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Technology effects in repowering wind turbines

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Abstract

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

KEYWORDS

dismantling, innovation, repowering, technological progress, wind energy

1 | INTRODUCTION

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

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

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Repowering a wind farm implies dismantling the existing wind turbines and installing new turbines of a larger size with new technology⁷ at or near the positions of the old turbines. Although repowering can apply (but has not been done so to date) to offshore wind farms, in this research, we focus on the experience of repowering onshore wind facilities.

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

Throughout the paper, the following definitions will apply:

- **Repowering:** the process of replacing existing wind turbines with new turbines, which either have a larger nameplate capacity or more efficiency, resulting in a net increase of power generation (according to del Rio et al⁸).
- **Dismantled:** refers to any turbine that has been decommissioned; **removed** refers to turbines that were decommissioned and dismantled in the context of a repowering project; and **new** refers to the replacing of turbines.
- **Repowering year:** the year the new turbine was commissioned.

2 | BACKGROUND—REPOWERING WIND TURBINES

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

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

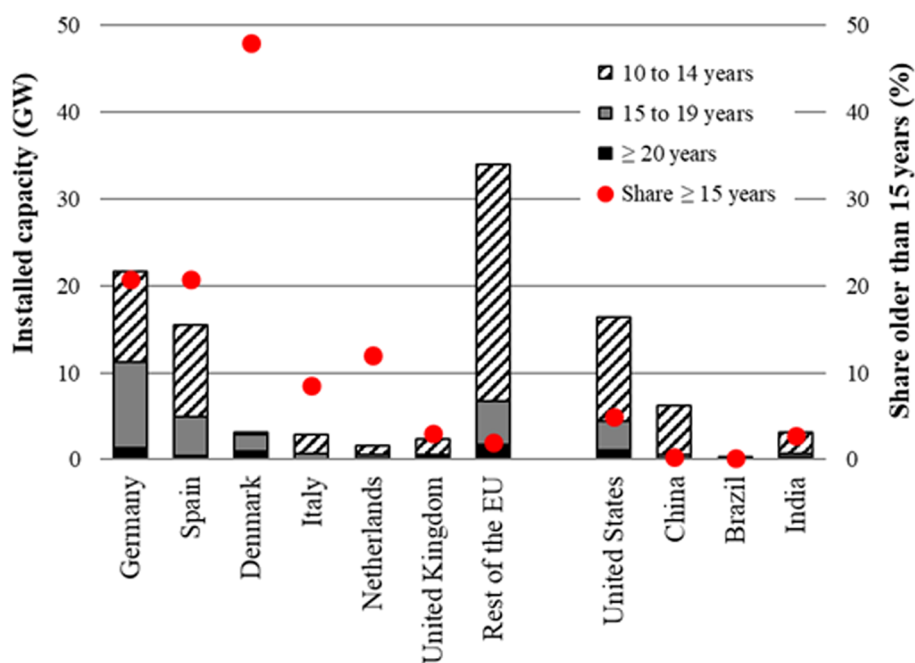


FIGURE 1 Age distribution of wind fleet in selected countries. Sources: Global Wind Statistics,²⁹ Wind in Power 2017,³⁰ and JRC Wind Energy Database³¹ [Colour figure can be viewed at wileyonlinelibrary.com]

Repowering of wind turbines also offers advantages for the whole electricity system⁸ and the society at large. In general, repowering will lead to a reduction of reactive power consumption and voltage variations.¹⁸ Turbines have evolved to better support the grid by adding increasingly complex features, such as low-voltage ride-through. Further, new turbines have lower rotational speeds with reduced noise emissions.²⁰ Bigger rotors and slower rotational speeds provide a less visually intrusive and more pleasant view than fast-rotating turbines.²¹

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

A significant portion of the installed European Union (EU) wind fleet will come to the end of its lifetime between 2020 and 2030.²⁸ Approximately, 3.3 GW of the wind turbines installed in the EU by the end of 2017 were 20 years and older. This group, along with the approximately 18 GW of turbines between 15 and 19 years old are the obvious candidates for repowering (Figure 1). Notwithstanding this, there are cases where younger turbines can be suited for repowering, and this would include some of the 33 GW of turbines between 10 and 14 years old. The largest markets for repowering in the EU are Germany, Denmark, Spain, and Italy. The repowering market is also large in the United States and India, with about 1.1 and 0.3 GW of wind turbines being 20 years and older.

