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WHITE PAPER

2024 Backcast Study and Methods Update

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LET’S GO

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Executive summary

UL Solutions refers to the process of verifying its energy production estimation methods against actual plant performance as a “backcast study.” UL Solutions has performed several onshore backcast studies over the years; the most recent relevant to the Americas was published in 2018, with an additional study performed for Europe in 2020, and updates to uncertainty considerations in 2021. As a result of those studies, adjustments were made to various loss factors employed within UL Solutions’ estimates.

The 2024 Backcast Study compares pre-construction energy estimates performed by UL Solutions, considering assessment methods according to the 2018 Backcast Study and 2021 uncertainty update, with operational energy analyses for 124 plants spanning the Americas, Europe and Asia-Pacific. The study finds a median bias of -0.4% and a mean bias of +0.2%, with negative values indicating an under-performance of the operational production or, similarly, an over-estimate of the pre-construction analysis. The bias is small compared to the typical energy uncertainty of 8% for individual projects and, to a 95% confidence interval, does not present a statistically significant difference from zero. In addition, the spread of individual results is consistent with UL Solutions’ uncertainty methodology. Regions with smaller sample sizes are exhibiting higher bias variability, though this is not unexpected given broad geographical footprints and considerable diversity of markets.

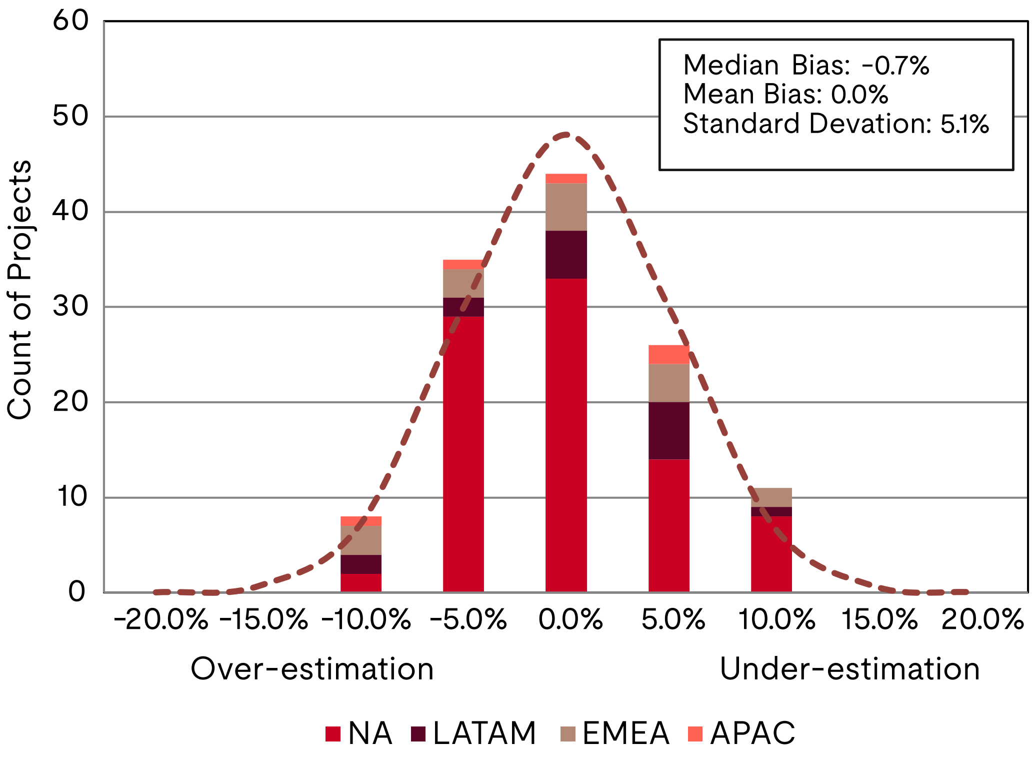
A small bias from a large dataset suggests a robust pre-construction energy methodology to estimate P50 production levels, however this exercise also serves to validate changes in methodology, reduce outliers, and maintain confidence in the derived results, while not introducing additional systematic error. Through the assessment, it is confirmed that UL Solutions can update assumptions around multiple loss categories, while maintaining or reducing the mean bias.

Table 1: Comparison of results by region

	Global	North America (U.S. and Canada)	Latin America (incl. Mexico)	EMEA	Asia Pacific
Count of projects	124	86	16	17	5
Pre-backcast bias* Mean (median)	0.2% (-0.4%)	0.0% (-0.7%)	1.8% (3.5%)	1.0% (-1.3%)	-4.5% (-2.7%)
Post-backcast bias* Mean (median)	0.0% (-0.7%)	0.0% (-0.7%)	0.9% (2.4%)	-0.4% (-1.9%)	-1.5% (-1.1%)

*Negative indicates under-performance of operational production or an over-estimate of the pre-construction analysis.

Figure 1: Global bias distribution after method updates



These changes include:

- A replacement of the 2018 era blockage loss model with updates to the Deep Array Wake Model, Eddy Viscosity, and incorporation of the Rankine Half-Body Induction model
- Removal of the Long-Term Availability Correlation with High Wind Events ("LACHWE") Availability loss category and updates to the turbine and plant energetic availability assumptions.
- Expansion of time dependency in availability losses for longer evaluation periods.
- Updates to the default power curve loss, coupled with refined site-specific considerations.
- Refinement of the underlying data and assumptions that inform lightning, electrical and blade degradation losses

UL Solutions will continue to monitor the accuracy of its methods, and additional method changes may be considered in response to emerging evidence.

Background

UL Solutions aspires to be the most trusted industry partner for wind energy assessment services.

The accuracy of our pre-construction energy production estimates is given utmost consideration as it is vital for maintaining trust and confidence in the energy estimation methods and results of our customers. As part of this commitment, energy assessment methodologies are periodically updated and validated. This report outlines our results with specific considerations for onshore wind energy assessments.

The process of verifying UL Solutions' energy production estimation methods against actual project performance is referred to as a "backcast study." Our experts have performed several backcast studies and methods updates since the first in 2008[1] , including updates in 2012[2], 2016[3], 2018[4], 2020[5], 2021[6] and most recently in 2024 focused on offshore assessment methods[7]. As a result of these studies, UL Solutions' methods have advanced to incorporate improved understanding in areas such as mesoscale modeling, array and plant losses, meteorological campaign design, improvements in data validation.

The 2024 Backcast Study compares pre-construction energy estimates performed by UL Solutions to energy estimates based on the historical operating data for a set of 124 operating wind projects spanning the Americas, Europe and Asia Pacific.

Backcast database

The 2024 Backcast Study relies on UL Solutions' database of complementary pre-construction energy models and corresponding operational energy production models for plants in operation. Pre-construction energy models employ wind resource measurements, long-term reference wind data, wind flow modeling, wake modeling, turbine characteristics, and assessed performance losses to estimate long-term energy production. Operational energy production models employ monthly operational data, adjusted for windiness and atypical events, to estimate long-term energy production based on actual performance. For the backcast database, all of the pre-construction modeling and the vast majority of the operational modeling was performed by UL Solutions; approximately 10% of the operational estimates were performed by third parties using methods judged sufficiently consistent with UL Solutions to qualify for inclusion in the analysis. Screening of the pre-construction modeled plant characteristics (location, capacity, turbine technology, hub height, etc.) compared to the operating project characteristics was done to ensure a valid comparison between the energy estimates.

A total of 124 wind plants representing 422 plant years of operation were selected for the study, with all pre-construction wind flow and energy modeling re-run with Backcast 2018 methodology and each region contributing projects that best represented the range of their typical conditions. This dataset improved on the previous backcast datasets by the number of projects and operating years, geographic coverage, and technology coverage, and also served to focus the validation on more recent and relevant project characteristics. A comparison of the 2024 Backcast Study dataset to previous iterations evaluated is made in the table on the right.

Table 2: Comparison of backcast database by study year

Study year	2008	2012	2018	2024
Wind plants	11	24	61	124
Wind plant region	NA	NA	NA/EMEA	NA/EMEA/LATAM/APAC
Total plant operational years	45	106	253	422
Average operational years per plant	4.1	4.4	5.1	3.4
Range of operational years per plant	1 to 7	1 to 11	1 to 10	1 to 11
Average plant capacity (MW)	74	82	83	128
Range plant capacity (MW)	10 to 160	10 to 210	5 to 239	10 to 500

A focus on more recent projects was implemented in order to limit the influence of outdated project designs and turbine characteristics. Where possible, UL Solutions selected projects that reflect modern turbine technology. The selected plants are sited in a variety of wind resource regimes with diverse terrain types and land cover. The figures below present the range of project characteristics that are represented in the study.

