System Performance, Availability
and Reliability Trend Analysis

Portfolio Review
2021/22

SPARTA
System Performance, Availability
and Reliability Trend Analysis

Introduction

What is SPARTA?

SPARTA is an offshore wind farm performance benchmarking tool, run by industry for industry. Standing for ‘System Performance, Availability and Reliability Trend Analysis’, this tool allows owner/operators of offshore wind farms to compare key performance indicators (KPIs) for their farms to aggregated and anonymised benchmarks. The SPARTA Joint Industry Project (JIP) is sponsored by The Crown Estate and the Offshore Renewable Energy (ORE) Catapult.

Offshore wind performance benchmarks are available from January 2014. In total, owner/operators can supply a maximum of 159 KPIs and then have access to over 500 benchmarks every month, including derived values, covering four main areas:

- **Availability**
- **Production and Lost Production**
- **Reliability**
- **Operations**

What is included in this report?

This report is split into 3 sections:

1. The Year in Review

The report gives highlights of benchmarks from the 2021/22 financial year, showing the trends of metrics such as capacity factor, production-based availability and turbine transfers. The year is compared to previous years in order to evaluate how the industry is changing. We also draw out more general insights from the set, including a further look at the effect of the pandemic and at component failures.

2. Grid Curtailment and Availability Loss

Examining a key factor during the year that led to lower availability figures, we highlight the impact that forced curtailment from system operators has on production.

3. Operations and Performance Throughout the Life of a Turbine

Delving into trends across the age of windfarms in the set, the review questions whether the common bathtub curve of reliability is apparent in the portfolio. It examines metrics such as availability, forced outages and major repairs across the lifespan of a turbine.

Introduction

Who is Involved?

All major owner/operators with offshore wind farms in UK waters are participating in the 2020/21 SPARTA Portfolio Review. The SPARTA group aims to continue gathering members across Europe in order to maximise system data and produce more robust benchmarks for industry.

Sponsoring Organisations

CATAPULT Offshore Renewable Energy

THE CROWN ESTATE

Participating Owner Operators

RWE

EDF

Ørsted

Eneco

SSE

equinor

VATTENFALL

SCOTTISHPOWER RENEWABLES

Principle of SPARTA

The SPARTA platform has been designed based on the following principles, which have helped establish SPARTA as the industry-leading performance benchmark provider for offshore wind:

- **Anonymity:** Generation of benchmarks requires sensitive operational data. To ensure operational KPIs are not shared, SPARTA aggregates metrics and securely uploads them into an anonymised data pool.
- **Transparency:** There is complete transparency in definitions and methodologies used and these are published in a Metric Handbook. Consequently, results are clear, comprehensive and consistent.
- **Quality:** Extremely high quality and reliable outputs are achieved through continuous metric assurance and verification activity.
- **Representative data volume:** SPARTA benchmarks are based on a representative population, with over 50% of all offshore wind farms in UK waters providing performance data on a monthly basis for over 6 years.
- **Industry-Led:** The SPARTA system was designed by owner/operators for owner/operators and is continuously improved to ensure it reflects industry needs.
- **Monthly Benchmarks:** New benchmarks are made available to members every month. This reveals seasonal variations and can inform detailed optimisation of operations and modelling of new wind farms.

Why is Benchmarking Important?

Benchmarking with SPARTA allows wind farms to compare their performance to an industry "norm". This allows a number of potential benefits:

- **Identify underperformance:** Find periods where your wind farm is not performing as well as the industry and be armed with the tools to ask why and perform more in-depth analysis.
- **Identify good practice:** When your wind farm is one of the higher performing wind farms, have the resources available to first identify this period and be able to review what made this period so good.
- **Future planning:** By filtering on certain dimensions see how older wind farms are performing and have the ability to compare these. This can then be used to plan what can be expected as your wind farm ages.
- **Industry collaboration:** Be part of the future and help the industry improve performance, reduce failures and optimise transfers, together. By getting industry to work together, SPARTA aims to help tackle climate change by improving renewables.

The Portfolio


Turbine Rating

Turbine Count

Original Equipment Manufactures

Distance to Shore

Figure 1 Number of windfarms in the SPARTA portfolio, categorised by rating, turbine count, OEM and distance to shore.

1607
Turbines

25
Windfarms

6348MW
Capacity

The Year in Review

Annual Performance 2021/22

↓

36.11%

Average Capacity Factor

from 38.86%*

↓

3135 MWh

Average Generation per MW

from 3380 MWh

↑

0.21

Major Repairs per Turbine

from 0.09

↓

91.94%

Average Production Based Availability

from 94.58%

↑

19.84

Crew Transfer Vessel Days per Turbine

from 15.11

↑

297 MWh

Average Lost Production per MW

from 192 MWh

↓

71.94

Transfers per Turbine

from 92.52

↑

28.47

Outages per Turbine

from 23.35

**Comparison figures are the average from datapoints before 2021/22*

Capacity Factor

Capacity factor can be treated as the achieved percentage of the total possible production assuming there were perfect environmental conditions. As conditions are seldom perfect, this figure is driven primarily by the wind speed at site, as is highlighted by the closely linked trends of capacity factor and wind speed throughout the year. However, the financial year did have a particularly low capacity factor given modest wind speeds, registering as the lowest rating year since 2016/17 (where wind conditions were worse).

What is Capacity Factor?

Capacity Factor is a measure of how much power a turbine is producing compared to its rated capacity. Generally, this is reported over a period of time for a wind farm, so is a measure of how well the farm is producing on average compared to its rated capacity.

Example:

A 500MW wind farm produces 219,000 MWh for a month. For a capacity of 500MW for a month (730 hours), the farm had the potential to produce 365,000 MWh.

219,000 MWh / 364,000 MWh = 60%

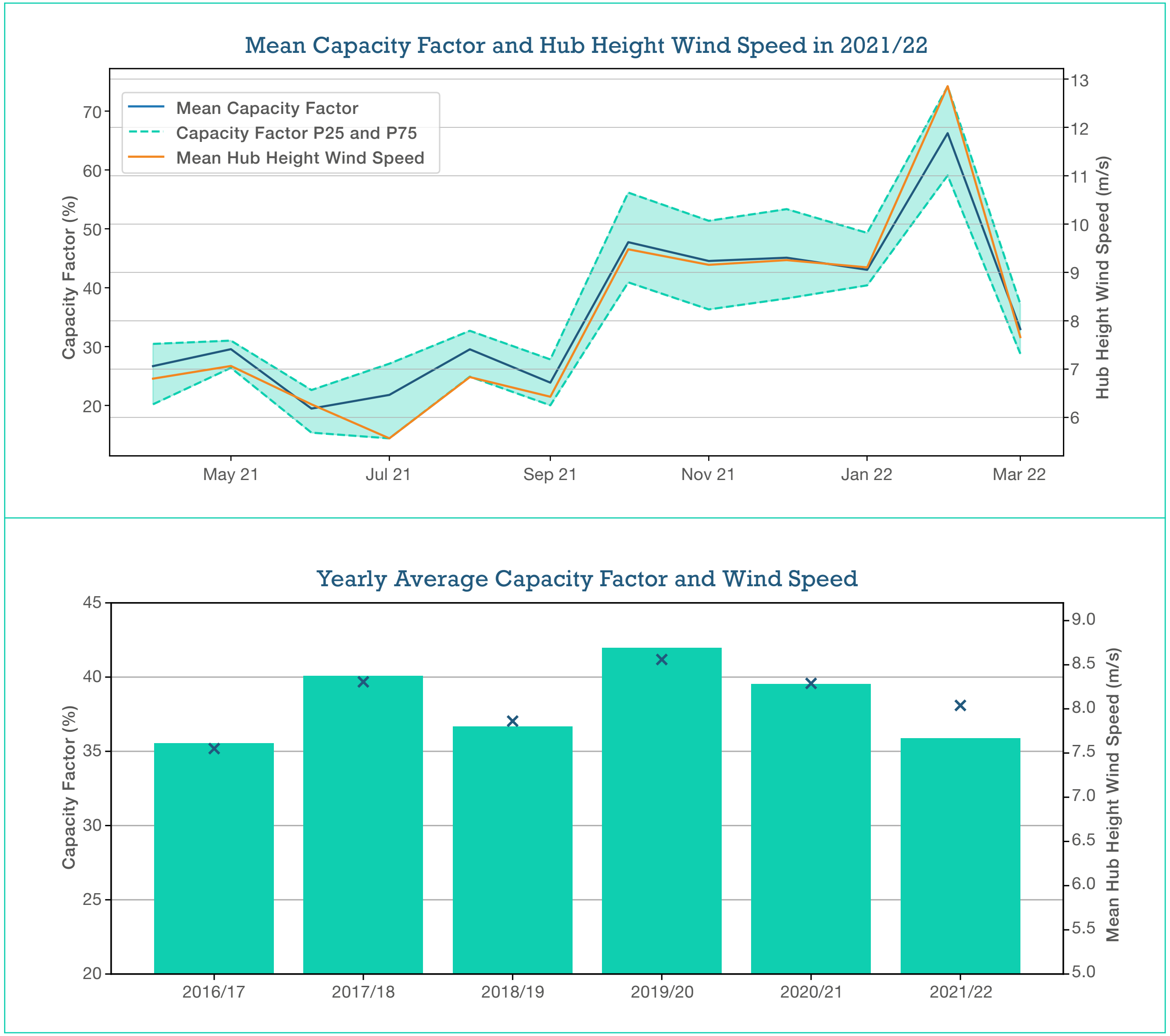


Figure 2 Mean monthly capacity factor and wind speed over 2021/22 (top) and annual capacity factor and wind speed from 2016-2022 (bottom).