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

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

So far, the technological effects, efficiency gains, and performance improvements of actual repowering projects have not been researched in a detailed manner. Some evidence is available from theoretical studies.^{1,10,34} Some case studies have been performed on an individual wind farm basis (see, eg, Castro-Santos et al³⁴ and Villena-Ruiz et al²⁰ for actual repowering wind farms in Spain), then the focus has been economic or techno-economic, rather than technological. Also, at a national level, the focus of the assessment or modelling of repowering has been from an economic (eg, de Simón-Martín et al,²⁷) or techno-economic (eg, Serri et al.,¹⁷) perspective.

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

3 | METHODOLOGY AND DATA USED

3.1 | Methodology

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

TABLE 1 Historical account of repowering in Germany

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

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

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

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

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

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

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

3.2 | Data sources and data availability

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

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

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

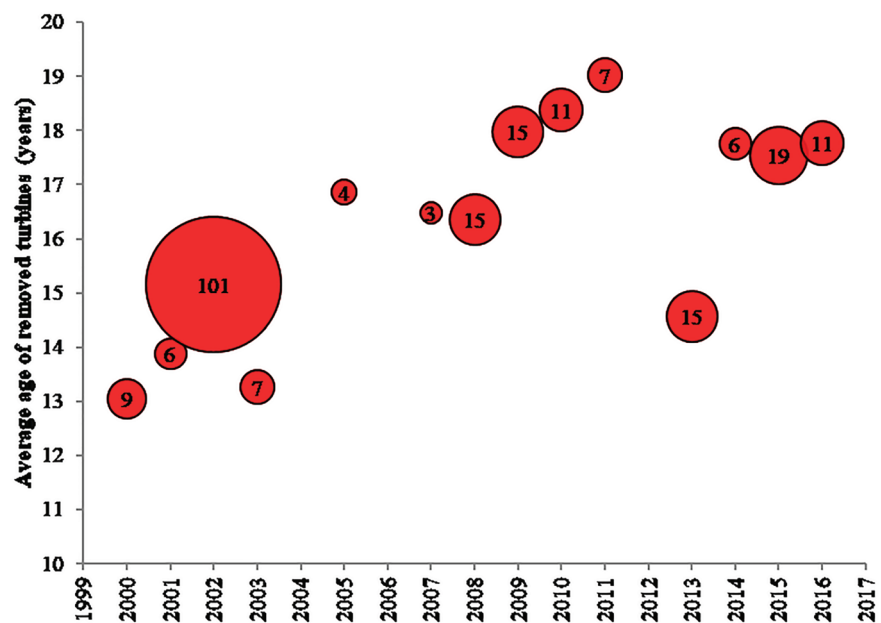


FIGURE 2 Evolution of the age of Danish removed turbines in this analysis. Size of bubble indicates number of wind turbines [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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

4 | RESULTS

In Denmark, three “waves” of repowering can be identified from the data: 2000 to 2003 (123 data points), 2008 to 2011 (48 data points), and 2013 to 2016 (51 data points). The first wave is broadly consistent with the first incentive programme for repowering—April 2001 to December 2003.³⁸ The second wave comes roughly at the end and after the second incentive programme (2005–2009). The third wave does not correspond to any incentive programme. The overall pattern of dismantled turbines is consistent with these waves, with a total of 1569, 727 and 467 turbines were dismantled during those periods. In particular, the number of data points is low in 2005, 2007, and 2012, whereas no repowering project was captured by the model in 2004 and 2005.