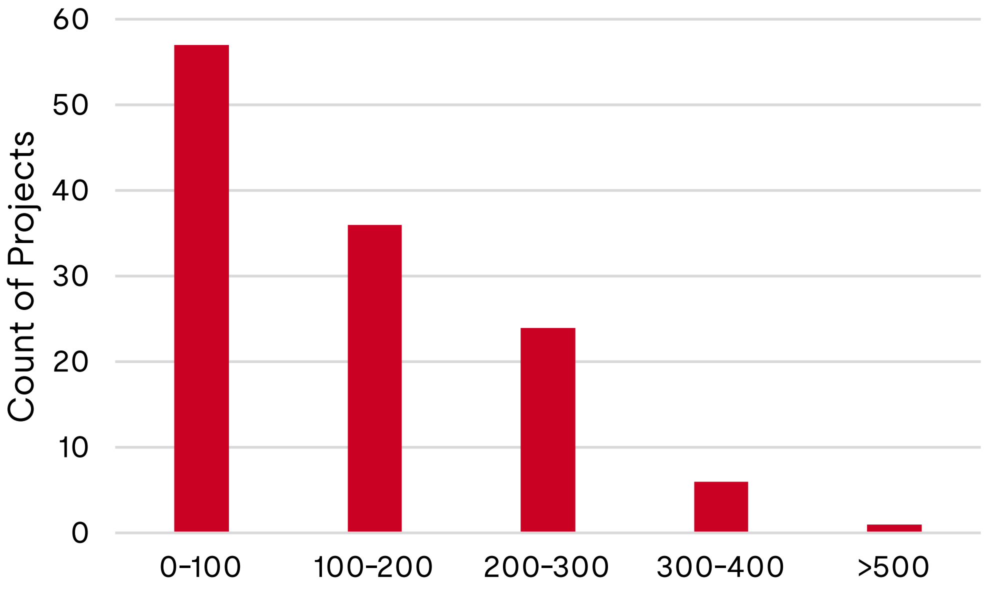


Figure 2: Distribution by project capacity (MW)

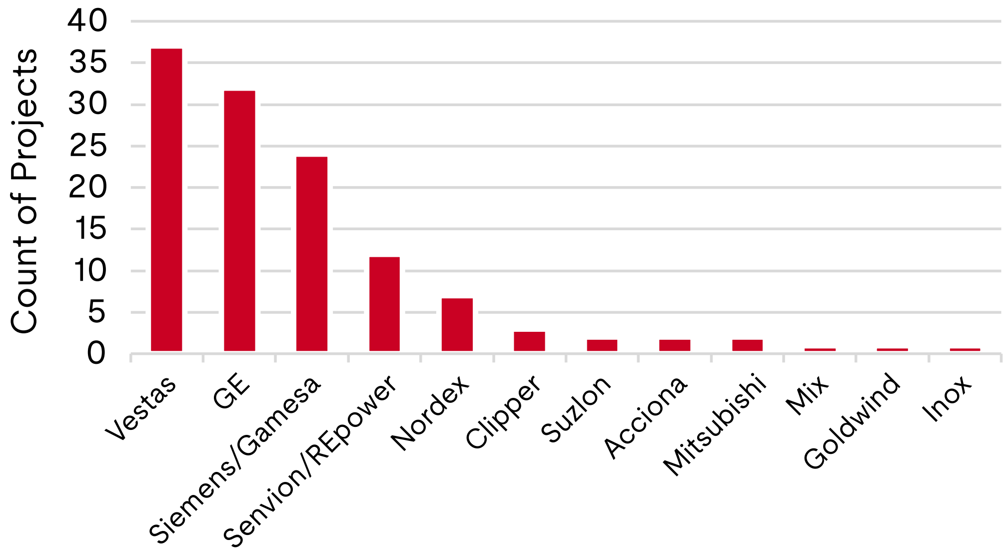


Figure 3: Distribution of OEMs

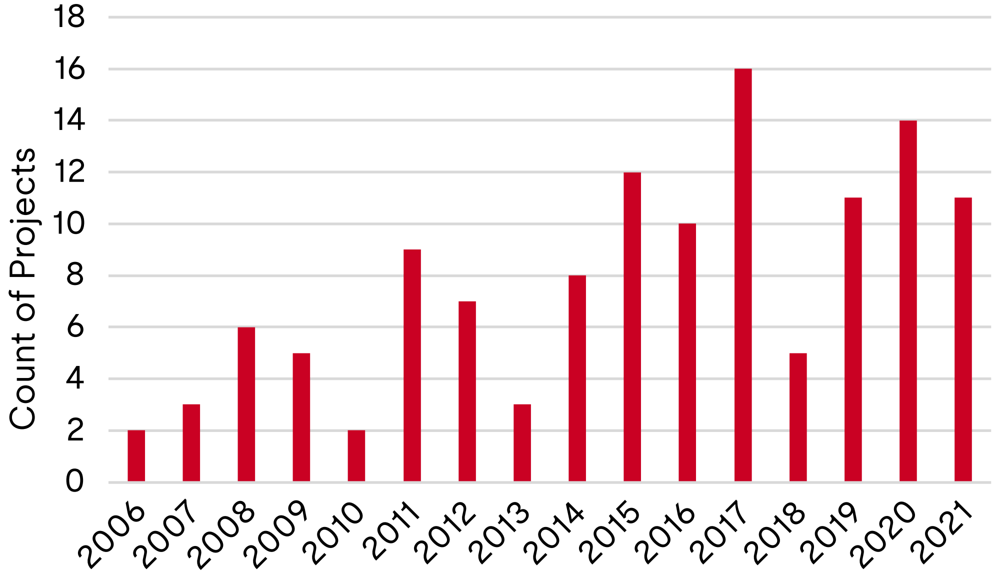


Figure 4: Distribution by COD year

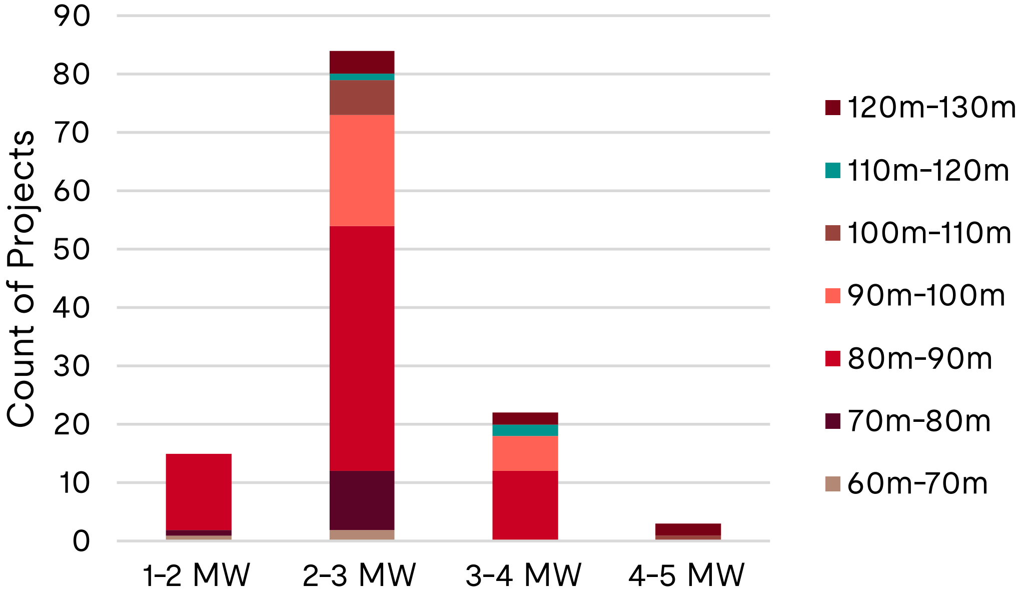


Figure 5: Distribution of rated power and hub height

For the results of the present study to be valid and useful, it is important that the database presents an unbiased picture of the accuracy of UL Solutions' pre-construction methods. Two possible sources of bias are identified. The first is selection bias. Such a bias could have been introduced, for example, if many of the operational assessments were performed at the request of plant owners because the plants were perceived to be underperforming. This could have resulted in an oversampling of underperforming projects compared to other plants. UL Solutions does not believe selection bias to be a significant problem in this study, as a broad spectrum of operational analysis bases were utilized, ranging from individual project requests, fleet analyses and repowering assessments.

