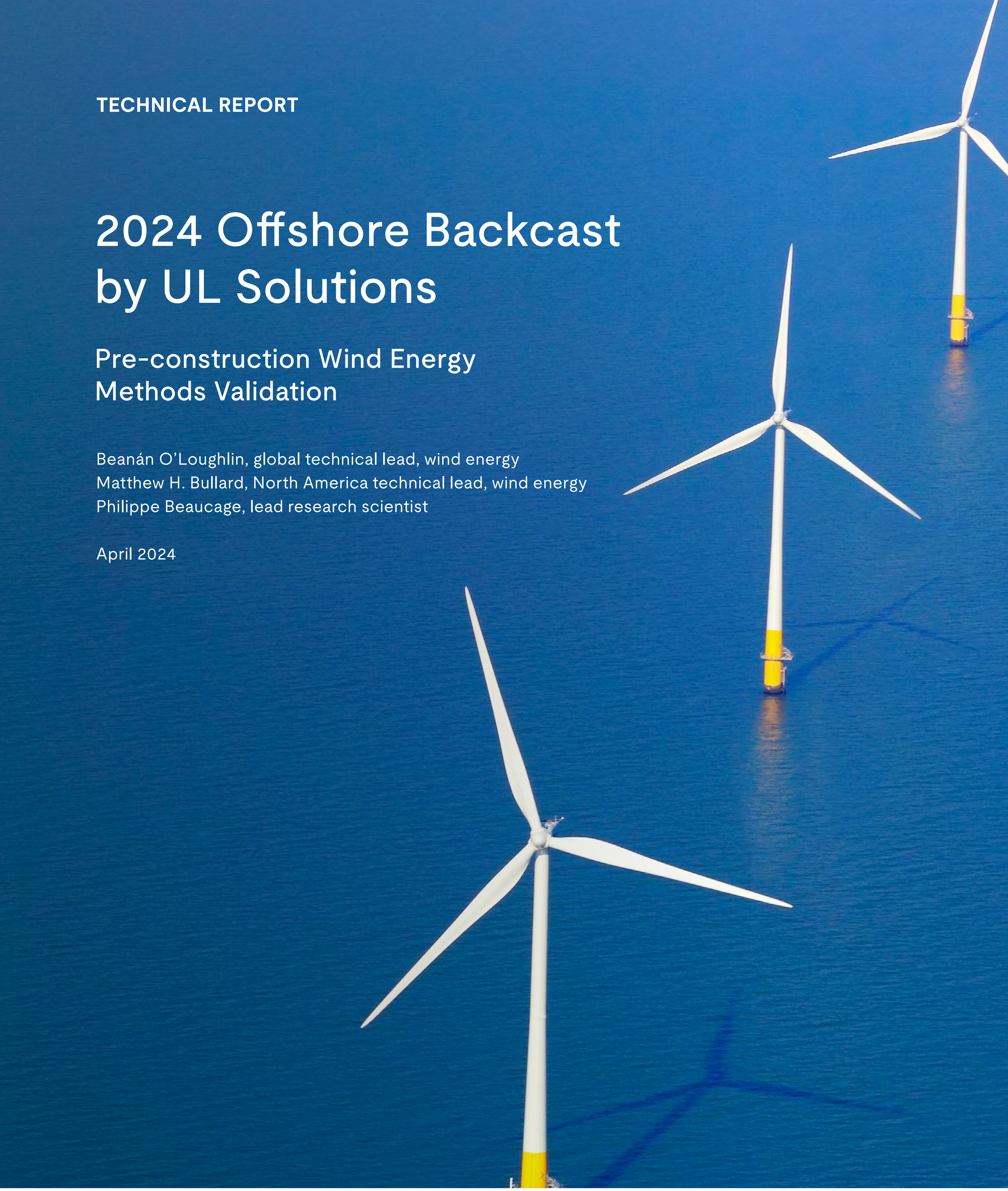

TECHNICAL REPORT

2024 Offshore Backcast by UL Solutions

Pre-construction Wind Energy Methods Validation

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April 2024

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Executive summary

UL Solutions has been engaged in offshore wind resource and energy assessment for many years, including experience with some of the earliest commercial wind projects in Europe and North America. Our methods for offshore wind resource and energy assessment have largely been derived from extensive experience with onshore wind including adaptations tailored for the offshore environment, but these methods have not been validated until now.

While the main objective of the 2024 Offshore Backcast is to validate bankable P50 energy estimates for UL Solutions, it also serves to establish a common method for pre-construction offshore wind energy analysis.