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

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

4.1 | Technological changes

4.1.1 | Power rating

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

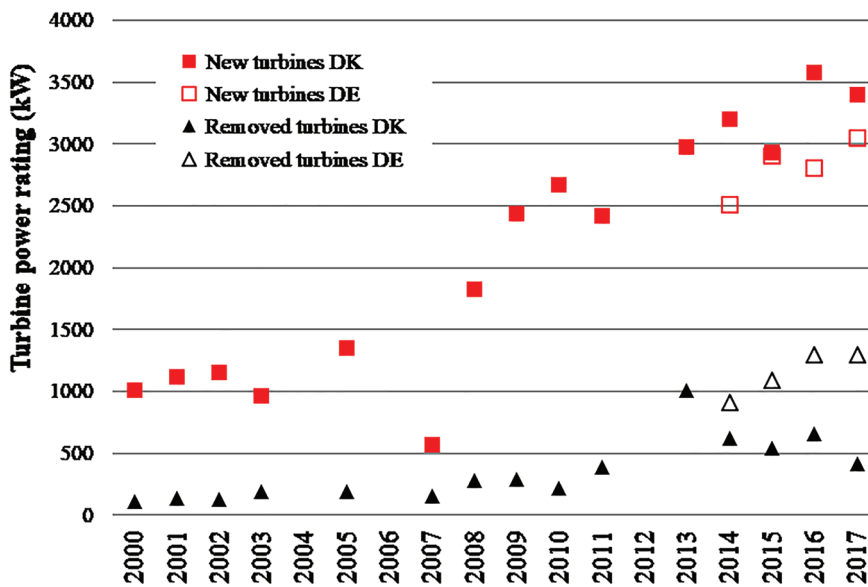


FIGURE 3 Evolution of the average power rating of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

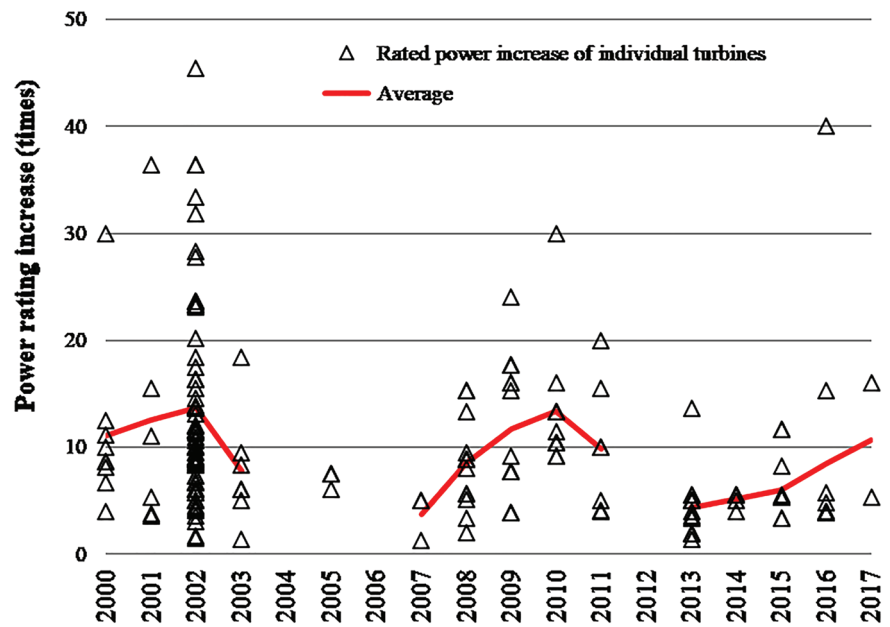


FIGURE 4 Power rating increase (times) between new and removed turbines in Denmark [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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

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

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

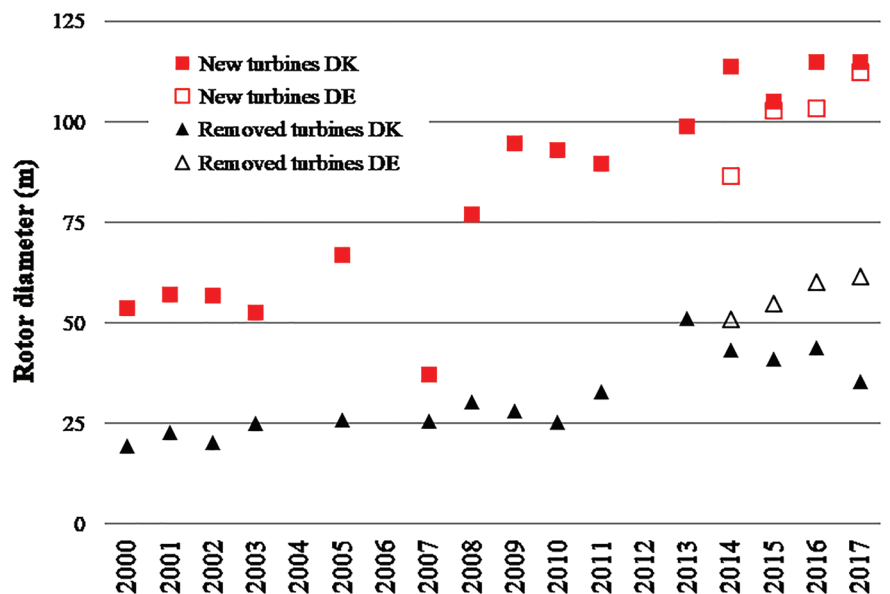


FIGURE 5 Evolution of the average rotor diameter of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