Second, some factors affecting energy production might not have been considered or quantified in the energy process. Two factors we have identified fall in this category: grid curtailments (usually resulting from transmission line congestion, and generally not evaluated in pre-construction energy estimates), and wake impacts from neighboring projects that did not exist and whose development was unknown when the analysis was performed. Where possible, UL Solutions mitigated these factors where they could be identified and believe the adjustments to be effective. However, the possibility of a residual bias cannot be excluded.

Method of analysis

As described, the projects selected for the Backcast Study spanned a wide range of COD dates, as did the vintage of their original pre-construction analyses.

To ensure a consistent and accurate comparison across the projects, UL Solutions completed up-to-date pre-construction energy production estimates considering assessment methods according to the 2018 Backcast Study and 2021 uncertainty update, as well as current modeling inputs and assumptions for each project prior to making the comparisons to the operational data.

Operational energy production estimates were prepared by UL Solutions for the majority of the backcast projects. Like in the 2018 Backcast Study, monthly historical operating data was used to complete operational energy assessments, which adjust for the relative windiness of the operational period and adjust to the long-term expectations.

For approximately 10% of the dataset, UL Solutions used third-party operational energy estimates that were reviewed for reasonableness and deemed to have followed similar analysis methods as UL Solutions would apply.

For both pre-construction and operational assessment methods, losses due to grid curtailment were excluded. Therefore, the net P50 comparisons are expressed, excluding such losses, where it was possible to quantify them. Last, external wake considerations due to surrounding farms were aligned so that the pre-construction scenario is consistent with the operational period of record assessed. After updating all energy analyses, the relative difference in operational and pre-construction net P50 values were calculated for each plant and converted to percent, according to Equation 1 below:

Equation 1: P50 bias calculation

$$\text{P50 Bias} = \frac{\text{Operational P50}}{\text{Pre-construction P50}} - 1$$

A positive value corresponds to an overperformance of the operational production relative to the pre-construction estimate or an underestimation of the long-term plant production. Conversely, a negative value indicates an underperformance of operational production, or an overly optimistic pre-construction estimate. The mean and median of all biases and their spread confer information about the overall accuracy of the UL Solutions pre-construction energy estimation process.

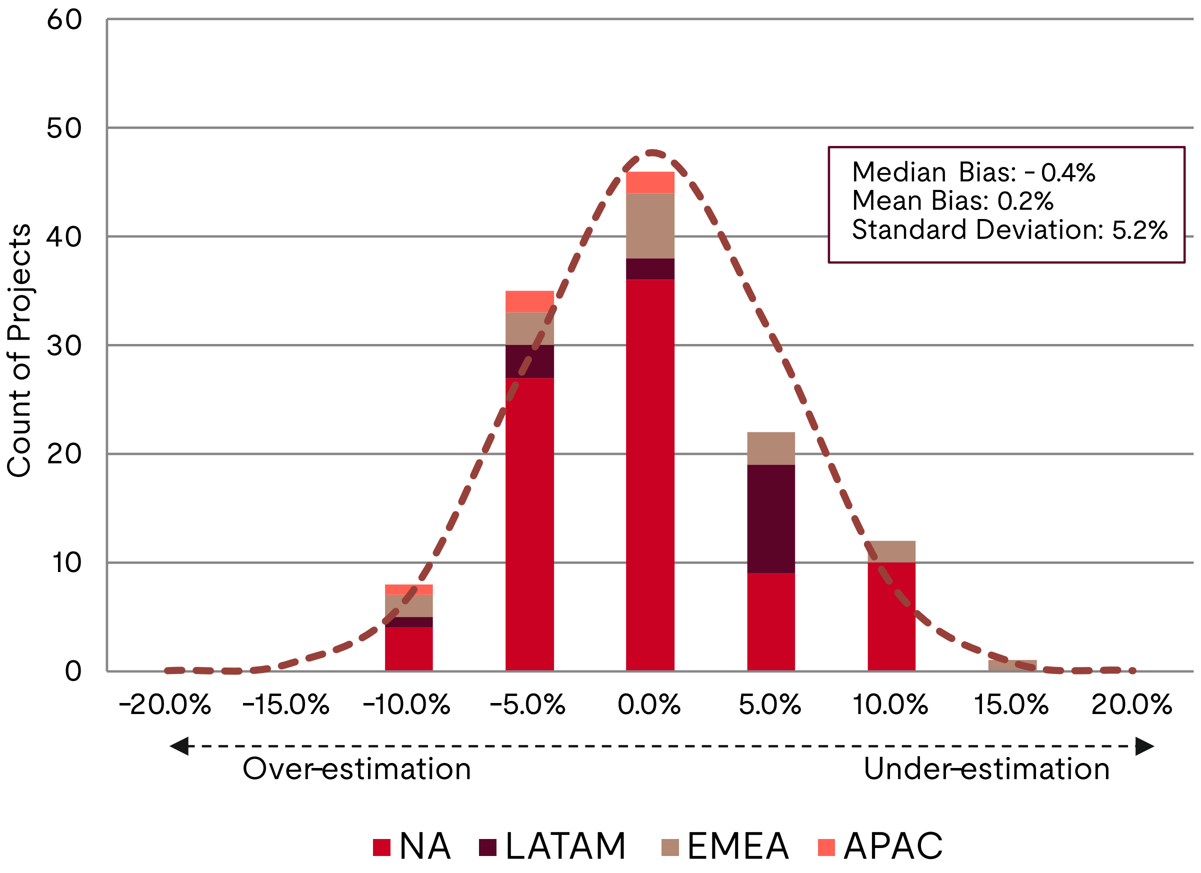
Key findings

Figure 6 shows the distribution of the 10-year evaluation period P50 bias values for the global 2024 Backcast Study dataset before any method updates.

The mean bias for all projects is 0.2%, The median is -0.4%, and the standard deviation is 5.2%. The mean difference of 0.2% is the expected bias, which indicates good overall agreement of the pre-construction estimates with the operational output. However, this value is somewhat influenced by the slightly skewed nature of the distribution, which has an extended tail to a small degree on the high (>0.0%) side. The median bias of -0.4%, which represents the bias exceeded by half the plants, should also be considered when evaluating the results of this validation study.

The standard deviation of the distribution, 5.2%, is smaller than the average uncertainty in the pre-construction estimates, which was 8.3%. Besides supporting the uncertainty estimates, the standard deviation provides an indication of the uncertainty in the mean bias. Assuming the 124 biases between pre-construction and operational estimates are statistically independent, the uncertainty in the mean bias is about 0.5%. The true uncertainty is probably somewhat larger than this, since the backcast database contains some projects that are closely related, and their energy estimates may not be truly independent while the operational assessments being compared against have their own uncertainty.

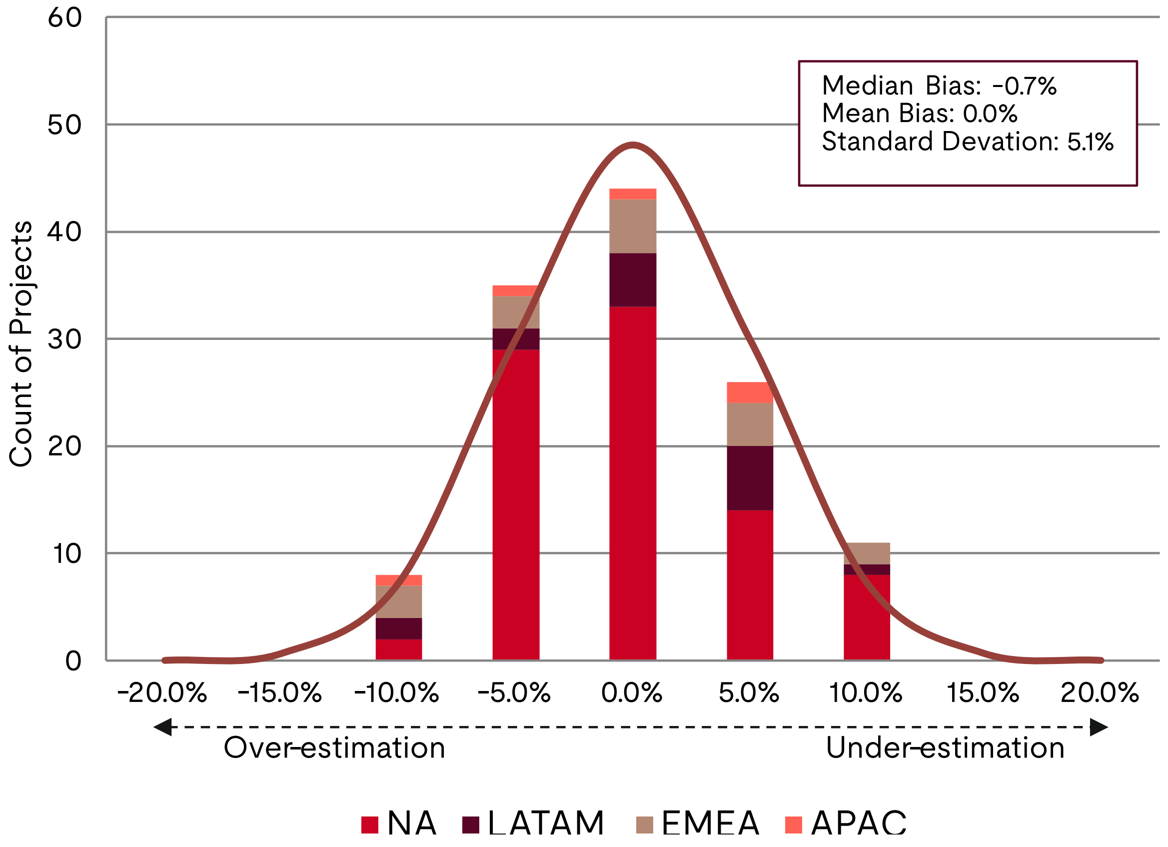
Figure 6: Global bias distribution – before method updates