Production Based Availability

PBA, which takes wind speed into account in its definitions of possible production, is generally accepted to be a more meaningful measure of availability than capacity factor. Average PBA was at its lowest in the set over the 2021/22 period and was below 94% for all months apart from May. The average sits on the lower end of the inner-quartile range, showing that this low PBA may be driven by a few farms with significantly low PBA dragging down the average. This is in large part driven by larger curtailment from Electricity System Operators (ESOs) which presents major problem for the development of offshore wind – this is explored more in the following section on Grid curtailment in 2020/21. It shows that despite the relatively good capacity factor owing to high wind speeds, the portfolio experienced its worst year in the set, in terms of availability.

What is production based availability?

Production Based Availability, or PBA, is a measure of how well a turbine is using the wind resource available to it. Unlike capacity factor, PBA does not punish for low winds, as it measures how well the turbine is performing compared to its power curve, given the wind speeds that occur at that site.

Example:

The wind at site is 6m/s and the power curve 'says' the turbine should be generating 1000kW but the turbine is only producing 700kW. This would give the turbine a PBA of 700kW/1000kW, so 70%.

700kW / 1000kW = 70%

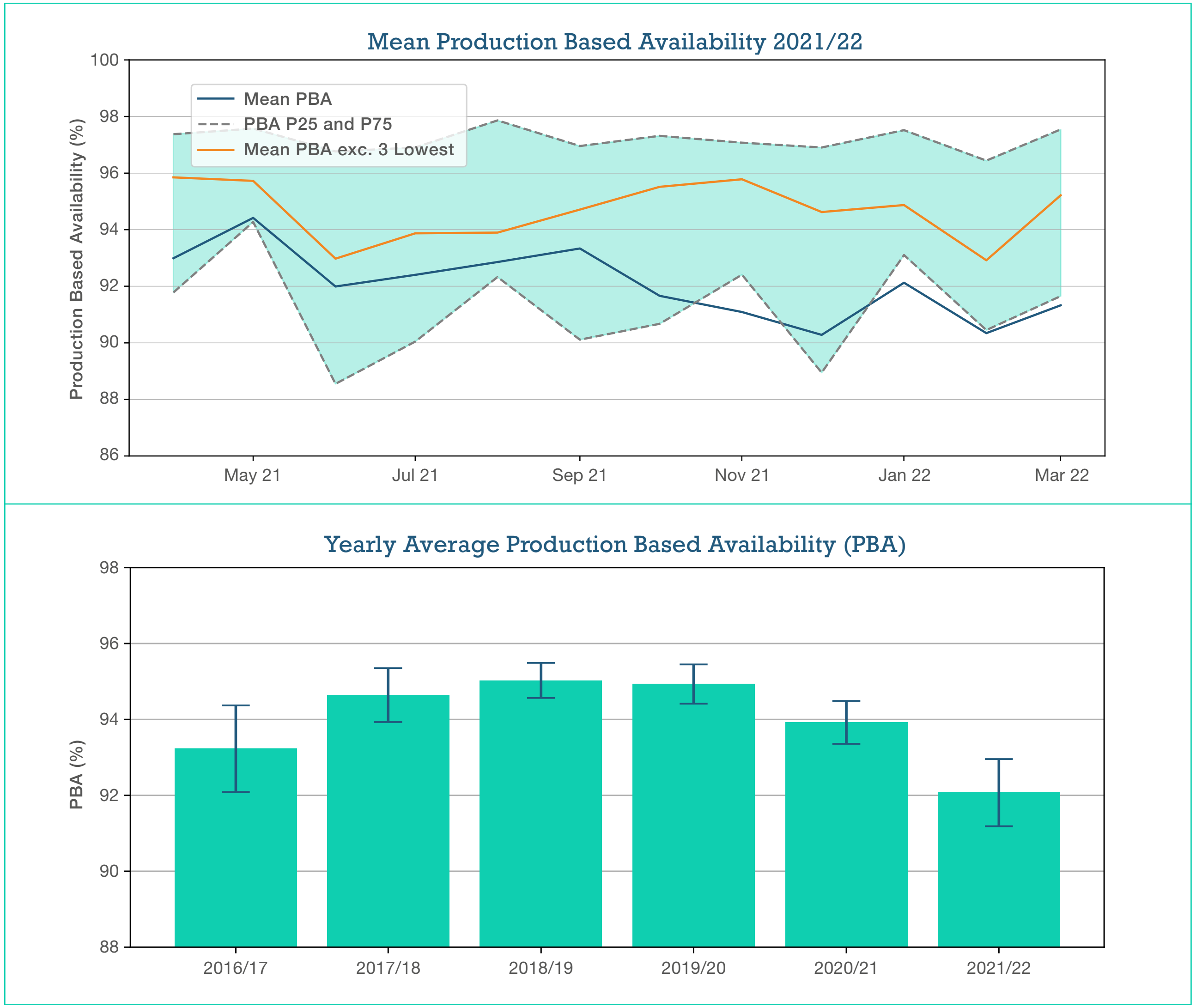
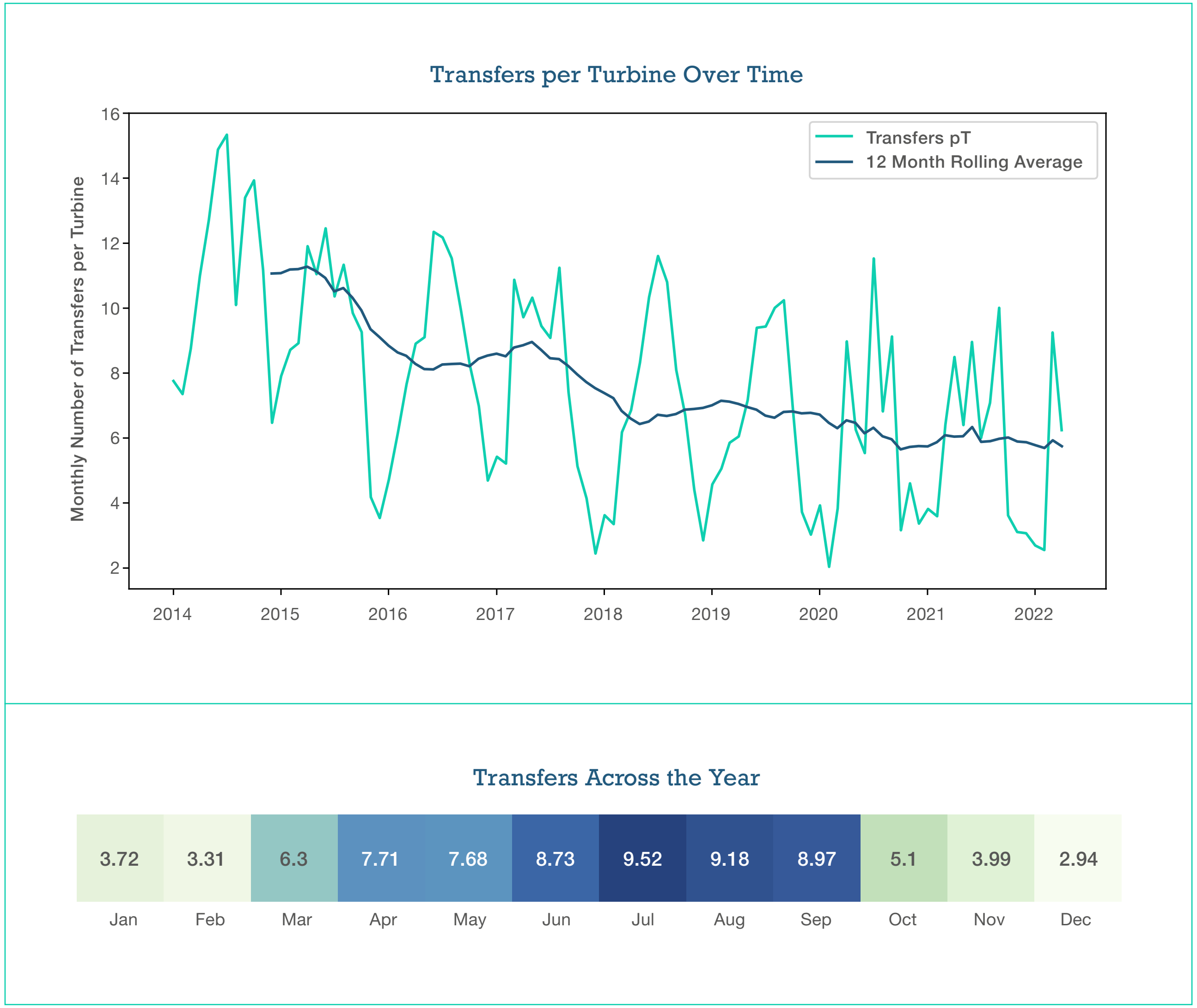


Figure 3 Mean monthly PBA and PBA excluding 3 lowest performers over 2021/22 (top) and annual PBA from 2016-2022 (bottom).

Transfers

As reported in previous reviews, the number of turbine transfers has been on a decreasing trend over the last decade and has continued its levelled trend over the last few years. A lower number of transfers is preferred both for cost and Health & Safety. Turbine transfers peak when operators carry out scheduled maintenance during low production periods in summer and fall through the winter when production is high and non-access days are more likely. The rolling yearly average of this trend has levelled off in recent years, showing that industry has either reached a minimum feasible number of transfers or has struggled to continue making improvements in this area.


Transfers per Turbine Over Time

Transfers Across the Year

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3.72	3.31	6.3	7.71	7.68	8.73	9.52	9.18	8.97	5.1	3.99	2.94

Figure 4 Mean monthly turbine transfers over time with rolling annual average (top) and average transfers across the year (bottom).

What is a turbine transfer?

A turbine transfer is defined as the number of completed transfers of technicians from a vessel onto a turbine or substation.