4.1.2 | Rotor diameter

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

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

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

4.1.3 | Hub height

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

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

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

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

4.1.4 | Specific power

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

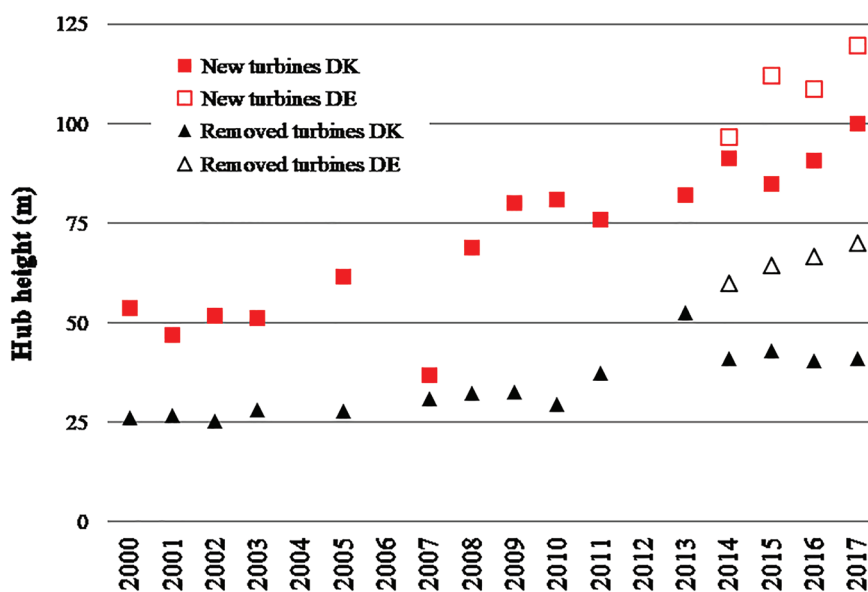


FIGURE 6 Evolution of the average hub height of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

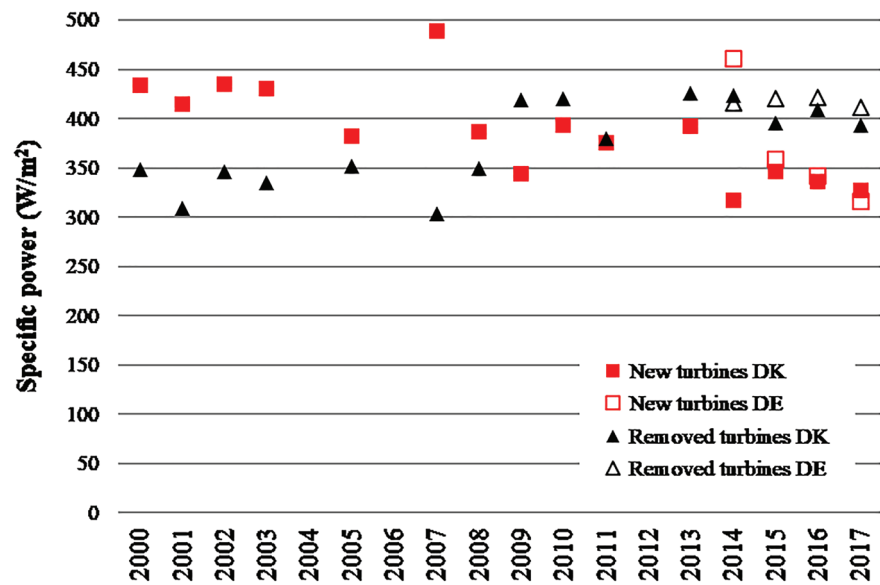


FIGURE 7 Evolution of the average specific power of new and removed turbines [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

At the beginning and throughout the first wave, new turbines had significantly higher specific power than the old turbines they replaced; 434 vs 344 W/m² in Denmark (Figure 7). This increase can be considered counterintuitive as it would reduce profile value. The reason can be traced back to the support mechanism in Denmark, which, by making remuneration based on a total amount of full load hours (22 000),⁴⁰ indirectly promoted turbines with high specific power compared, eg, with a support mechanism based on a number of years of production. Reinforcing this Danish feature, another database of 3606 wind turbines or wind farms commissioned in Europe during the period from 2001 to 2006, which is based mostly on the database provided by GlobalData,⁴¹ shows that Danish turbines had an average specific factor of 420 W/m² compared with 396 W/m² in Germany and 378 W/m² in Spain, the two big markets of the time.