Considering a target bias of zero, we assessed the statistical significance of the mean and median biases of the dataset, using T-Tests for the mean and Signed-Rank tests for the median, and found them to not be significantly different from zero with a 95% confidence interval. This indicates that the small biases are not a sign of systematic errors in the pre-construction model.

However, while the pre-construction model does not exhibit significant biases, UL Solutions considers it important to continue to improve energy assessment methodologies and validate any method updates. As detailed in Section 6, a number of method changes were implemented to advance loss methodologies and maintain accuracy in the net production. Each individual loss category considered in an analysis is uniquely complex and continued accuracy in the combination of all losses and the resulting net production estimate is paramount. Figure 7 shows the distribution of the 10-year evaluation period P50 bias values for the global 2024 Backcast Study dataset after the method updates.

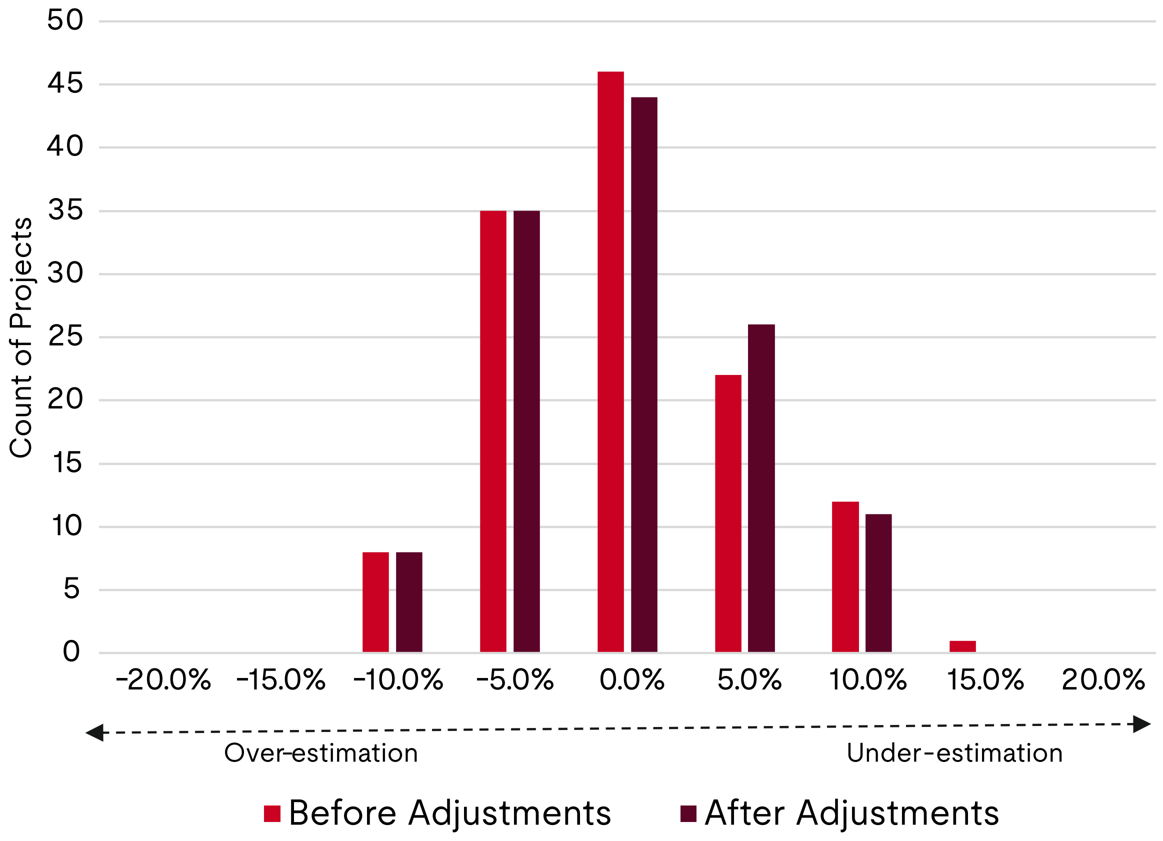
Figure 7: Global bias distribution – after method updates



After applying updated methodologies, the average bias is 0.0%, and the median is slightly more negative at -0.7%. Tests show that these new biases are still not significantly different from zero, indicating that the pre-construction model remains accurate and reliable, and the slight changes in median bias are not significant enough to cause concern.

The resulting change in distributions can be seen in Figure 8 below.

Figure 8: Global bias distribution – before and after adjustments



Key findings – North America (United States and Canada)

The majority of the projects in the global dataset are from North America, and it is therefore a large driver in the global results. Table 3 contains a summary of the data utilized for North America. Figure 9 shows the relative distribution of the projects across the states, with opacity increasing with the number of projects.

The initial results for North America showed the mean bias to be 0.0%, with the median of -0.7%. These differences from zero bias are not found to be significant with a 95% confidence interval. While this provided confidence in the pre-construction methodology, methods updates are applied as described in this report and the resulting mean and median biases do not change. While there is no change in those metrics, the standard deviation and standard error of biases are reduced slightly, and the magnitude of some higher bias projects is reduced. This is visualized in Figure 10 below.

Table 3: North America backcast database subset

Wind plants	86
Total plant operational years	332
Average Operational Period of Record (years)	4 (1 to 11)
Average Age per Plant (years)	6 (1 to 12)
Average plant capacity (MW)	157 (14 to 500)
Average Turbine Hub Height (m)	86 (78 to 122)
Average turbine rated power (MW)	2.5 (1.5 to 4.5)