A technician transferring onto and then subsequently off of a turbine counts as one transfer.

A single technician can transfer onto several turbines in a day and a vessel can transport several technicians to a singular turbine.

COVID and Operations

The 2020/21 portfolio review examined the impact of the pandemic on operations and maintenance, noting slightly reduced availability and a higher number of chartered vessels, perhaps motivated by social distancing. Figure 10 shows the usual seasonal variation in CTV rentals throughout the year, which closely matches the seasonal trend of turbine transfers. However, this trend was much flatter throughout the pandemic, implying that windfarms retained CTVs through the winter to accommodate for greater social distancing offshore. Following easing of restrictions in Europe after July 2021, the seasonal trend looks to have returned. There is a case to say that the effects of reduced maintenance during the pandemic will have long term effects on reliability, but that does not yet appear to be justified.

What is a Vessel Day?

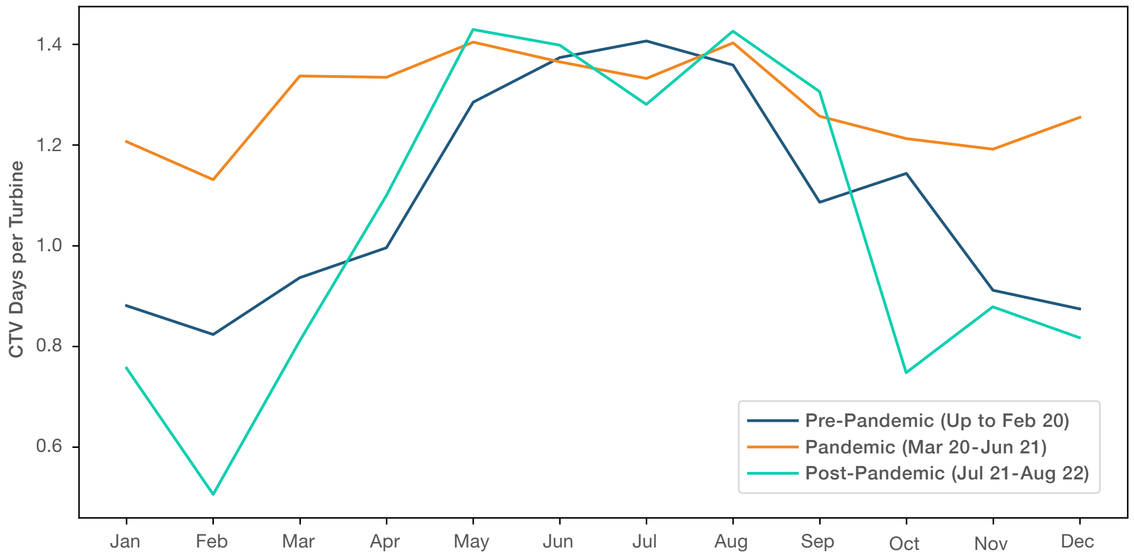
The number of vessel days in a month is the total number of available vessels multiplied by how many days those vessels were available for. SPARTA collects this metric for crew transfer vessels (CTVs), special operation vessels (SOVs) and helicopters but for the purposes of this report, only CTV vessel days are analysed.

If additional CTVs are chartered in for only part of the month then these are included.

Example:

If 5 vessels are each chartered for 10 days of a month in a windfarm this equates to 50 vessel days, whether the vessels were used or not.

Vessel Usage Throughout the Pandemic



CTV Days per Turbine Across the Year

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.98	0.87	1.06	1.11	1.36	1.39	1.42	1.39	1.22	1.13	1.03	1.0

Figure 5 Average CTV Days per turbine across the year before during and after the pandemic (top) and average CTV Days across the year (bottom).

Component Outages

In order to understand what parts of the turbine require the most attention, the turbine is broken down into several components and sub-components. The group uses the non-vendor specific component taxonomy created by the Reference Designation System for Power Plants (RDS-PP) Renewables Best Practice group (formerly known as the RDS-PP Nordic group) - a group of Turbine OOs and OEMs who agree common identifications for wind turbine subcomponents.

The component that triggers alarms the most is that of the transmission system, the electrical section that transmits the energy provided by the generator system into the medium voltage grid. However, the yaw system contributes to more lost production all around due to its higher impact on the turbine. The second most frequently triggered group of alarms is that of the control and protection system (CPS). This is akin to the central nervous system of the turbine, allowing the exchange of data from turbine control units to the central park communication network. Failures in the CPS are often incorrectly identified as the root cause as it is the principal point of measurement.

The 3 components that were most serious upon failing were the balance of plant system (BoP), the drive train system and the central lubrication system. None of them – particularly BoP and the lubrication system – have failed often in the set, but the failures that did occur had large consequences.

What is a forced outage?

A forced outage is defined as when an immediate action to disable the generating function of the wind turbine is required as unforeseen damage, faults, failures or alarms are detected. The SPARTA methodology dictates that members should take the first in a cluster of alarms as the one that is the most likely root cause of the failure. Forced Outages do not include major repairs – instances where a jack up barge is required for significant maintenance or replacement.

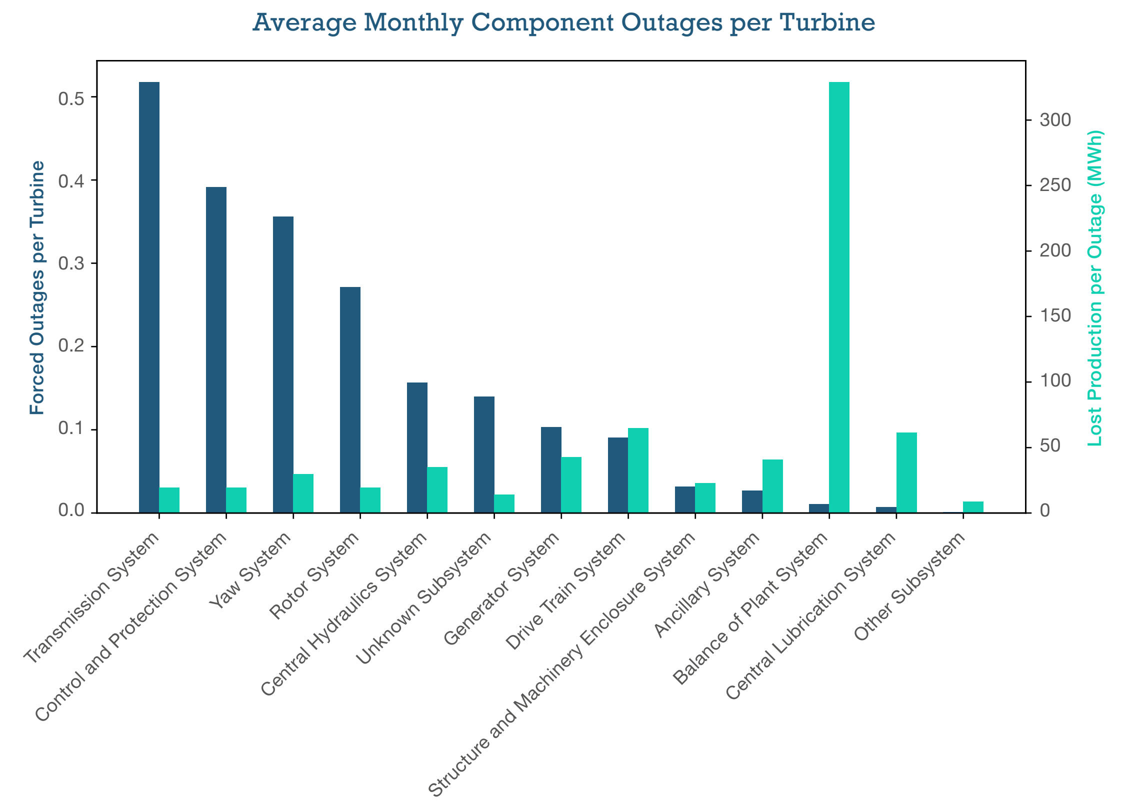


Figure 6 Average monthly forced outages per turbine and lost production per outage, by component.

Level B Components

Further following the RDS-PP taxonomy, 4 of the turbine's components can be split down to another level of detail. Some of these alarms cannot be identified fully as the cause of failure may be ambiguous and are therefore marked as 'unknown'.

In the transmission system, the component which is flagged the most, the convertor system is flagged as the main root cause, constituting 95% of the known transmission failures at this 'Level B'.

For the blade, it is the system controlling the pitch that leads to the highest amount of failures, though many happen in the hub. In the generator system, the generator itself fails more often than its cooling system and additional elements. In the drive train, the gearbox is the most likely candidate for those turbines that have it.