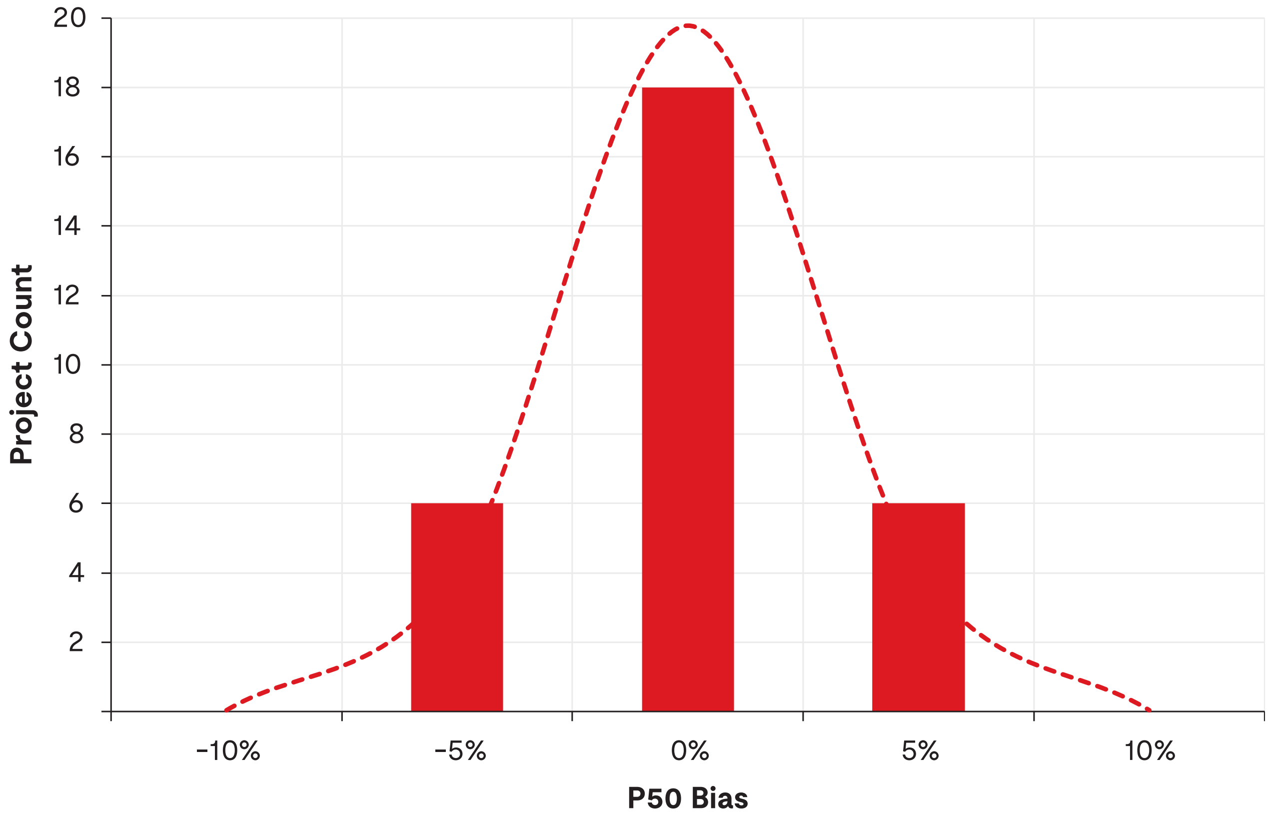

Figure 1: Distribution of production ratios for the 2024 Offshore Backcast (<0% = over-optimistic)

The 2024 Offshore Backcast focuses on validating updated methods and assumptions for array (wake and blockage), availability, electrical, and power curve adjustment losses for offshore wind projects, according to the following revisions:

- Array losses will continue to be modeled using the UL Solutions Deep Array Eddy Viscosity Wake Model (DAWM-EV), but with the 2018-era empirical blockage model being replaced by a combination of the Rankine Half-Body Induction Model and updates to the DAWM-EV settings.

- Availability losses are assumed to be energy-based and inclusive of the availability of turbines, balance of plant (BoP) collection and substation, and the utility grid. The impact of site access will now be assessed as a component of turbine and BoP availability. Turbine availability loss (inclusive of contractual and non-contractual availability) typically ranges from 3.0% to 5.0%.