Figure 9: North America backcast database map

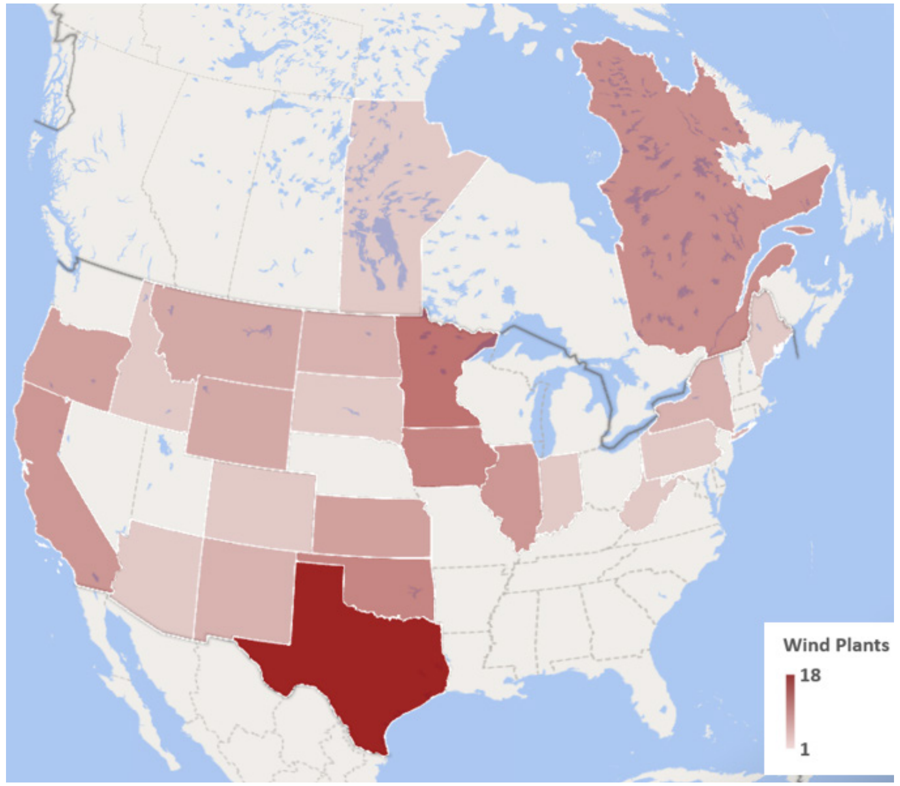
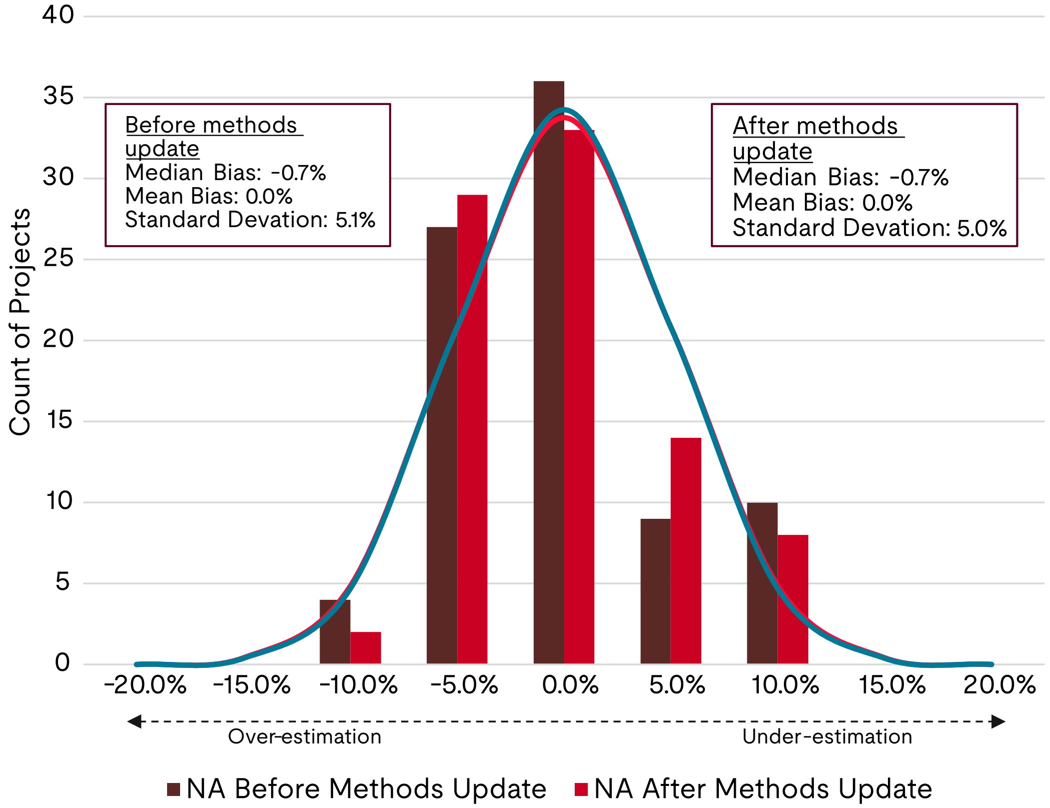


Figure 10: North America bias distribution – before and after methods update



Methods Changes

Flow effect losses

The Flow Effect loss, also known as array loss, turbine interaction, or wakes and blockage, generally constitutes a significant component of overall losses in an onshore wind project. The Deep Array Eddy Viscosity Wake Model (DAWM-EV) is used as standard, which combines the standard Eddy Viscosity model with a UL Solutions-developed boundary layer model. Previous validations of the DAWM-EV in 2012[8] and 2017[9] (validated at five sites, two onshore and three offshore) have proved robust through an offshore benchmarking study by Orsted[10, 11], where it exhibited the lowest mean bias of all independent providers of wake models.

In addition to the DAWM-EV in 2018, UL Solutions adopted an empirical wind project blockage model derived from operational bias observations. This model uses wake losses, project size and array geometry as a proxy for estimating blockage loss. As part of the 2024 Backcast Study, that blockage model is retired and replaced with the Gribben Rankine Half-Body Induction (RHB) Model coupled with increases to the DAWM turbine roughness settings and removal of the Eddy Viscosity Near Wake Filter. The RHB model combines uniform flow with a point source to simulate how the flow field is impacted by the presence of a turbine. While it does not take account of atmospheric stability, turbulence intensity or atmospheric boundary layer (ABL) height, and therefore does not attempt to model the global blockage effect, it is added to include some measure of the local induction effects. An updated validation study[12], based on onshore turbine SCADA data and meteorological data from 13 sites, is available on request.

The backcast projects cover a large range of turbine and project sizes, as well as buildout scenarios. The modeled flow effect losses, using the updated settings, range from 2% to 19% and include cases of external array effects of up to 11%. The implemented changes represent an average increase of approximately 0.5% to the flow effects losses compared to using the previous model settings. Flow effect loss changes will vary by project configuration, but across the global dataset, the RHB Induction Model makes up approximately 1.2% of an increase and impacts all projects. The removal of the Near Wake Filter reduces array losses by approximately 1.0% but is more impactful on tightly spaced (<5.5 RD) turbine arrays. The third adjustment to the DAWM turbine roughness settings results from the wake model validation study and compensates for the remainder of the legacy approximation of a blockage effect.

UL Solutions remains committed to developing, validating, and providing access to its turbine flow effect models and is advancing other wake model developments that will be validated in future backcast studies.

Availability assumptions

Over the past 20 years, UL Solutions has had opportunities to validate availability loss assumptions against historical operational data to make sure that they are appropriately describing the expectations for project operations. Each validation has built on the previous and incorporated the latest operational data available. The same is the case for the availability validation undertaken as part of the 2024 Backcast Study. Several parallel reviews were completed, and then compared, to arrive at updated assumptions regarding turbine, Balance of Plant (BOP), grid and site access availability components. The resulting changes to the availability assumptions include:

- Elimination of the Long-term Availability Correlation with High Wind Events (LACHWE) subcategory and switch to all production-based assumptions
- Updates to turbine, grid and BOP (formerly called collection and substation) availability values
- Site Access subcategory moved from the environmental to availability loss category
- Introduction of time varying components

SCADA availability study

UL Solutions' potential production and classification algorithms were leveraged to calculate operational availability for more than 35 wind farms, made up of over 2,250 individual turbines. These algorithms were applied uniformly to all plants which are representative of a general sample, both geographically (11 countries) and inclusive of all major turbine original equipment manufacturers (12 OEMs). UL Solutions' potential production and classification algorithms leverage, by design, a minimal amount of turbine information, making them suitable for bulk analysis for different wind turbine types.

Classification

UL Solutions utilized a Parameter Space Classifier, which leverages Supervisory Control and Data Acquisition (SCADA) signals of turbine power, nacelle anemometer wind speed, air density, time, and the OEM power curve and assigns a defined category to each record. The classifier works by projecting these signals into a space that is defined along, across, and perpendicular to the OEM power curve. The across dimension corresponds to air density and the distribution of observations in the along and perpendicular dimensions are then used to assign categories according to IEC61400-26-2 Full Performance and Partial Performance. Several other thresholds are used to categorize observations into other categories; wind speed out of range and turbine non-operative. Potential production is then calculated and used in a refinement step with time and several low pass filters to further classify periods of derating, short period off time, long period off time and grid curtailment.

The table on the right presents the IEC61400-26-2 availability categories with an additional sub/aggregate level specified by UL Solutions. The grey cells in the table represent those classifiable by this approach.

Table 4: IEC61400-26-2 categories, with added sub/aggregate levels

IEC Level 1	IEC Level 2	IEC Level 3	IEC Level 4	Assumed Sub/ Aggregate Level
Information Available (IA)	Operative (IAO)	Generating (IAOG)	Full Performance (IAOGFP)	
			Partial Performance (IAOGPP)	IAOGPP-control
			Partial Performance (IAOGPP)	
		Non-Generating (IAONG)	Out of Environmental Specification (IAONGEN)	Low Wind (IAONGEN-low)
				High Wind (IAONGEN-high)
				Other
			Technical Standby (IAONGT)	IAONG-TS-RS
			Requested Shutdown (IAONGRS)	
			Out of Electrical Specification (IAONGEL)	
		Scheduled Maintenance (IANOSM)		
	Non-Operative (IANO)	Planned Corrective Action (IANOPCA)		
		Forced Outage (IANOFO)		
		Suspended (IANOS)		
	Force Majeure (IAFM)			
Information Unavailable (IU)				

Potential production

For this study, UL Solutions developed nacelle wind speed turbine power curves to use in the calculation of potential production. These were derived from the SCADA data using one of three estimation techniques: MLE Minimum Chi-square Estimation (MLE), Path Classifier Deviation from Ideal Curve (Path Classifier) and OEM Power Curve with Free Stream Transfer Function. The majority of plants used the MLE technique, and the OEM curve was used for the fewest number of plants. Potential production was calculated for each time step using these nacelle wind speed power curves, along with wind speed from the turbines. Where no wind speed can be gauged from on-site data, a reanalysis dataset is used to determine wind speed and potential production. The calculations yielded a complete time series of potential production at each turbine location in a plant.