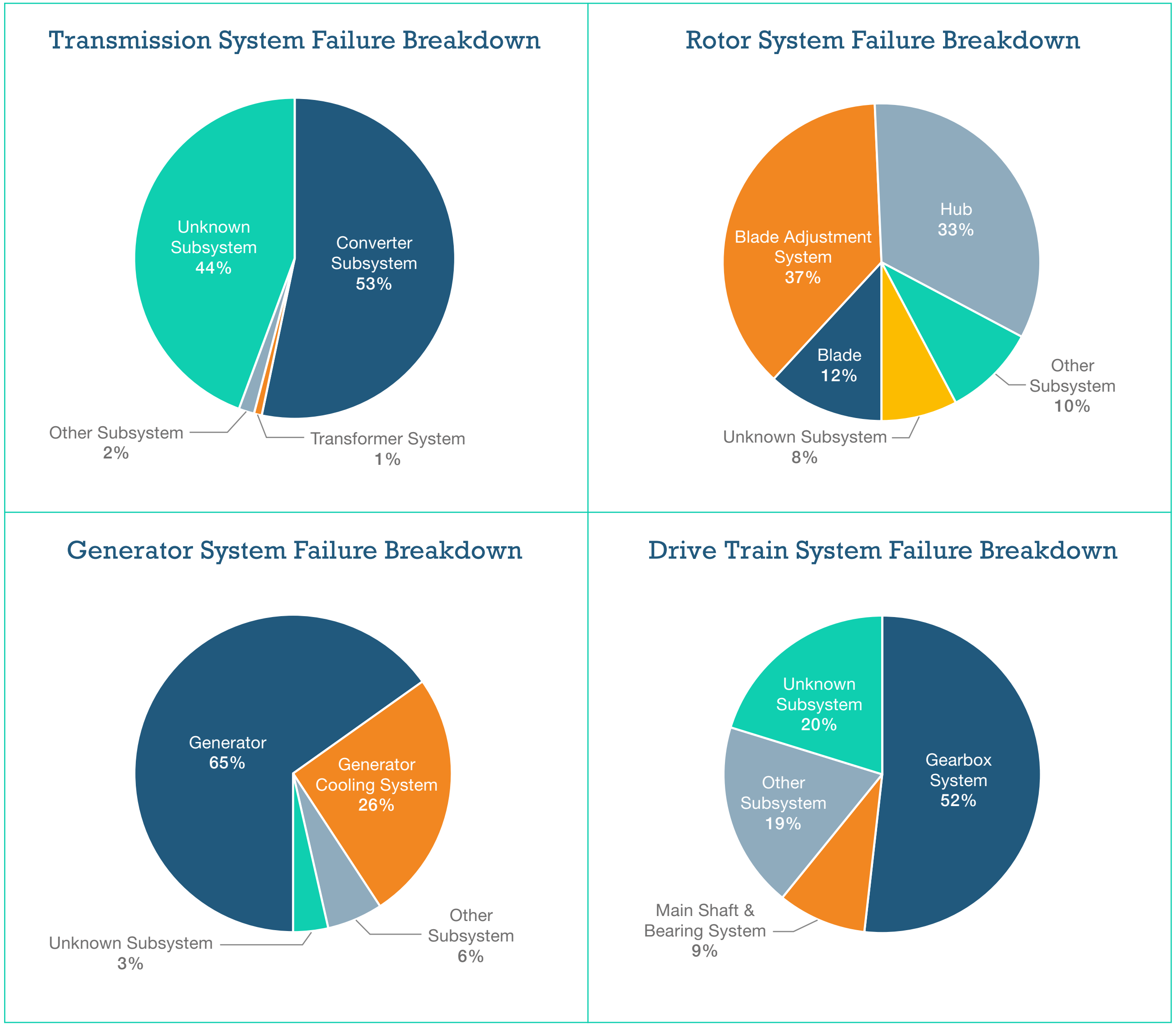


Figure 7 Breakdown of percentage of forced outages for 'Level B' subcomponents.

Grid Curtailment and Availability Loss

Grid Curtailment and Lost Production

Data from the UK Government shows just how important Offshore Wind is as a portion of the energy mix - as much as 13% in 2020 and 11.5% in 2021. This presents a new set of challenges for Electricity System Operators (ESOs) as they try to facilitate the integration of a variable energy source in the mix. In its current state, the electricity system is not fit to utilise all of this energy. Particularly in the windiest periods, when supply greatly surpasses local demand and there are no means to transport or store the energy, ESOs may have to request that certain wind farms limit their output so that the grid does not get overloaded.

This process occurs through the 'Bid-Offer-Acceptance (BOA) mechanism, in which an ESO requests ahead of time that an energy producer either limits or increases their output. In Offshore Wind, where output is generally limited rather than increased, the producer will usually get compensated for their losses.

As of 2021, National Grid has started publishing records of BOAs, allowing us to see their effect on offshore wind. In Figure 8 we can see that grid curtailment has been significant throughout the Winter when wind speed was at its highest. Other factors such as increases in capacity and demand are also important, as can be seen for comparison of March 2021 (with very little compensated production) and March 2022.

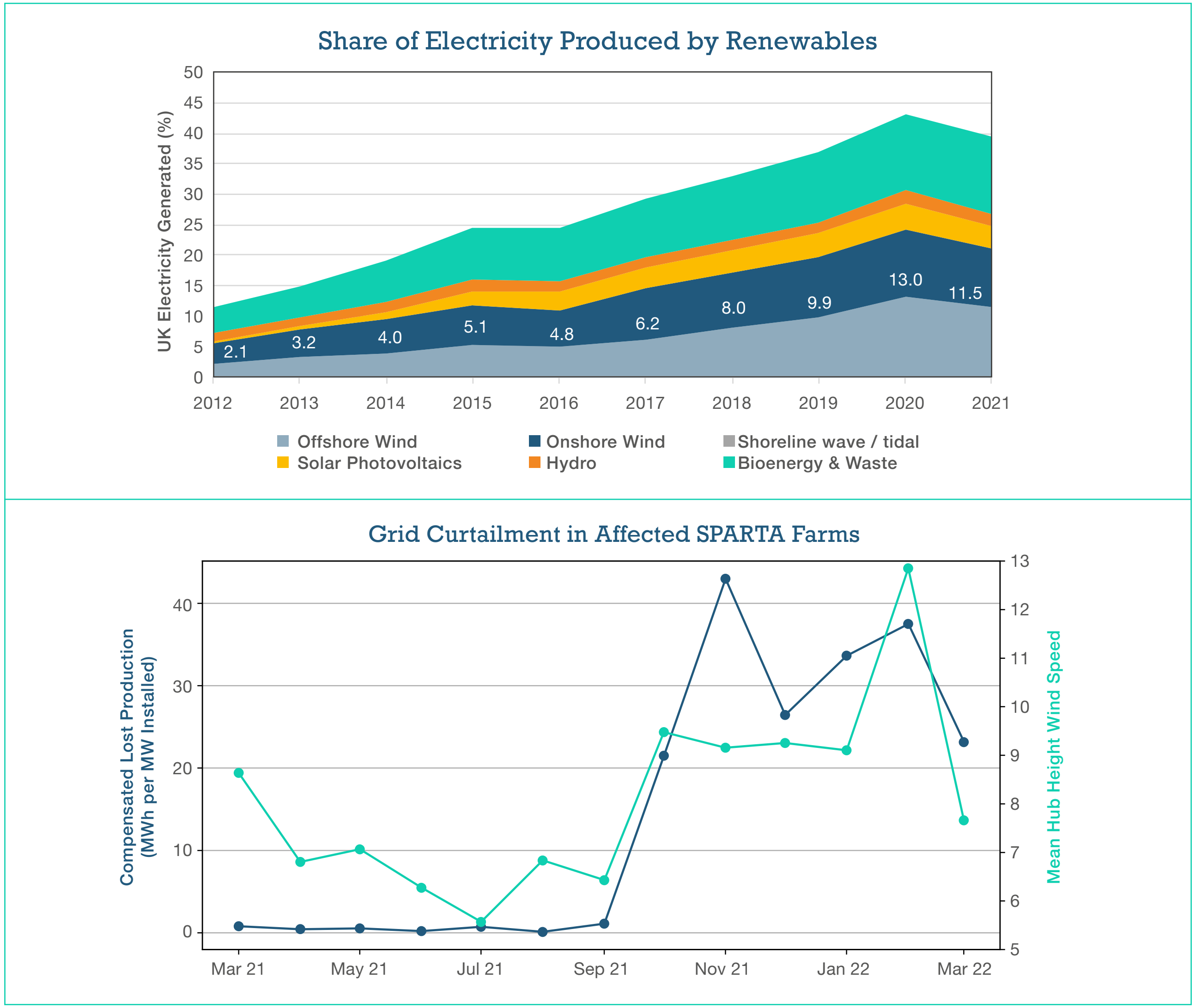


Figure 8 Share of electricity produced by renewables in the UK (top) and compensated lost production from BOAs according to Elexon and mean wind speed (bottom).

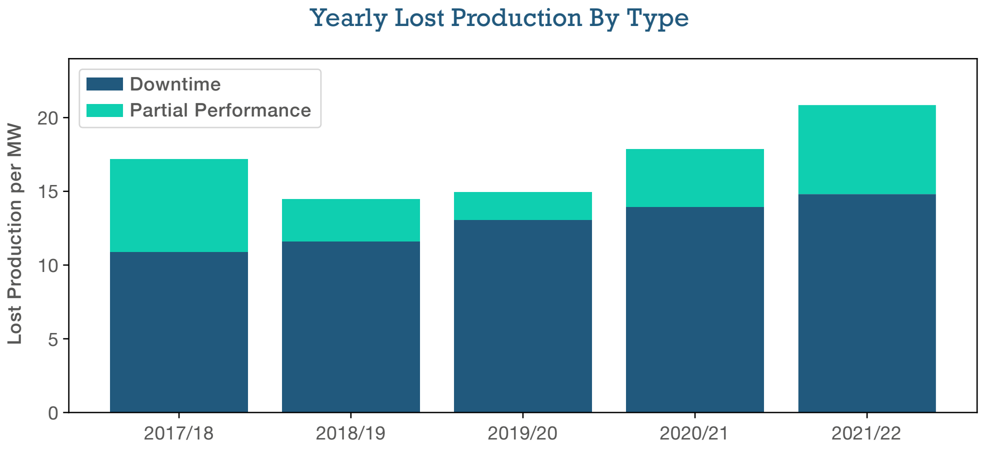
Reference:
Data from UK Government (Energy Trends: UK renewables - GOV.UK (www.gov.uk)) and Elexon Portal https://www.elexonportal.co.uk/

Grid Curtailment and Availability

In the SPARTA methodology, lost production is calculated for turbines that are classified as down or in partial performance. This means that curtailment from BOAs will automatically register as lost production for a farm and consequently have an impact on its availability figures.