- Electrical losses in the absence of project-specific design criteria will encompass turbine transformers (as applicable), collection system cabling, offshore substation transformer, high-voltage landfall cabling, any additional high-voltage onshore cabling, and the on-shore substation. The standard electrical loss assumption in the absence of project-specific design criteria will be 3.8%.

- Power curve loss will be based on aggregated offshore power curve test data and average roughly 1%.

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 (EPE) is given paramount 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, we periodically update and validate our energy assessment methodologies. This report outlines our results with specific considerations for offshore wind energy assessment.

We refer to the process of verifying our energy production estimation methods against actual project performance 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] and 2021[6]. As a result of these studies, our methods have advanced to incorporate improved understanding in areas such as mesoscale modeling, array and plant losses, meteorological campaign design, improvements in data validation, and other areas. These backcast studies have, until now, been performed using onshore projects. As a result, our offshore analysis methods have been a derivative of these validated onshore methods.

The 2024 Offshore Backcast compares pre-construction energy estimates performed by UL Solutions to energy estimates based on the historical operating data for a set of 30 operating offshore wind projects spanning the Irish Sea, English Channel, Thames Estuary, English North Sea, and German North Sea. The study finds a median and average bias of 0%, with a standard deviation of 2.8%. The spread of individual results is consistent with our uncertainty methods and reflective of the level of project-specific information available.

Offshore wind project database and method of analysis

The 2024 Offshore Backcast relies on data from a set of 30 operating offshore projects spanning the Irish Sea, English Channel, Thames Estuary, English North Sea, and German North Sea, totaling approximately 8.2 gigawatts (GW) of installed capacity. Project data, including pre-construction meteorological and ocean (metocean) conditions data, wind project coordinates, turbine specifications, and operational production data, were collected from publicly available repositories[7,8] and included with UL Solutions' proprietary datasets.

We then utilized typical methods for analyzing available pre-construction meteorological data. For each project, onsite meteorological data from both floating lidar systems (FLS) and fixed meteorological towers were adjusted to represent long-term conditions using the measure-correlate-predict (MCP) method. The resulting long-term adjusted time series were then incorporated into our wind flow modeling system, Sitewind.

Sitewind combines mesoscale and microscale models to simulate the wind climate over a wide range of scales. The mesoscale model used for this project is the open-source Weather Research and Forecasting (WRF[9]) model run on a grid scale of 1 km. It assesses regional climate conditions and simulates complex meteorological phenomena such as island and mountain wake, channeling through mountain passes (i.e., gap flows), lake and sea breezes, low-level jets, and coastal barrier jets.

WindMap, also developed by UL Solutions, is the microscale mass-conserving model we used for this study — and was run on a grid scale of 200 m.[10] WindMap accounts for the localized influences of topography and surface roughness changes, producing a detailed wind resource map and grid. As a final step, the wind resource grid was adjusted to expected long-term wind conditions using long-term adjusted wind speed, direction and temperature time series resulting from the MCP process described above.

Openwind, our modeling and layout design software, and a project-specific analysis of plant and array losses were then used to model EPEs for the 30 individual projects. The pre-construction wind resource assessments and EPEs for each project were carried out using our current methods regardless of project age.

We prepared operational energy production estimates (OEPE) for each of the 30 operating wind projects. These OEPEs utilized a mix of publicly available production data[2], monthly operating reports and supervisory control and data acquisition (SCADA) data. Then, we adjusted for windiness and atypical events to estimate long-term energy production based on the actual performance of each project. In some cases, we truncated operational data to include only periods with consistent wake impacts from neighboring projects such that the projects were assumed to be representative of a large-scale buildout. Additionally, single-year OEPEs were compiled for each project resulting in a set of OEPEs representing 112 wind farm years.

Due to the source and age of the available data, assumptions were made to reconcile differences between pre-construction and operational datasets, including measurement heights and locations, turbine hub heights, project layouts and power curves.

Prior to any adjustments and assuming pre-backcast methods, the mean bias of the pre-construction energy estimates for the 30 projects in the 2024 backcast dataset is 4.0% with a standard deviation of 2.8% and a maximum bias of 10.0%. This implies that, on average, operational projects overperform relative to the pre-construction estimate or, conversely, that pre-construction estimates underpredict actual project performance.

Key findings

UL Solutions has historically applied loss assumptions for offshore assessments derived and adapted from our validated onshore methodology. The primary goal of the 2024 Offshore Backcast study is to refine a suite of offshore-specific loss assumptions that are combined to produce a validated, offshore-specific EPE methodology.