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

During the second wave, both new and old turbines had similar specific power, albeit the former already below the latter: 373 vs 392 W/m². During the third wave, the situation reversed, with new turbines having significantly lower specific power: 354 vs 411 W/m². This reversal can be linked both to technological evolution—the average specific power of a wind turbine has been decreasing with time,⁴² and because of changes in 2014 to the Danish support scheme, which incentivised lower specific power turbines.⁴³

Interestingly, in Germany, average specific power was between 411 and 422 W/m² for removed turbines and 461 and 316 W/m² for new turbines in 2014 to 2017, revealing a clear downward trend that increased the profile value of new turbines.

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

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

4.2 | Electricity production

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

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

4.2.1 | Absolute annual energy production and increase

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

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

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

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

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

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

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

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

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

4.2.2 | Specific annual electricity production

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

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

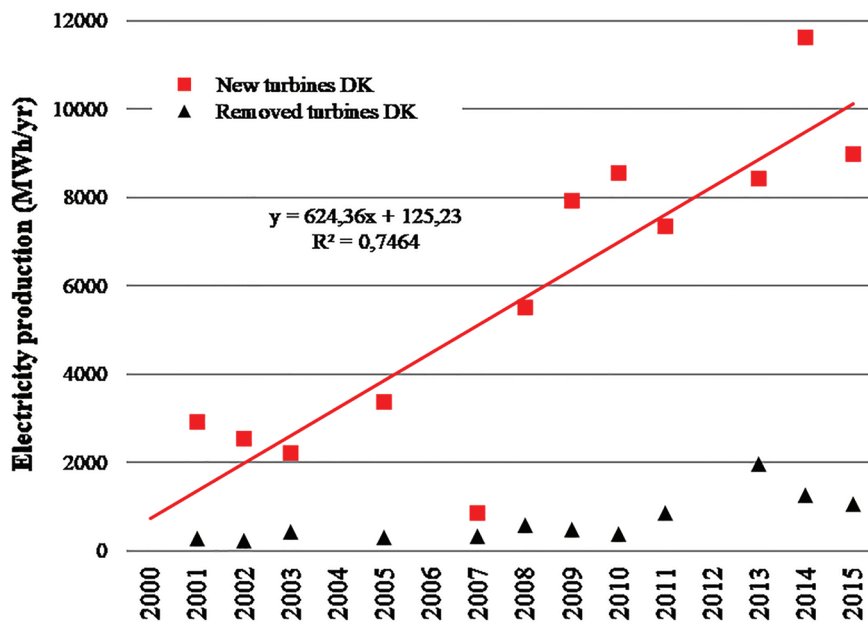


FIGURE 8 Evolution of the average annual electricity production of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

