger tracts of offshore seabed to their investment, policymakers should be aware of the implications in regard to managing public acceptance of these types of projects. It may very well be that certain sites, where esthetic concerns are less of an issue, might need to be prioritized in order to avoid levels of public opposition that might derail project development.

The promise of onshore wind farms in forested areas

On the one hand, our data set confirms the preconception that the unfettered capacious seabed means that offshore wind sites allow developers to increase spacing between the turbines. On the other hand, this does not translate into less power production variance, when compared to onshore wind farms in forest areas. This is a remarkable finding because it suggests that offshore wind farms might not be the only attractive option for increasing installed wind power capacity without engendering public opposition. Our data set suggests that onshore wind farms can be developed in a more concentrated manner and still produce a more consistent power output portfolio than offshore wind farms.

We consider it to be remarkable that onshore wind farms in forest areas, which are subject to large scale wake effects due to the physical disruption that the forest has on wind patterns, exhibit such high levels of consistency when comparing minimum and maximum energy generation profiles. Therefore, our finding gives rise to questions on: i) current assumptions related to large-scale wake effects (for offshore wind farms, enhanced spacing between turbines does not appear to significantly enhance power output) and ii) current assumptions related to the impact that trees have on wind effects. Indeed, in regard to the latter question, we wonder if it is not possible that, like mountain ranges, some forest formations actually force winds upward, thereby enhancing wind conditions at higher altitudes, which can be captured due to the increased hub heights for wind turbines installed in forests. More research is required in this regard but our initial finding clearly suggests that onshore wind farms in forested areas represent the best of both worlds, attractive wind conditions without the high costs of developing wind farms in marine environments.

New is not necessarily better

When wind energy experts talk about the future promise of wind power, they're quick to point out that each successive generation of wind turbine is capable of capturing far more energy than older models are. Since energy capture is directly influenced by the windswept area of the turbine, it is difficult to argue against this assertion. However, the findings from our research suggest that these benefits might not be immediately realizable when it comes to the adoption of new technology. Our data set suggested that new wind farms do not necessarily generate more energy on a per installed megawatt basis.

There are a few factors that we can speculate on as the cause for this. The first is our previously mentioned concern that the proxy we used to define the age of a turbine (which was the establishment date of the wind farm) might not be accurate. It may very well be that turbines on older windfarms have been upgraded and this would confound our estimate of age. Another potential causal factor is that newer models do not enjoy the same level of field-tested reliability that the older models enjoy. As a consequence, newer models break down more often and this added downtime reduces aggregate annual output per turbine. Finally, another potentially confounding factor in regard to our finding here is that older wind farms are typically established at sites that are most preferred when it comes to wind quality. As these older sites become saturated, developers start to move to other sites that might not necessarily be as attractive. This has been demonstrated in Taiwan (Valentine, 2010). Clearly further research is merited in order to try to understand further why turbines that on paper should generate more energy per installed megawatt do not achieve this level of performance in real life.

Conclusion and policy implications

This research has examined three wind farm configurations, (1) Offshore, (2) Onshore in rural areas, and (3) Onshore in forests, in order to gain developmental insights into energy productivity. Four preconceptions and hypotheses were constructed based on previous contributions from scholars and industrial reports, and analyzed using a dataset consisting of 44 farms, all with operational data for 2015. By doing so, this research reveals not only the latest trends in the wind industry but also yields information on challenges and opportunities for future installations of wind farms. Although our conclusions face some threats to internal and external validity due to the nature of the proprietary dataset that we were working with, the statistical evidence from such a large dataset suggests that further studies will likely validate our findings.

In closing, it is clear that the answer to our research question – “Do onshore and offshore wind power development patterns differ” – is a resounding yes. Offshore wind farms are characterized by turbines that are more widely spaced and they are much larger entities – generating far more power in aggregate than onshore counterparts. However, this appears to be motivated by a desire on the part of developers to offset higher offshore wind farm costs through larger farms. This does not mean that the wind quality is actually better.

Indeed, the most significant finding was the evidence from the dataset that offshore wind power is not as superior as perhaps it has been billed. There is evidence that onshore wind farms constructed in forested areas might be a preferred alternative when the higher costs of offshore wind power are factored in. Clearly, the performance of onshore wind farms in forested areas merits closer study.

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