While each individual loss category is uniquely complex, accuracy in the combination of all losses and the resulting net production estimate is paramount. The distributions in Figure 2 present the resulting biases in net production estimates before and after the application of our updated loss methodologies resulting from this backcast comparing pre-construction estimates to operational estimates.

Greater than 0% implies the operational project is overperforming relative to the pre-construction estimate.

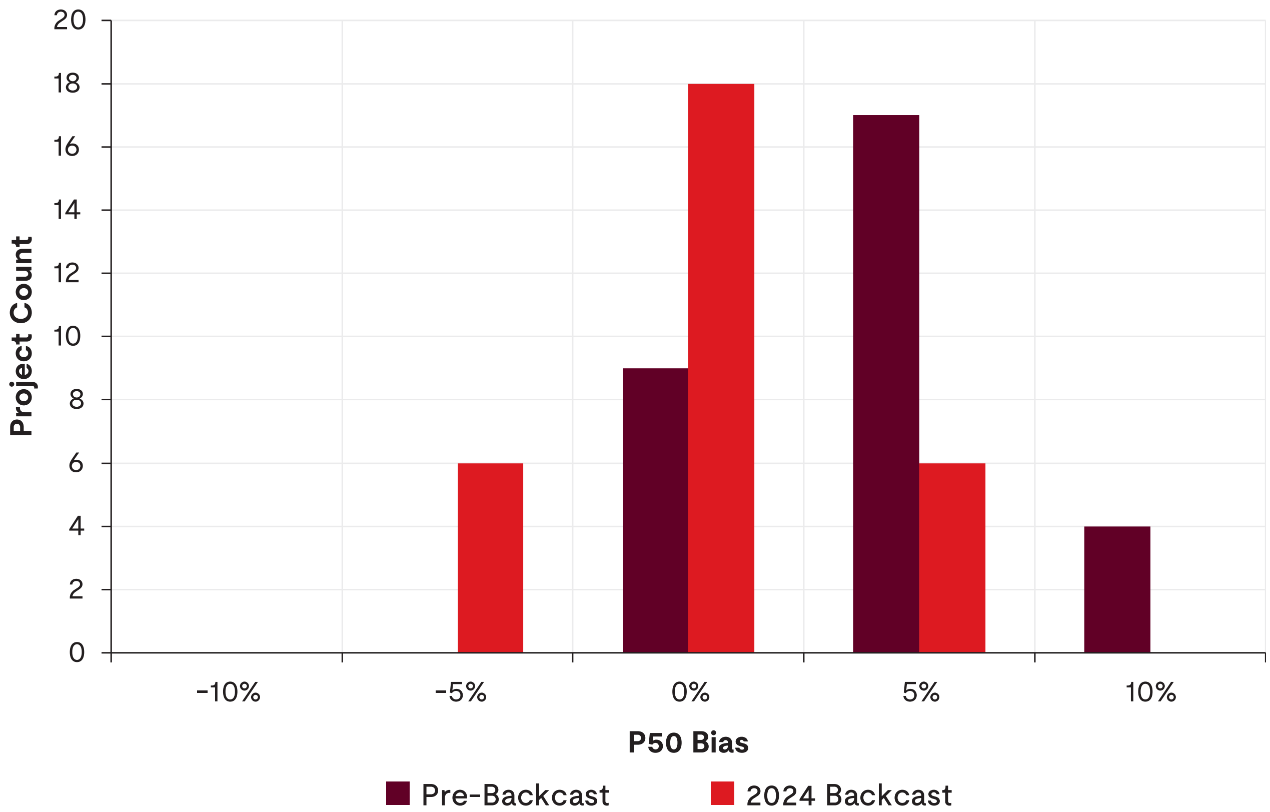

Figure 2: Effect of methods adjustment on distribution of production ratios for the 2024 Offshore Backcast projects (<0% = Over-optimistic)

Prior to adjusting our methods, the average bias of the 30 projects was 4.0%. After applying our updated loss methodologies, the average bias is reduced to 0.0%.

Since the data set is limited to 30 projects and the operational information does not contain enough to isolate major loss categories with high confidence, it can also be useful to examine individual wind project years, of which we had 112 with consistent operation to study. The annual results shown in Figure 3 achieve a mean bias of -0.1%, with a standard deviation of 3.8%.