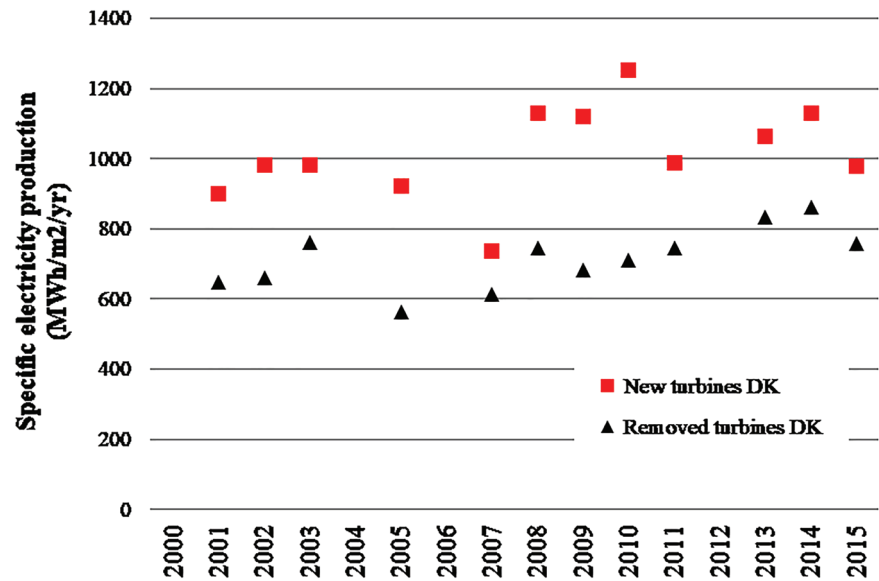


FIGURE 9 Evolution of the average annual specific electricity production of new and removed turbines [Colour figure can be viewed at wileyonlinelibrary.com]

With no data after 2015, it is not possible to define whether the 2015 effect is short or long term. On average, specific electricity production increased by 320 kWh/m²/yr—a 45% increase—from 702 to 1021 kWh/m²/yr.

4.2.3 | Capacity factor

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

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

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

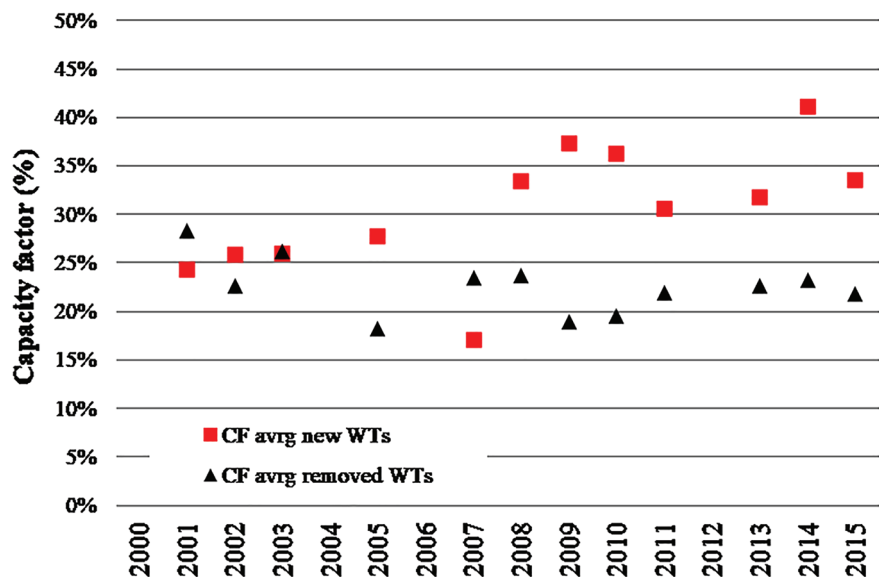


FIGURE 10 Capacity factors of old and new turbines [Colour figure can be viewed at wileyonlinelibrary.com]

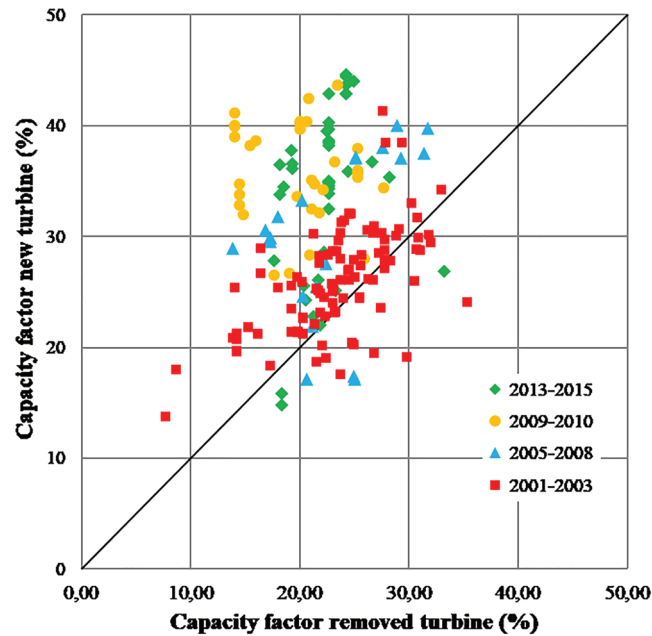


FIGURE 11 Capacity factors of new and removed turbines (colour indicates year of repowering) [Colour figure can be viewed at wileyonlinelibrary.com]

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

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

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

TABLE 2 Results of the regression analysis

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

4.2.4 | Regression analysis

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

Regression analysis has been applied in the energy field, eg, by Lee and Yang,⁴⁵ Fumo and Rafe Biswas,⁴⁶ and Ma et al.⁴⁷ In the wind energy field, Arias-Rosales and Osorio-Gómez⁴⁸ have applied regression analysis to wind turbines based on estimates of the cost of energy.