BOAs may have had a role in increasing lost production figures in past years and is certainly doing so now. In 2020/21, we remarked at lower PBA values likely impacted by disruption to operations through the pandemic. While this is likely the case, grid curtailment is sure to also play a part. In 2021/22 this seems to be the case more than ever, with over 10% of values registering less than 80% availability and approximately 10% more that were 80-90% available.

The cumulative distribution graph shows the share of datapoints that were submitted at or below each availability. This means that higher lines are actually worse due to the high share that achieved lower availability figures. The latest 2 years in the set are the ones with the lowest availability figures.


Yearly Lost Production By Type

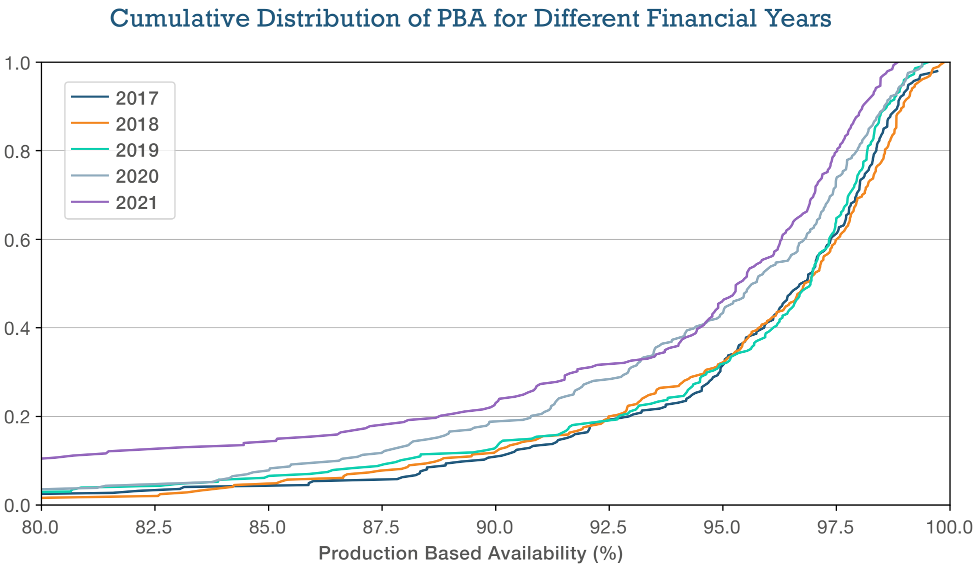

Cumulative Distribution of PBA for Different Financial Years

Figure 9 Lost production by downtime and partial performance from 2016-2022 (top) and cumulative distribution of PBA for each financial year (bottom).

Accounting for BOA Losses

In order to take account of BOA losses in availability, we must come up with an alternative definition for availability or for lost production. For the purposes of this report, we will remove estimated BOA losses from the lost production figure. These values are not provided by SPARTA members but sourced publicly from National Grid and Elexon.

As can be seen from Figure 10, PBA has significantly dipped throughout the winter of 2021/22, and it seems to be driven by a small number of low producing farms given the shaded P25 and P75 areas. When this is compared to the figure without losses from BOAs, it's clear that these high losses are driven mainly by grid curtailment and the true availability is actually quite consistent. In fact, Figure 10 shows that without these losses, the year's PBA actually bested the PBA of recent years.

How can we factor grid curtailment into availability?

In SPARTA, Production Based Availability is calculated using lost production and generation through the following equation:

$$\text{PBA} = 100 \times \frac{\text{Generation}}{\text{Generation + Lost Production}}$$

To factor in grid curtailment, we must remove estimated BOA losses (according to National Grid) from lost production and effectively disregard any curtailment that occurred. As it is already included in lost production, we may subtract it from the denominator of PBA.

$$\text{PBA w/o BOA Losses} = 100 \times \frac{\text{Generation}}{\text{Generation + Lost Production} - \text{Grid Curtailment Loss}}$$

Figure 10 Availability with and without BOA periods counted as potential production, with P25 and P75 range shaded (top) and PBA without BOAs in annual context (bottom).

Regional Grid Curtailment

According to data from Elexon's Balancing Mechanism Reporting Service (BMRS), over 1,200 GWh of potential production was lost from the system due to balancing constraints throughout the year. This equates to approximately 2.7% of the year's total potential production in the UK. Out of 30 farms identified in the BMRS set (including those not in SPARTA), 21 had some level of grid curtailment during the financial year. Those that were curtailed in SPARTA were affected on average 4.1 months out of the year.

As shown by the heat map of grid curtailment across the country there are 3 farms that are affected more than any other during the period. The 2 curtailed most often were Beatrice and Moray East in the North East of Scotland, which lost 16% and 23.5% of potential production, respectively. The third farm was the Walney Extension, North West of England, which lost 5% of potential production. All other farms lost less than 1% of their potential production due to grid curtailment.

The significant lost production in the North East shows the truly regional nature of the problem – with constraints on transmission and no means to efficiently store offshore wind power, the grid simply can't cope with so much supply. An owner/operator might not complain about this situation as they'll get paid anyway, but it highlights a clear mismatch between national goals and capabilities. In late 2022, Ofgem approved significant investments in transmission infrastructure including substantial investments in connections from the North East of Scotland to England.

