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How does wind farm performance decline with age?☆

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ABSTRACT

Ageing is a fact of life. Just as with conventional forms of power generation, the energy produced by a wind farm gradually decreases over its lifetime, perhaps due to falling availability, aerodynamic performance or conversion efficiency. Understanding these factors is however complicated by the highly variable availability of the wind.

This paper reveals the rate of ageing of a national fleet of wind turbines using free public data for the actual and theoretical ideal load factors from the UK's 282 wind farms. Actual load factors are recorded monthly for the period of 2002–2012, covering 1686 farm-years of operation. Ideal load factors are derived from a high resolution wind resource assessment made using NASA data to estimate the hourly wind speed at the location and hub height of each wind farm, accounting for the particular models of turbine installed.

By accounting for individual site conditions we confirm that load factors do decline with age, at a similar rate to other rotating machinery. Wind turbines are found to lose 1.6 ± 0.2% of their output per year, with average load factors declining from 28.5% when new to 21% at age 19. This trend is consistent for different generations of turbine design and individual wind farms. This level of degradation reduces a wind farm's output by 12% over a twenty year lifetime, increasing the levelised cost of electricity by 9%.
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1. Introduction

Ageing is a fact of life. Its effects are inevitable for all kinds of machinery, reducing the efficiency, output and availability of steam and gas turbines, solar PV modules, batteries and automobiles alike. Previous work on wind turbines has considered the reliability of individual components and the effect of ageing on availability, but any impact on the energy production of turbines or farms has not been widely reported.

If load factors (also known as capacity factors) decrease significantly with age, wind farms will produce a lower cumulative lifetime output, increasing the levelised cost of electricity from the plants. If the rate of degradation were too great, it could become worthwhile to prematurely replace the turbines with new models, implying that the economic life of the turbine was shorter than its technical life, further increasing its cost.

This could have significant policy implications for the desirability of investing in wind power, as argued in a recent report by Hughes for the Renewable Energy Foundation (REF) [1]. That report suggested that the load factors of wind farms in the UK have declined by 5–13% per year, normalising for month-by-month variations in wind speeds. These findings could represent a significant hurdle for the wind industry, but they require replication.

Several factors can confound the relationship between age and observed output in a fleet of wind farms, given that a turbine's output is dependent on wind speeds at its site and the efficiency with which it captures the energy in that wind. For example, if wind speeds have fallen slightly over time, farms would have lower load factors in recent months, when they were at their oldest, giving a spurious correlation between age and poor performance. If improvements in design increase a turbine's output relative to capacity (its power coefficient) then newer turbines (of the improved design) will have higher load factors than old turbines, so that turbine output appears to decline with age, when really it improves with newer generations. On the other hand, if the best (windiest) sites were occupied first, then old farms could have higher load factors than new ones built on inferior sites, so that turbines would appear to improve with age.

This paper uses public domain data to infer the hour-by-hour wind speeds at the site of every wind farm in the UK, and the power curve for each farm's model of turbine to estimate the output that they would ideally produce. This technique corrects for the

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confounding factors (wind patterns, turbine model and site quality), and validates well for farms that report their half-hourly output to National Grid. Simulated ideal outputs are compared with actual monthly load factors from a large portion of the UK's fleet over the last decade (282 wind farms, 4.5 GW, 53 TWh), yielding the normalised performance of each wind farm accounting for its wind resource availability, and a set of weather-corrected load factors which reveal the effects of ageing. We measure the level of age-related degradation at the national level, accounting for the vintage of turbine and local site conditions at each wind farm. We test different generations of technology and individual wind farms to confirm that specific units experienced similar declines in performance. We find the ageing effect to be present, but much smaller than predicted by Hughes, in line with experience of other rotating machinery. The specific causes of this performance loss and their relative contribution are not considered in this paper, although an overview of potential reasons is given in the discussion and conclusions.

Due to the amount of data and processing required for this study we provide online supplementary material which documents our sources and their validation in greater depth, along with downloadable datasets of UK wind farms and their energy output histories.

2. Previous studies

All machinery experiences an unrecoverable loss in performance over time. Gas turbine efficiency suffers an unrecoverable decline of 0.3–0.6% per year despite regular washing and component replacement, or by 0.75–2.25% without [2]. Similarly, the output of solar photovoltaic panels declines by 0.5% per year on average [3]. This loss in performance is not routinely accounted for in studies of the levelised cost of electricity (LCOE) of wind power. Recent studies by Mott MacDonald, Parsons Brinckerhoff and Arup accounted for the efficiency of conventional plants falling by 0.15–0.55% per year, but omitted any such factor for wind turbines [4–6].