UL Solutions pre-construction equivalent availability

UL Solutions used the classifications and potential production to calculate availability values for the three standard IEC61400-26-2 definitions: system operational production-based availability (SOPBA), turbine operational production-based availability (TOPBA) and technical production-based availability (TPBA). All three definitions are based on a basic equation described in Equation 1 below, but with variations to the loss categories in the numerator and denominator.

Equation 2: Generalized production-based availability (PBA)

$$\text{PBA} = 1 - \frac{\text{Lost production}}{\text{Actual Production + Lost Production}}$$

In addition to these IEC definitions, the study calculated pre-construction equivalent availability values to align with the turbine availability assessed in pre-construction energy estimates. This quantification consists of short period and long period downtime not associated with partial production, with carve-outs for lightning, high wind hysteresis and temperature. Periods that experienced other types of downtime, for example, icing and curtailment from acoustic, avian and wind sector management (WSM), were filtered out of the records considered based on background knowledge of the project-specific characteristics. The definition uses categories consistent with IEC61400-26-2 (IAONGTS, IAONGRS, and IANO), and accounts for the removal of the impact of the downtime events, which are quantified elsewhere in the pre-construction analysis. This is described by Equation 2 below, which refers to the IEC classifications found in Table 4.

Equation 3: UL Solutions pre-construction equivalent availability

where,

- P_{LP} = Lost production
- P_A = Actual production
- F_L = Lightning loss
- F_{HWH} = High wind hysteresis loss

$$\text{Pre-construction PBA} = 1 - \left(\frac{\text{IANO:}P_{LP} + \text{IAONGTSRS:}P_{LP}}{\text{IAOGFP:}P_A + \text{IAOGPP:}P_A + \text{IANO:}P_{LP} + \text{IAONGTSRS:}P_{LP}} - F_L - F_{HWH} \right)$$

Results

The application of the pre-construction equivalent availability yields values that fall between the TOPBA and TPBA definitions, which is expected due to the relative definitions. When aggregated to monthly values, filtering for first-year levels and other data unrepresentative of long-term availability, the metric provides a reasonable estimate of expected energetic availability for pre-construction energy estimates.

The distributions of the four availability definitions which were calculated from the SCADA can be seen in the figure on the right. The distributions are non-normal and the median value can be assumed representative of the central tendency, or expected value; for the pre-construction equivalent availability the median is approximately 95.5%.

A review of the monthly availability, considering this consistent, energy-based definition, formed the basis of UL Solutions' updated turbine availability assumptions, confirmed with the statistics from other operational data sources as discussed below.

Monthly operational availability statistics

UL Solutions has access to several large sets of monthly historical operating data, which were aggregated and reviewed. The challenge of considering these large datasets lies in the variability in the availability definitions across projects. However, when considered in aggregate, UL Solutions finds that the summary statistics can be used for comparison purposes and to inform various aspects of our assumptions.

Based on almost 2,000 years of data across over 330 operating plants, plant availability levels by age are found to be reasonably consistent with the SCADA study and suggest availability levels are likely to reduce in later years of operation.

Figure 11: Pre-construction equivalent availability relative to IEC definitions

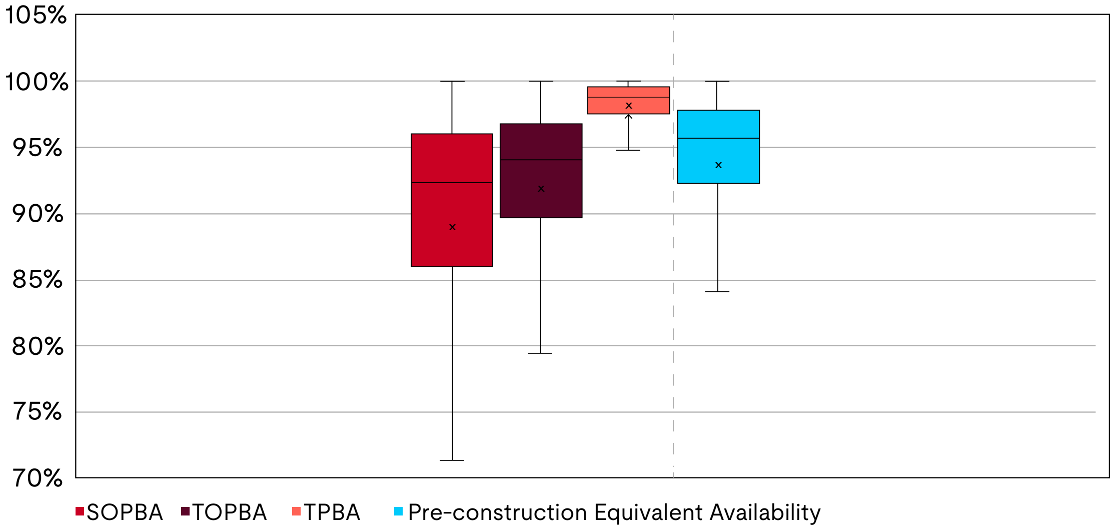
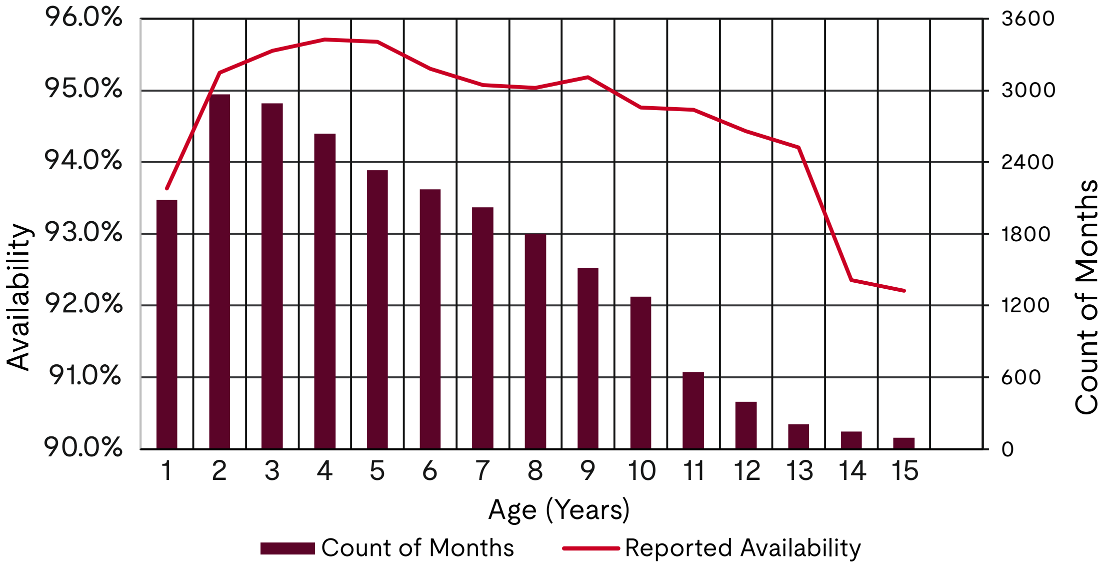


Figure 12: Monthly operational availability statistics over time



Balance of plant and grid availability

UL Solutions has changed the terminology from “collection system and substation availability” to “balance of plant (BOP) availability.” A review of 100 years of monthly operational reports found this loss to approximate to 99.5%. In addition, it is found that first year BOP availability is expected to be 1% lower than mature operational levels.

As part of IE services, UL Solutions has the benefit of reviewing multiple transmission reports and has extracted expected grid availability levels from those. From these reports, the grid availability levels average approximately 0.4% to 0.5%. UL Solutions will assume a grid availability level of 0.5% going forward, inclusive of any plant restart-related lag in production.

Availability updates

From the results of the study and operational statistics described above, UL Solutions was able to re-evaluate its availability loss assumptions for the purpose of pre-construction energy production estimation. The updated first year, 10-year, 20-year and 30-year evaluation period availability assumptions that will be considered going forward are presented below.