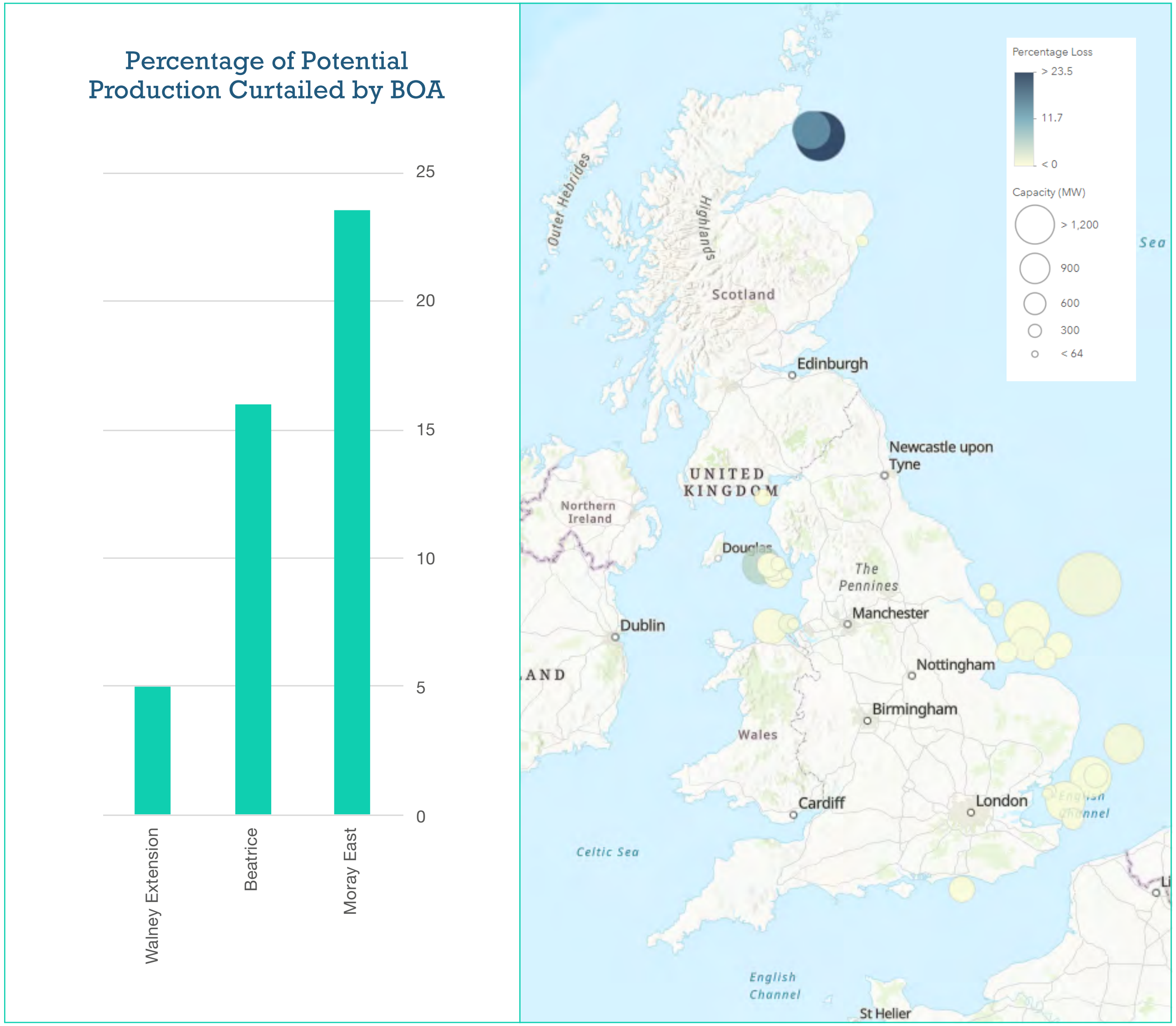


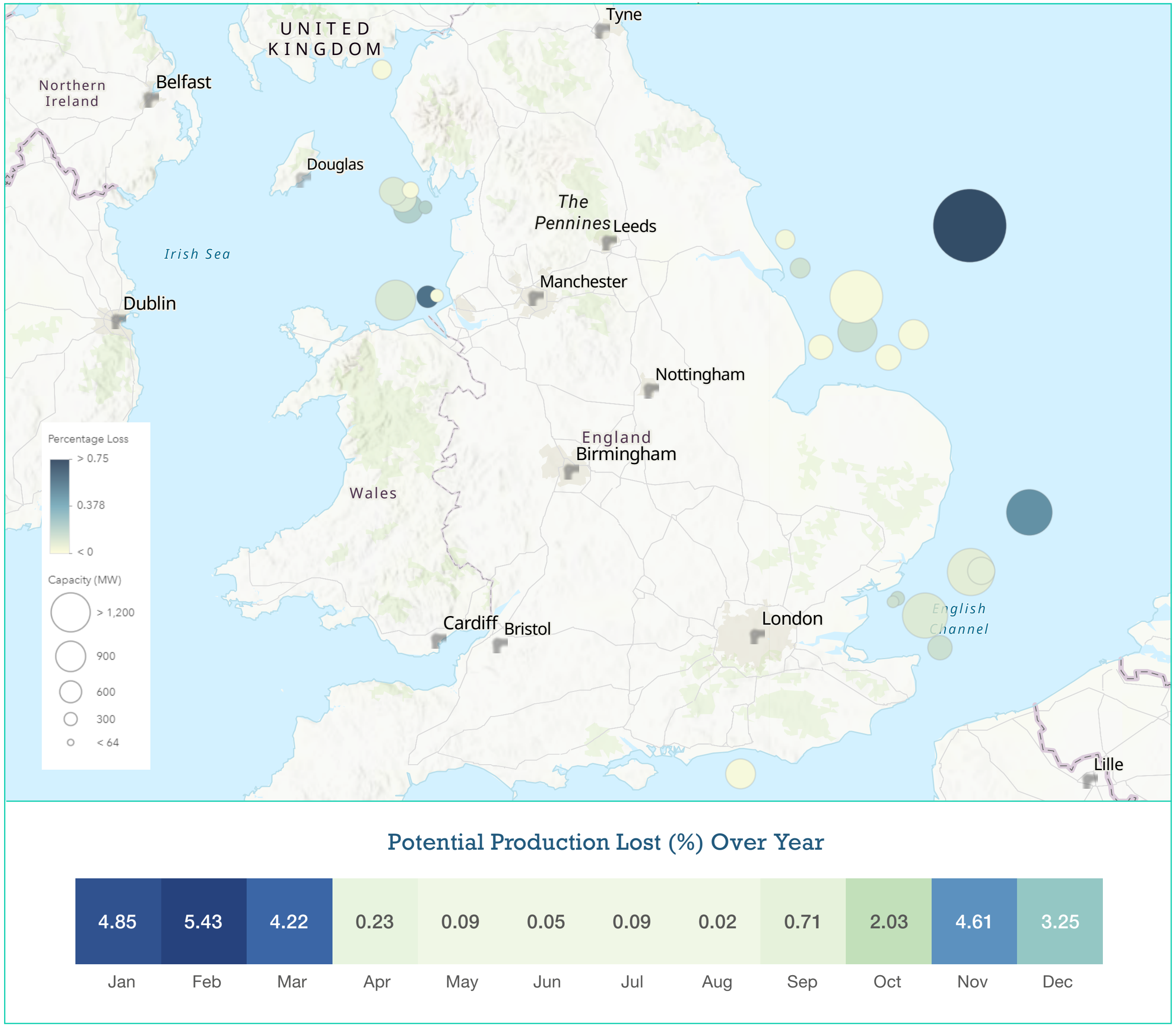
Figure 11 Percentage of potential production curtailed by BOAs for 3 farms that lost the most (left) and map of losses for farms in Elexon set (right).

Additional Factors

Curtailment from ESOs occurred on farms big and small, though the 3 biggest losses did come from farms in the top 10 in terms of capacity.

The map to the right shows the losses which represented less than 1% of potential production, with the largest being 0.75% in Hornsea 1. In total, the losses from all these farms accounts for over 83GWh of electricity.

In general, grid curtailment losses are more likely to occur in the winter, when production is highest. A heat map over the year shows that losses were significantly higher between November and March. This is true for both the farms in the North of Scotland and those that were curtailed less. The time of day did not significantly affect curtailment, though losses were slightly more common throughout the evening when demand was lowest.



Potential Production Lost (%) Over Year

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.85	5.43	4.22	0.23	0.09	0.05	0.09	0.02	0.71	2.03	4.61	3.25

Figure 12 Map of farms with minor losses from BOAs (top) and potential lost production over year for all farms (bottom).

Operations and Performance Throughout the Life of a Turbine

The Lifetime of a Turbine

It is well known in industry that failure rates are likely to follow a bathtub curve trajectory through the life of an asset, driven by early 'infant' failures and late 'wear out' failures. This corresponds with availability figures of the wind farms in SPARTA, which appear slightly lower in early life and lower still in later life.

The SPARTA fleet contains windfarms from 0 to over 17 years old, but discerning the impact of an ageing system is no simple task. As industry develops technology develops with it, meaning faults in older farms may be addressed and new issues might emerge. Developers are also pushing further and further offshore, where harsh conditions put systems at higher risk of failure and require more complex solutions. The farms in early and late life in the set are therefore operating under various different conditions.

With these diverse conditions in mind, this section examines the SPARTA data through the lens of a turbine going through the course of its first 10 years of life. We group the dataset based on the age of the turbine at the time of the instance and examine how these values change across the age of the windfarms.

Through this first decade of a turbine's life it will go through the early 'infant mortality' period where system faults will be diagnosed and resolved. The farm will then see the end of its warranty period with its manufacturer - a significant landmark for turbine, particularly if the owner/operator decides to change providers afterwards. Although the farm will likely not be in its last phase of life, certain components will also begin to wear out, along with random failures that will be unrelated to age.

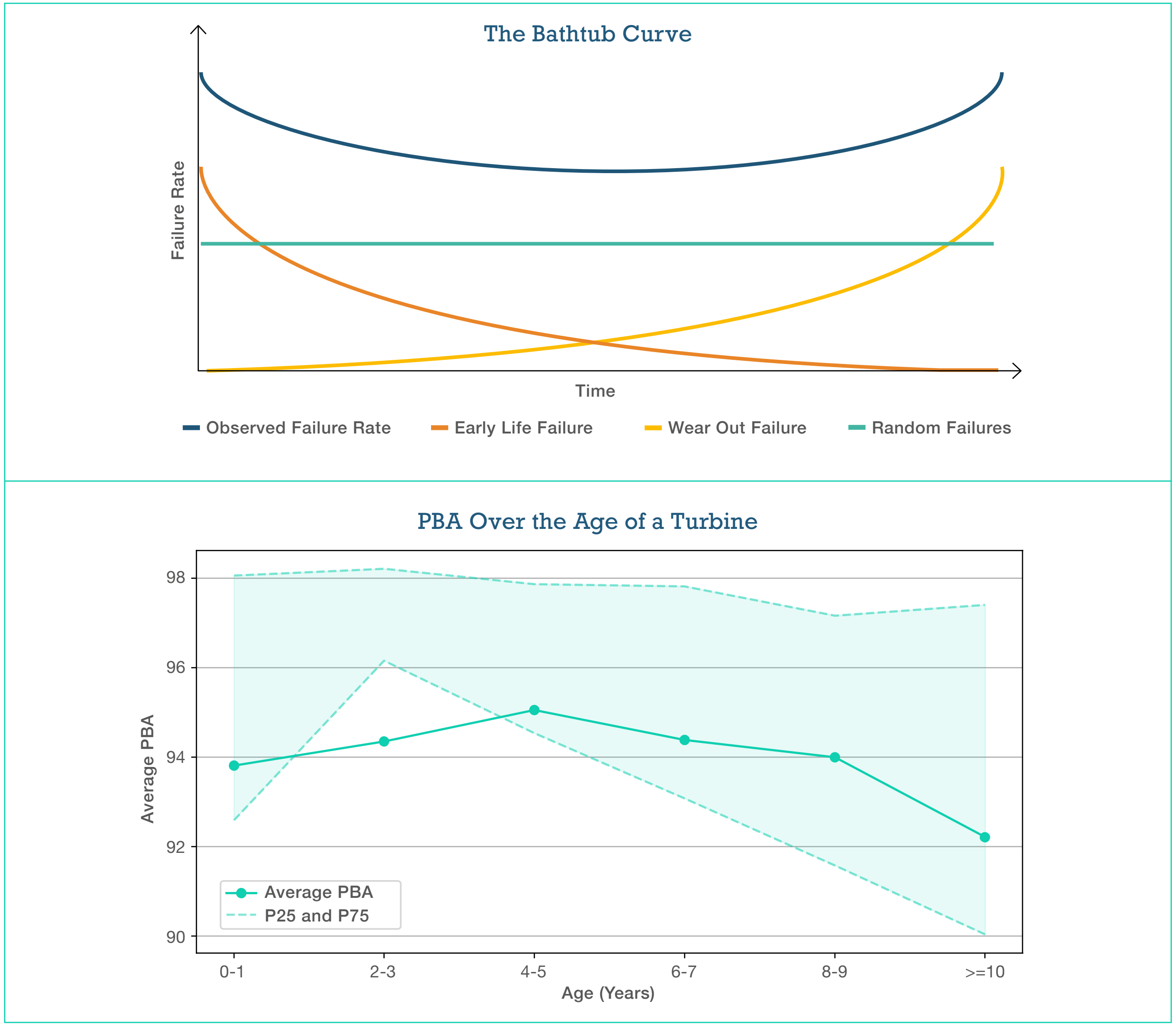


Figure 13 Illustration of bathtub curve (top) and average PBA by year of operation with P25 and P75 (bottom).