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

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

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

ΔTR = Change in turbine rating (MW)

ΔHH = Change in hub height (m)

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

YR = Repowering year.

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

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

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

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

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

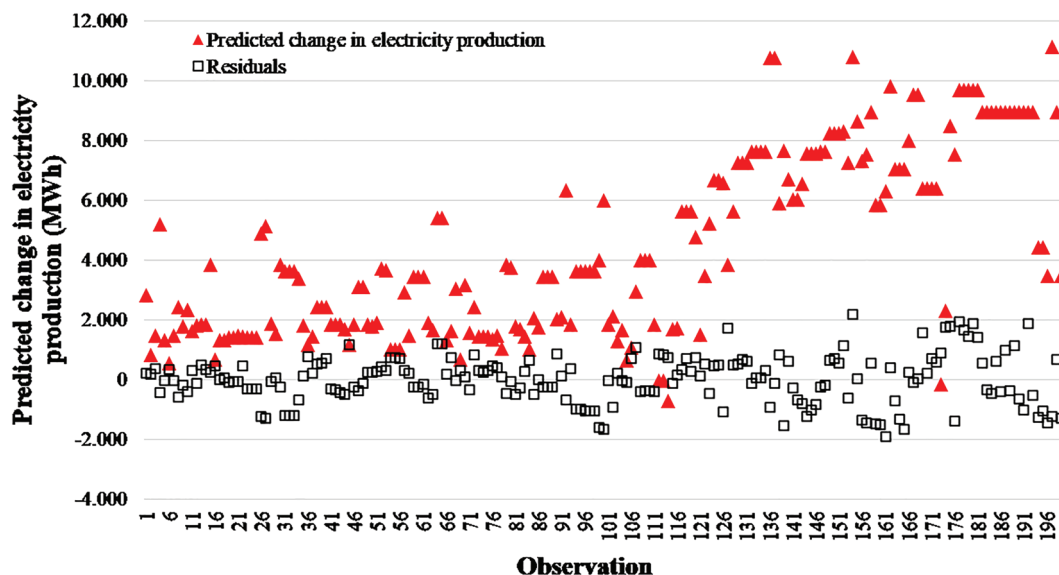


FIGURE 12 Probability plot: predicted change in electricity production and residuals of the regression [Colour figure can be viewed at wileyonlinelibrary.com]

Note that the ratio between turbine rating and swept area is very important: it is used by turbine manufacturers to design products better suited for local wind conditions. For example, Siemens Gamesa currently offers two different rotor diameters (155 and 170 m) for their 5.8-MW wind turbine, and two different rated powers (3.4 and 4.5 MW) for their 132-m rotor diameter turbine.⁵⁰ Because of this reason, we carried out further analyses: the swept area (SA, m²) was tried instead of specific power (W/m²) in the regression analysis. Somehow, although R² reached 95%, the results showed a VIF value of 7.83 for both statistically significant variables ΔTR and SA, indicating a possible problem of multicollinearity.

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

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

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

The coefficients can be explained as follows:

- for each increase of turbine rating by 1 kW, annual electricity production increases by 3.22 MWh.
- For each decrease in specific power by 1 W/m², annual electricity production increases by 8.62 MWh.

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

5 | CONCLUSIONS

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

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

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

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

Also, the study shows that specific energy production (per m² swept area) has increased in 99% of the cases. On average, specific electricity production increased by 320 kWh/m²/yr.

A regression analysis was performed to assess the impact of the underlying changes in technology on energy output. It showed that the increase in energy production was directly related to the increase in turbine rating and the decrease in specific power of the new turbines. On average, every additional kilowatt of rated power added 3.22 MWh to the annual energy production, and each W/m² of lower specific power increased annual electricity production by 8.62 MWh.

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

at the end of their life. A further research question would also be to analyse the financial aspects of repowering, for example, was the repowering performed at the optimal time from a cost perspective?

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

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