Notably absent from the future categories is the Long-Term Availability Correlation with High Wind Events (or LACHWE) loss, which was a part of UL Solutions assessments prior to the 2024 Backcast Study. The latest availability validation has allowed for direct evaluation and application of production-based availability definitions and reflects that back in the updated turbine, BOP and grid availability assumptions, essentially eliminating the need for this additional loss category.

UL Solutions has historically considered a loss associated with the inability to access a site to perform repairs and remediate production-related issues due to environmental conditions (site access loss) as part of the Environmental Loss category. Going forward, UL Solutions will consider the site access impact as a component of turbine availability loss.

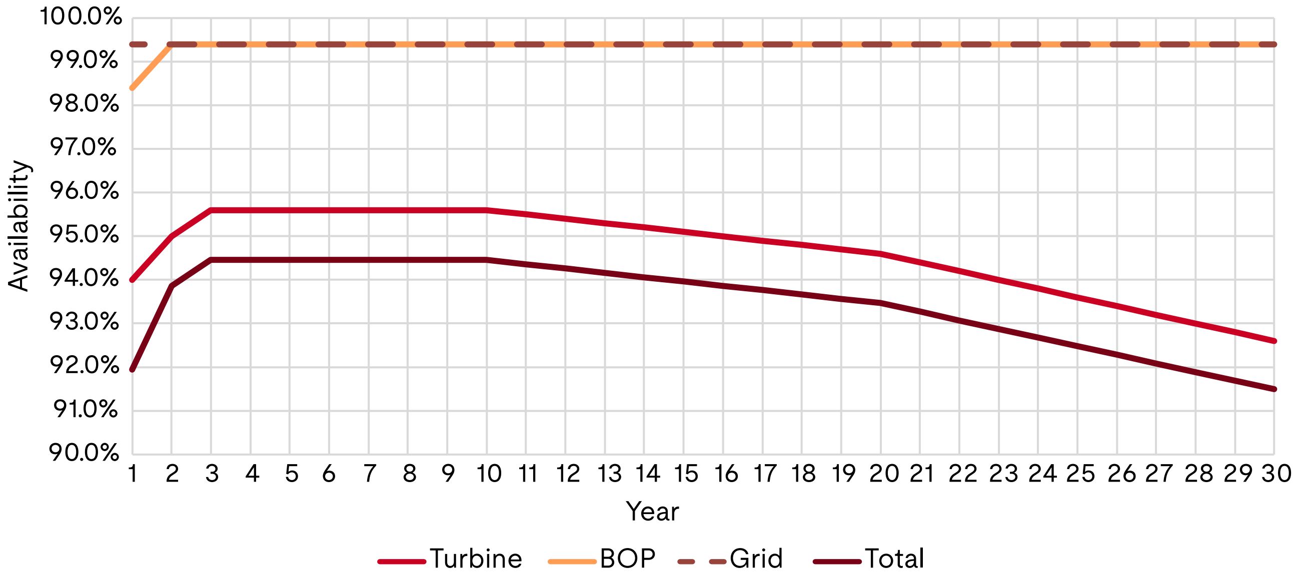
While UL Solutions’ previous assumption was that an appropriate O&M budget would be maintained to sustain the same availability over the mature operation of the project, the data has shown that there is a reduction in availability over time. Based on industry feedback, even with a robust O&M budget, the cost/benefit-based decisions regarding maintenance change as the projects age, along with the incidence of component failures and issues. The figure below shows the time varying aspect of UL Solutions’ availability assumptions following the 2024 Backcast Study.

Table 5: 2024 Backcast study updated availability categories and loss assumptions

Availability component	Year 1	Years 2-10	Years 11-20	Years 21-30
Turbine availability*	6.0%	4.5%	4.9%	6.5%
BOP availability	1.5%	0.5%	0.5%	0.5%
Grid availability	0.5%	0.5%	0.5%	0.5%

*Varies slightly with site access

Figure 13: Indicative time varying availability losses



Power curve loss

UL Solutions has consistently monitored and modified power curve loss modeling through successive validation exercises, leveraging its growing power curve test database. The database, which now contains over 600 tests across approximately 10 OEMs, is used to inform turbine-specific and default loss assumptions.

Subsequent to the 2018 Backcast Study, UL Solutions introduced the concept of a Power Curve Prediction Method Verification (PCPMV)[13]. This was designed to allow for more forward-looking power curve loss adjustments, rather than solely relying on acquiring sufficient applicable tests for a particular turbine type. With the PCPMV, UL Solutions examines in detail the processes by which an OEM develops its power curves and assesses consistency with power curve generation of specific future turbine models. Based on those reviews and their findings, an adjusted power curve loss is assigned. To date, these exercises have been successfully performed on Vestas, GE and Nordex turbines. As the target turbines are introduced to the market and their test results become available, it is possible to compare to UL Solutions' initial predictions in terms of the test AEP efficiency. A comparison of the results from the initial available tests for the three OEMs is shown below:

Table 6: PCPMV results comparison to OEM tests

OEM	PCPMV estimate	Initial test results	Number of tests*
Nordex	98.6%	98.8%	6
GE	99.1%	102.1%	2
Vestas	98.7%	99.9%	30

*Disparities in the number of tests are in part due to the timing of PCPMV studies across OEMs and the range of target turbines assessed.

The UL Solutions Power Curve Adjustment loss has three fundamental bases; being informed by available turbine test results, being informed by fleet PCPMV results, or having no turbine or fleet-specific information to adjust the loss. In each case, unless sufficient turbine-specific test results are available, a default power curve loss is incorporated into the overall loss estimate.

Following the 2018 Backcast Study, the Default power curve adjustment loss was set at 2.1% and was based on 69 tests that did not qualify for any loss adjustment at that time. While the database has grown threefold since 2018, the number of turbines not qualifying for any loss adjustment has reduced, leaving insufficient representative data to inform this loss going forward. UL Solutions evaluated the full database of power curve test results to determine which are most representative of the unproven turbine performance that the default power curve loss is intended to represent.
As the PCPMV process has proved to be robust in capturing expected performance for newer turbines and allows UL Solutions to clearly understand the processes by which the power curves are being developed, tests for turbines that have undergone the PCPMV evaluation process were removed from the calculation.

Figure 14 provides a breakout of the tests in UL Solutions' power curve database by OEM and PCPMV status, and a comparison of the test results for PCPMV and non-PCPMV turbine models is shown in Figure 15. The remaining dataset, including all power curve test results except for those reviewed for PCPMV, results in a new estimate of 1.6%, which now serves as a basis for different loss adjustments.

The reduction of this default power curve loss from 2.1% to 1.6% does not result in a net improvement in the overall P50 bias and is estimated independent of site-specific wind shear and turbulence conditions. To compensate, UL Solutions now adds a variable component to all power curve adjustment loss estimates, which is based on site wind shear and turbulence conditions and considers timeseries data from over 90 power curve tests. The inclusion addresses a limitation of the previous loss implementation, which did factor in site-specific speed distributions and high-level turbulence quantification but was limited in capturing the impact of shear and turbulence distributions. The average loss from the new site-specific component in the backcast database is 0.4%, and replaces any previous turbulence filtering of test results. In effect, turbines where we do not have sufficient test results or PCPMV information, the total default loss will approximate to 2.0%, similar to the previous 2.1%, but vary to a small degree with site conditions. Additionally, for turbines with a lot of test information, the site-specific component will likely increase the loss.

These changes result in a net increase of power curve adjustment losses of approximately 0.3% across the backcast database and provide robust mechanisms for assessing nascent turbine technology in various site conditions.