Previous studies of wind turbines have focussed on availability and reliability [7–9]. There appear to be no long term fleet-level studies into loss of output from wind farms in open literature. Regardless of technology, quantifying performance degradation is difficult because consistent and validated field data is hard to obtain [2]. The recent study by Hughes [1] is therefore significant, in that we believe it is the first to attempt to estimate the rate of decline in wind farm load factors on a national scale.

Hughes analysed over 10 years of operating data from the British and Danish fleets of turbines, finding rates of performance degradation that are much higher than for other technologies, and which vary remarkably between the UK and Denmark, and between onshore and offshore turbines. This was based on econometric analysis of monthly load factors, using a regression which corrected for the quality of each wind farm's location, the monthly variation in national wind conditions, and the age of each farm. Hughes argues (and shows mathematically) that accounting for monthly wind conditions with a set of 'fixed effects' determined by the regression is econometrically superior to using a measure of average wind speeds across the country, since site-specific conditions differ from the national average and the output of wind turbines depends non-linearly on the wind speed at every moment in time, which is very poorly captured by its average over a month.

We therefore use wind speed data with high temporal and spatial resolution, and measure the performance of wind farms by estimating their theoretical potential output over the course of a month and comparing this with the actual reported load factors. While we believe we are the first researchers to assess wind farm performance with this kind of *ex-post* data, a number of papers present techniques to estimate output levels from time series of wind data.

Many studies have used hourly wind speed data recorded by met masts; for example investigations into wind variability by Pöyry [10] and SKM [11], and estimates of future national output by Green et al. [12,13] and Sturt and Strbac [14]. Hourly met mast speeds have been directly compared to metered wind farm load factors in Northern Spain [15] and Scotland [16], showing that accurate estimates can be made for monthly energy generation, but not for hourly power outputs.

More recent studies use reanalyses as a source of wind speed data: atmospheric boundary layer models which process physical observations from met masts and other sources into a coherent and spatially complete dataset, and are widely used to produce wind atlases. Kiss et al. [17] were first to compare the European ERA-40 reanalysis to nacelle measurements of wind speed and power output at two turbines in Hungary, finding "surprisingly good" agreement. Hawkins et al. [18] were able to replicate UK monthly load factors using a custom reanalysis model, while Kubik et al. [19] compared the global NASA reanalysis to half-hourly farm output in Northern Ireland, finding it to be more accurate than met mast data. The first practical application appears to have been made by Ofgem to estimate the equivalent firm capacity of the UK's wind fleet during winter peaks in demand [20]. Both Hawkins and Ofgem noted that the reanalysis outputs need to be scaled down by a constant factor (29% and 20% respectively) in order to match actual production in the UK, a finding which we elaborate upon in this paper.

3. Data sources

Predicting a given wind farm's output is far from being a new science: on-site monitoring of conditions using wind turbine SCADA systems is commonplace; and software tools such as WaSP or consultancies such as GL Garrad Hassan are widely used in the field. Data is not made publicly available, and these services come at a price of several thousand Euros.

On the other hand, national average data cannot reveal what is happening at individual wind farms. We therefore employ farm-specific data for output and site-specific data for wind speeds, taken from free and publicly accessible datasets. The primary data used in our main analysis are described in this section, and additional data used for validation are described in Section 4. Further information on our data is given in the Supplementary Material.

3.1. Ofgem/REF output data

All wind farms enrolled in the UK government's incentive scheme, the Renewables Obligation, publish their monthly outputs (in MWh) in the Ofgem Renewables and CHP Register.[1] Hughes extracted and cleaned this data, cross-linking outputs with details about each wind farm (its capacity and date of commissioning), and ensured that each wind farm contained only the same model and vintage of turbine [1]. This cleaned dataset was published on the internet by the Renewable Energy Foundation (REF) [21]. We are very grateful to Prof. Hughes and the REF for making this rich data source available to the community.

We further validated this dataset, corrected the commissioning date for 15 wind farms (which were incorrectly reported by Ofgem), integrated further meta-data for each farm (the geographical location, wind turbine model and hub height), and extended the time-series by 8 months, adding data from April to December 2012.

Our modified dataset is provided as Supplementary Material to this paper. It contains 1687 farm-years of load factor data, covering onshore turbines built from 1991 onwards and spanning 11 years of

[1] www.renewablesandchp.ofgem.gov.uk.

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