Outages Over the Life of a Turbine

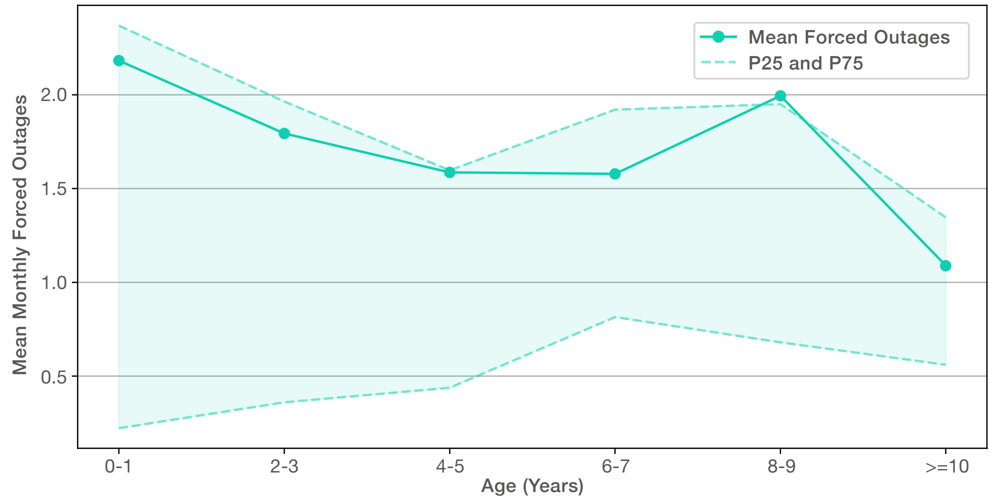
Examining forced outages, which exclude major replacements, there appears to be slightly more failures in the first years of the farm compared to the next few years. On average failures decreased in the first 7 years of life from an initial failure rate in year 0 of 2.6 monthly outages per turbine. However, the large spread of failure rates throughout these years makes the application of the bathtub curve difficult.

The set contained multiple farms with higher failures in years 8-9 of their life. In particular, one farm contained a significantly higher failure rate during these years that appeared to relate to a farm-wide issue. For the purposes of more general analysis of the set, this outlier has been removed from these graphs.

Components are not necessarily built to last the full life of a turbine. The failure of some minor components reaching the end of their lifetime up towards year 10 may also contribute towards a peak during the 8-9 year period.

The length of outages are on average lower before 5 years of operation. While the majority of outages last less than 5 hours long in early life, requiring a mere remote reset, some outages will require physical maintenance and pull the mean up. This appears to become more common as the turbine ages and the mean downtime per outage rises above 10 hours.

Recorded Outages Over the Age of a Turbine



Downtime per Outage Over the Age of a Turbine

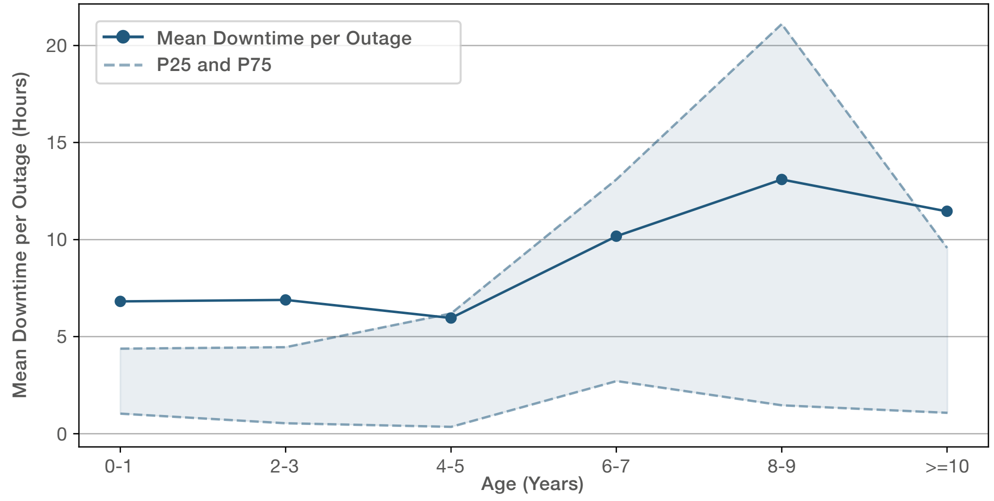


Figure 14 Average number of forced outage by year of operation with P25 and P75 (top) and average downtime per outage (bottom).

Age and Component Failure

Broken down by component, transmission and yaw system failures appear to become much less common throughout the first decade of a turbine's life. Generator failures have followed a bathtub curve, albeit with a lower rate of failure than most other components.

It is expected that some components will be replaced throughout their lifetime.

Major repairs – those that require a jack-up vessel to fix – appear to increase with age. However, there is also a clearly significant peak in major repairs around the 4-5 years mark. This is directly before the end of the warranty period, so it's possible that owners will be looking for major replacements to be dealt with before this ends. The most common major repairs in this period are Blades (65.6%), followed by Electrical replacements (17.8%). Removing blade repairs from this set diminishes the peak in failures and shows the large impact of blade repairs in general. The peak in blade failures is driven by a small number of farms that had blade repair campaigns throughout these years.

Major repairs are rare occurrences compared to other types of maintenance, and the 75th-percentile is 0 at all ages.

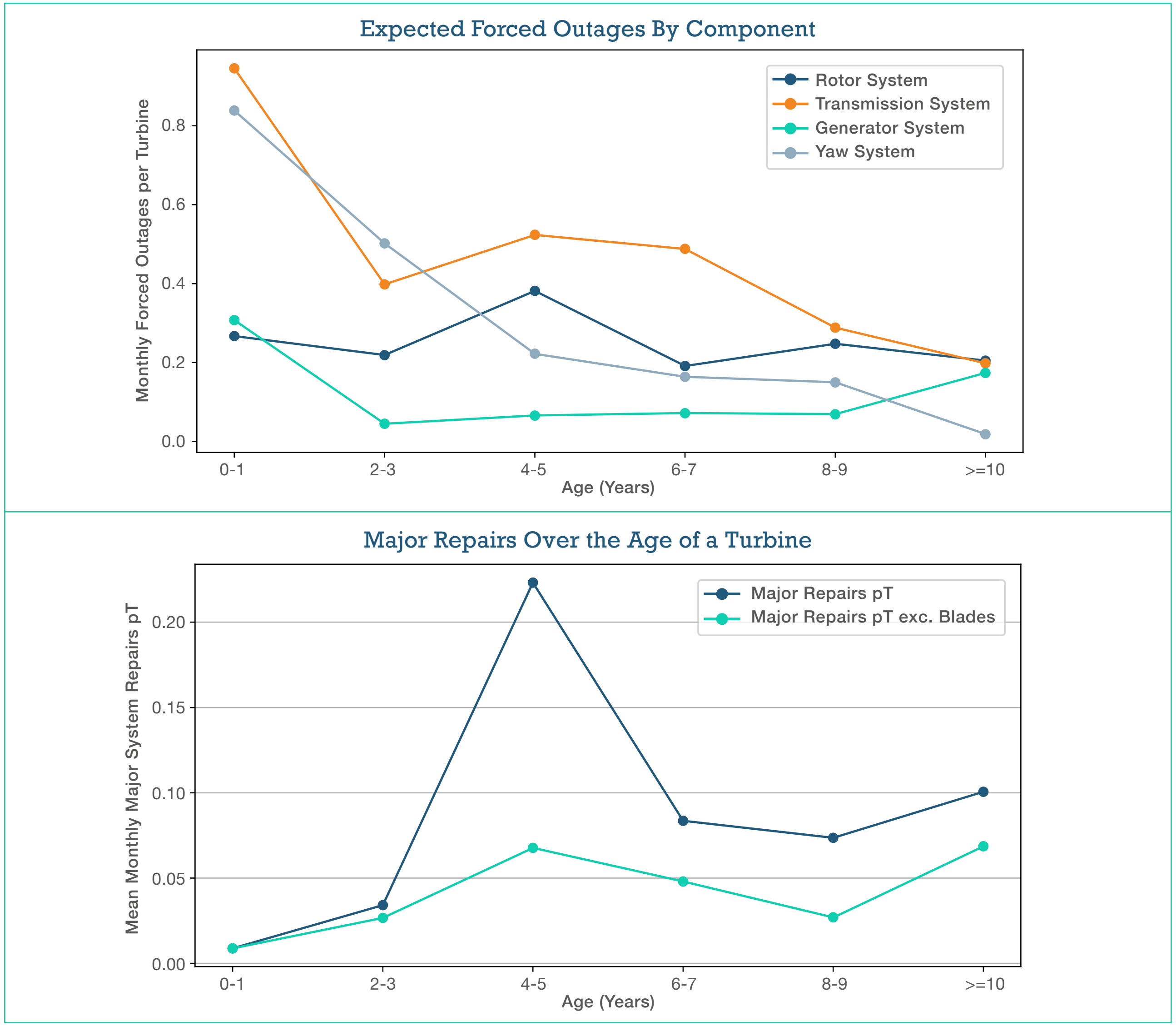


Figure 15 Average monthly number of forced outage per turbine by year of operation, per component (top) and average major repairs per turbine with and without blade repairs (bottom).

Changing Operations

Where operations are concerned, it appears that turbine transfers are also more frequent in the first years of life. However, the large spread of turbine visits makes it difficult to accurately determine any trend.

Meanwhile, the CTVs used to transport those technicians follow a different trend. Farms have hired more CTVs throughout the warranty period, but have also hired CTVs for longer the older they get. Apart from the first year of operation, where CTV days are lower, the trend of chartered vessels is also a bathtub curve.