Figure 14: UL Solutions power curve database

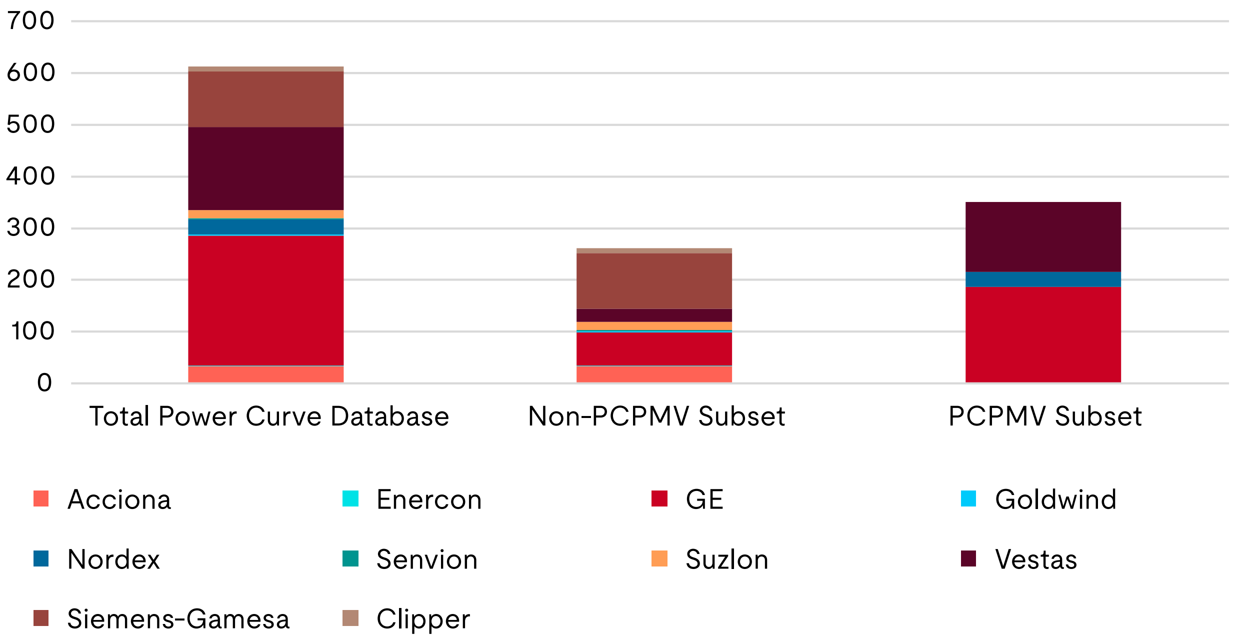
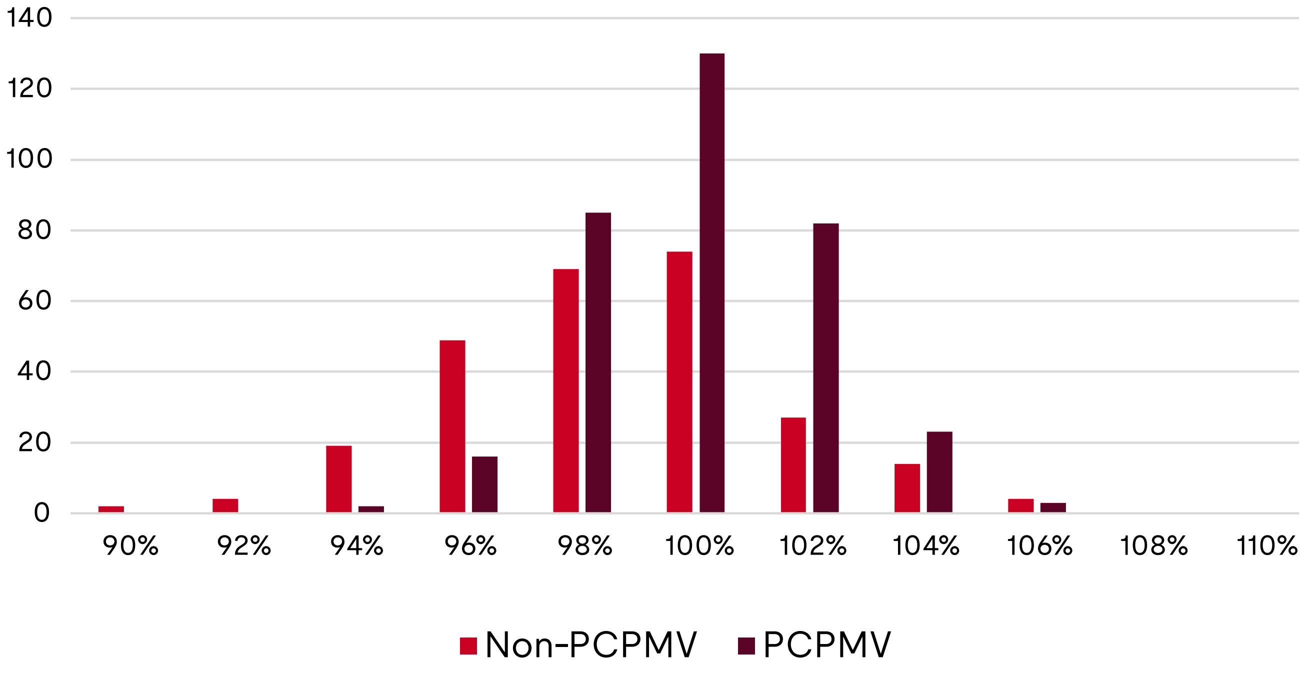


Figure 15: Distribution of power curve test AEP efficiency for non-PCPMV and PCPMV turbines



Other updates

Default electrical loss

A review of projects for which UL Solutions has received electrical loss estimates based on detailed design show that the average loss is approximately 2.3% to the point of interconnection (POI). This represents a minor update from the previous default of 2.4% and, with over half of the projects in the backcast dataset already including a site-specific loss, the impact on the results is negligible.

In addition to the overall electrical loss, a more detailed component level assessment was performed. This resulted in the following breakdown of component averages for typical projects configurations.

For projects or regions where certain components of the design may have negligible losses, the default of 2.3% can be adjusted accordingly, though a detailed design estimate is recommended.

Lighting loss

UL Solutions identified lightning loss calculations as an area of potential refinement and alignment with the detailed lightning risk review scope of work offered by UL Solutions Asset Advisory team. Previously, the lightning loss calculations have relied on a single conversion factor applied to the lightning flash density for a project area. In the new calculations, UL Solutions calculates the number of turbine lightning strikes expected at a project per year based on the IEC-61400 24 Ed 2.0 Standard for Lightning Protection Systems. This calculation considers the turbine height and rotor diameter and relies on lightning strike density for the project location as an input.

For the United States, the lightning strike density data is from the NCEI NOAA National Lightning Detection Network dataset[14, 15]. Outside the United States, UL Solutions applies the conversion from the IEC Standard for lightning flashes to lightning strikes to the lightning flash density dataset that has previously formed the basis of our loss. Using the calculated turbine strikes, UL Solutions applies reasonable but generic assumptions to estimate the amount of damage and resulting downtime the wind project will experience to estimate the energy loss.

Table 7: Average site-specific electrical loss over time

Year	Electrical loss	Count
2012 to 2015	2.6%	40
2016 to 2019	2.2%	109
2020 to 2024	2.3%	109
Weighted average	2.3%	

Table 8: Breakdown of electrical loss by component

Component	Loss
Turbine transformers	0.8 %
Collection system	0.8 %
Substation transformers	0.3 %
Transmission to the POI	0.4 %
Total	2.3 %

Blade degradation

Prior to the 2024 Backcast Study, it has been UL Solutions' assumption that blade refinishing is conducted 10 years after COD, and therefore the portion of the blade degradation loss associated with damage to the blades would "reset" back to zero at that point. Recent reviews of wind projects' operational histories have indicated that rarely is a single large blade refinishing undertaken on this schedule and more often, blade refinishing and aerodynamic improvements are made on an ad hoc basis depending on the project's specific characteristics and needs. Even with the attention to blades, although variable by project, degradation is observed in the operating data as wind projects age. Therefore, UL Solutions assumption going forward will be that blade degradation energy losses will continue at the rate of 0.1% per year throughout the project life, in the absence of a specific refinishing plan and schedule provided for a project. This change will impact estimates extending beyond 10 years from COD.

Conclusions

The 2024 Backcast Study is essential for maintaining and increasing the confidence of all stakeholders in onshore wind energy estimation methods and results. UL Solutions used this study to understand both how the current methods were performing compared to operational data, as well as to introduce and validate various method changes aimed at refining and improving future pre-construction energy predictions across a variety of projects.

Before these updates, our mean bias of 124 evaluated projects using the pre-2024 Backcast Study methods was 0.2% (median of -0.4%), indicating that those pre-construction energy assessment methods underestimated actual production. A small bias from a large dataset suggests a robust pre-construction energy methodology to estimate P50 production levels; however this exercise also serves to validate changes in methodology, reduce outliers, and maintain confidence in the derived results, while not introducing additional systematic error.

The mean bias was maintained at a similar level of 0.0% (median of -0.7%) with the following methods changes incorporated:

- A replacement of the 2018 era blockage loss model with updates to the Deep Array Wake Model, Eddy Viscosity, and incorporation of the Rankine Half-Body Induction model.
- Removal of the Long-Term Availability Correlation with High Wind Events ("LACHWE") Availability loss category and update to the turbine and plant energetic availability assumptions.
- Expansion of time dependency in availability losses for longer evaluation periods.
- Updates to the default power curve loss, coupled with refined site-specific considerations.
- Refinement of the underlying data and assumptions that inform lightning, electrical and blade degradation losses.
- Our experts continue to monitor the accuracy of these methods and may consider updates from time to time in response to emerging evidence.

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