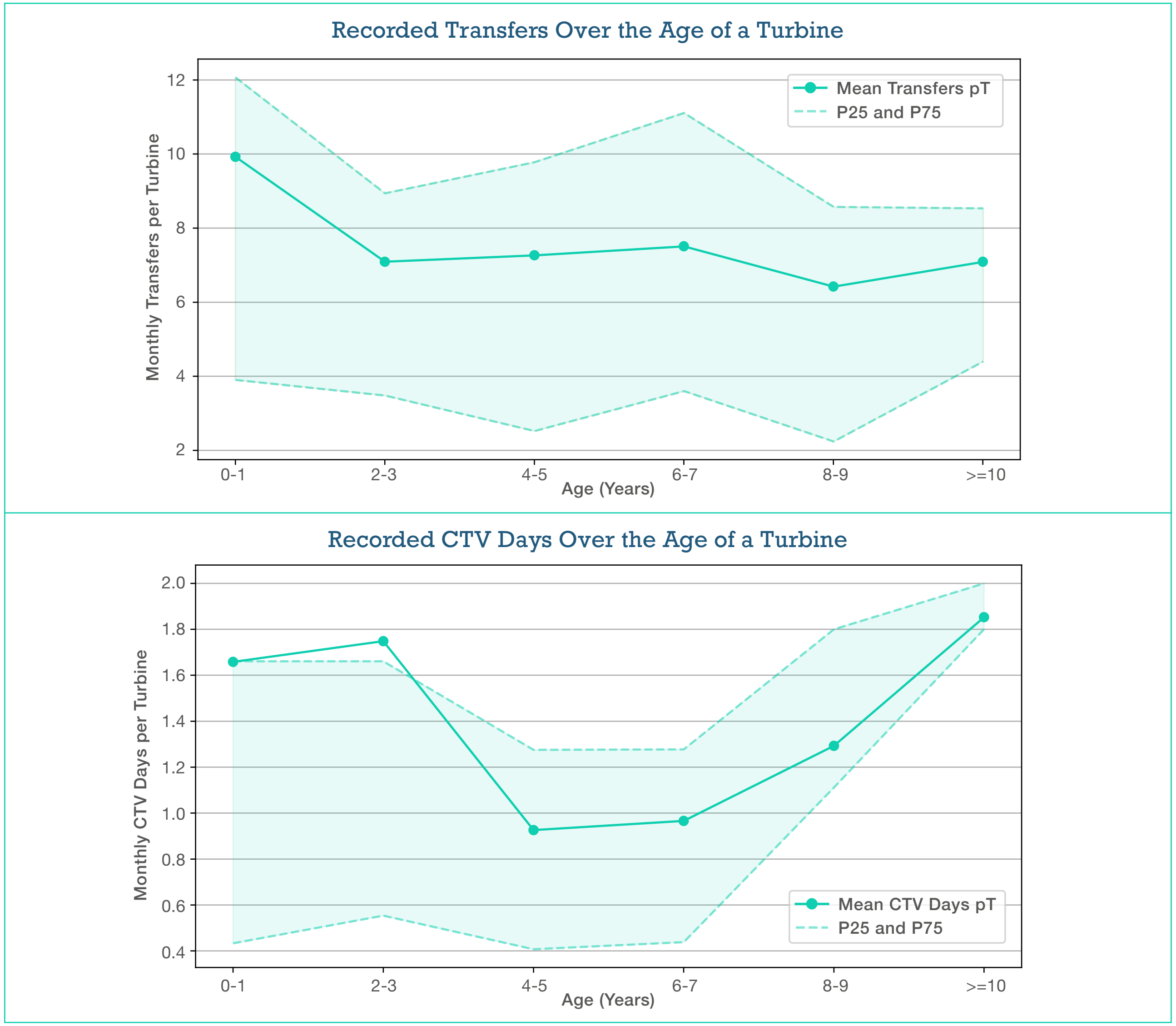


Figure 16 Average monthly transfers per turbine by year of operation with P25 and P75 (top) and average monthly CTV days (bottom).

O&M Providers

Two fifths of farms in the SPARTA set choose not to be fully maintained by the OEM after warranty. This means that they are either fully not maintained by the OEM or they have some other mixed strategy, in which some elements of the farm are maintained by a third party.

The dataset exhibits a larger number of Forced Outages for farms not fully maintained by OEMs after the warranty period. While farms still maintained by the OEM keep failure rates consistent after warranty, other arrangements may lead to a high number of outages following the period. This could be a result of the different strategy itself, leading to a higher number of forced outages which have a smaller impact per failure.

These extra stops therefore do not necessarily result in lower availability. As the PBA shows for non-OEM maintained farms, high outages do not necessarily result in lower production.

The average transfers per turbine between the strategies was not significantly different.

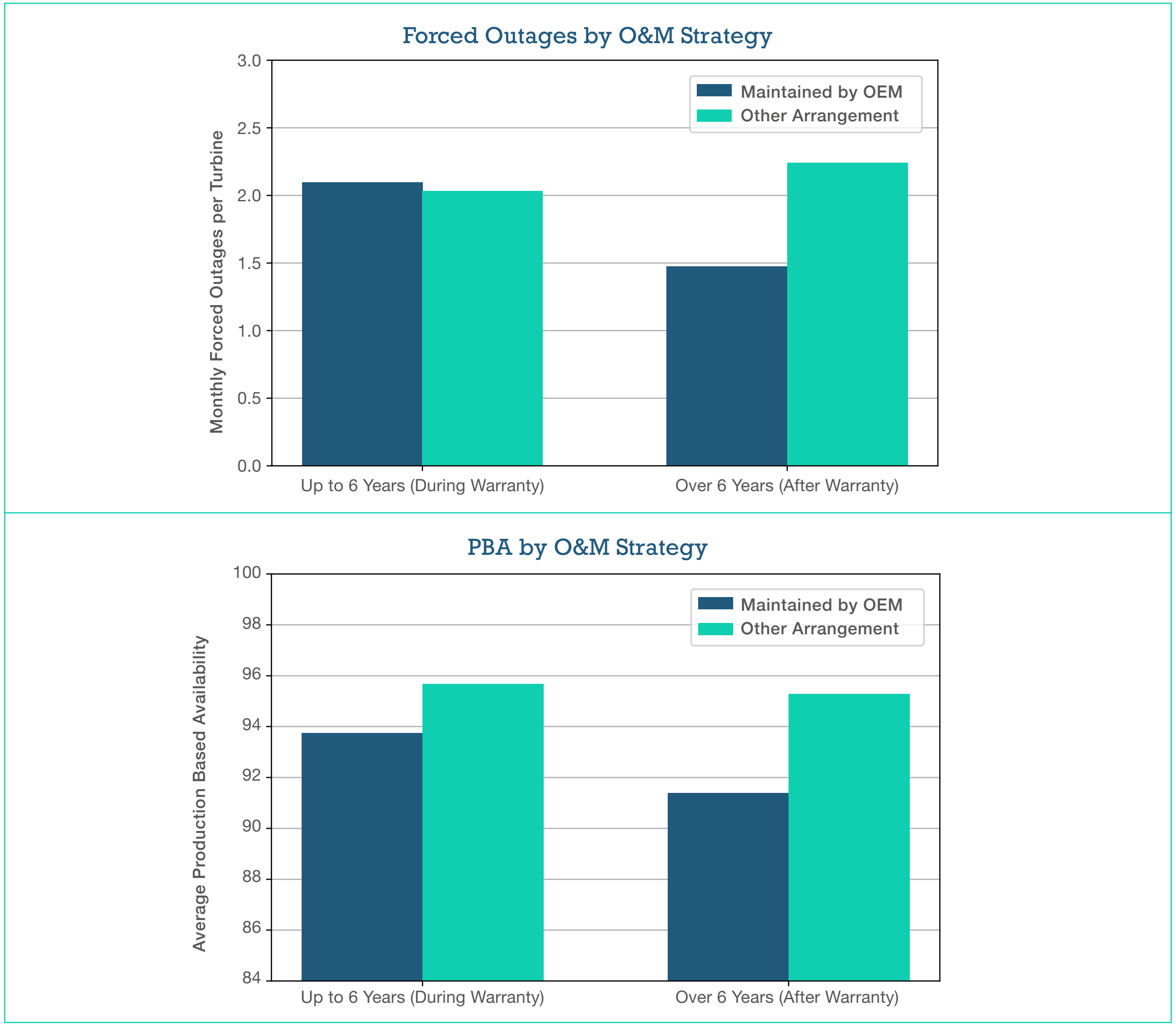


Figure 17 Average number of monthly forced outages per turbine by O&M strategy before and after typical warranty period (6 years) (top) and corresponding average of PBA (bottom).

Summary

In general, the offshore wind industry had another momentous year of production, with 3135 MWh generated for every MW installed in the SPARTA portfolio. In spite of this lofty production the year also brought its own challenges, particularly with increasing intervention from network operators to limit production in certain farms. Through an analysis of public datasets in combination with the SPARTA data, we investigated the effect on availability of curtailments from BOAs. As expected, the main factor in grid curtailment is region, and until the appropriate transmission capacity is in place then the country will continue to lose potential renewable production.

The review also put the spotlight on ageing farms, investigating different metrics compared by age including availability, forced outages and major repairs. Availability did follow something of a bathtub curve during the first 10 years of life, with lower PBA in the first 2 years and then also in later life. As for forced outages, this failure rate appeared to decrease across the lifespan of the set while the downtime from those outages seemed to increase. Different options exist for maintenance strategy and the set does seem to suggest that changing O&M provider has not hindered performance. However, any change of strategy is very dependent on circumstance and must be taken with caution.

Membership

Owner/operators not currently involved in the SPARTA programme are invited to join the group through the members' collaborative agreement, to add to the anonymised benchmarking data set and benefit quickly from an analysis of their performance against their peers.

Participation in SPARTA also provides owner/operators with the opportunity to work with seasoned professionals in the field of offshore wind farm O&M performance measurement.

Applications or enquiries for new members may be made at any time by contacting the SPARTA team:

Callum Reid
Business Development Manager

callum.reid@ore.catapult.org.uk

Andrew Yardley
SPARTA Technical Lead

andrew.yardley@ore.catapult.org.uk