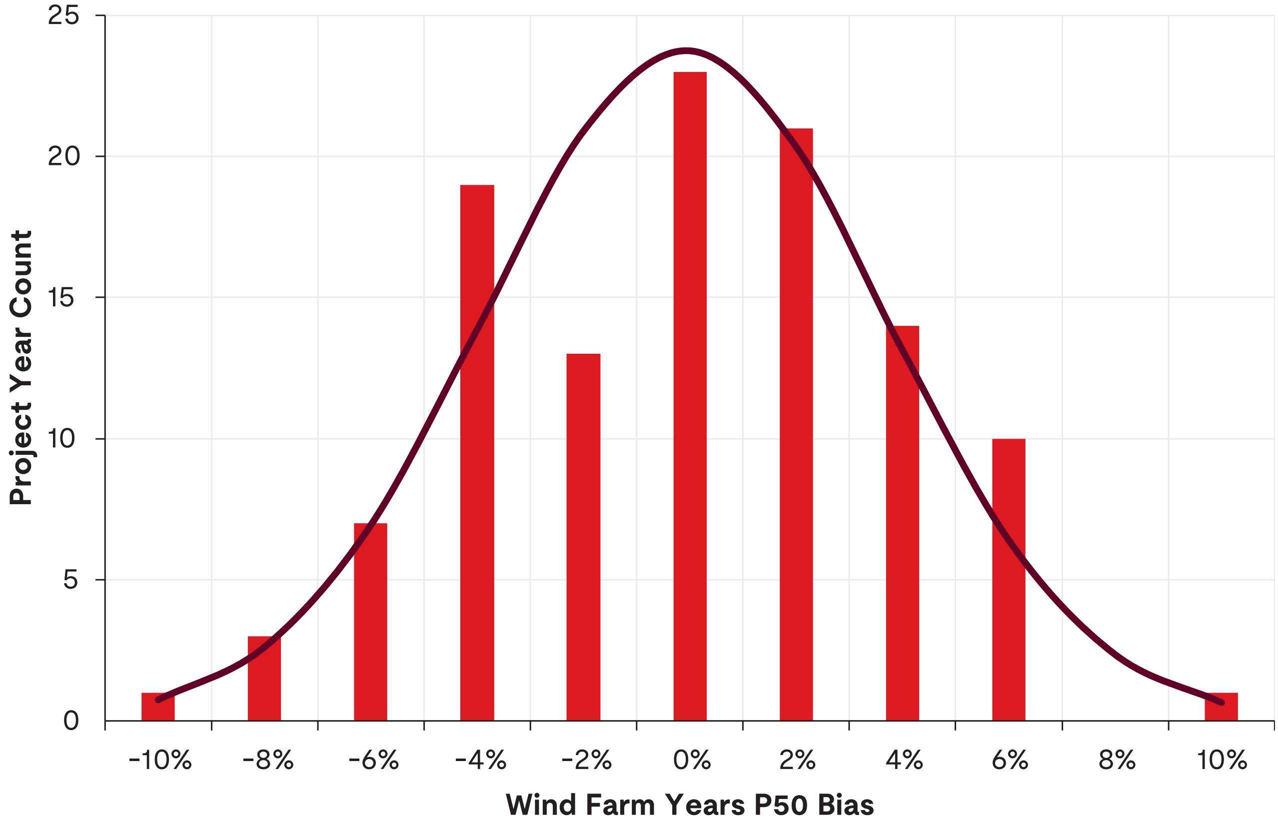

Figure 3: Distribution of production ratios of 2024 Offshore Backcast projects – wind farm years (<0% = over-optimistic)

This is an improvement compared to using the pre-backcast, onshore-derived losses, which result in a significant underestimation of actual production, on average.

Figure 4 presents the proportion of projects exceeding a certain p-value. Presenting results relative to the uncertainty-derived p-values illustrates the unbiased nature of our post-backcast methodology and the reasonableness of the UL Solutions uncertainty model. The dashed gray line shows the expected proportion of projects versus p-values. In this ideal case, 50% of the projects should perform above the P50 and 50% should perform below. The brown (pre-backcast) and red (2024 Backcast) lines show the proportion of the 30 backcast projects (y-axis) found to be above the indicated p-value (x-axis). The dashed-red line shows the same but for the 30 backcast projects subdivided into 112 wind farm years, thereby providing more samples to verify the efficacy of the uncertainty model.

The pre-backcast dataset (red line) shows the bias inherent with those pre-construction loss assumptions where the majority of OEPEs exceed the P50 pre-construction estimate. Both 2024 Backcast datasets (projects and wind farm years) indicate near parity, with a roughly 50% proportion of projects above and below the P50.

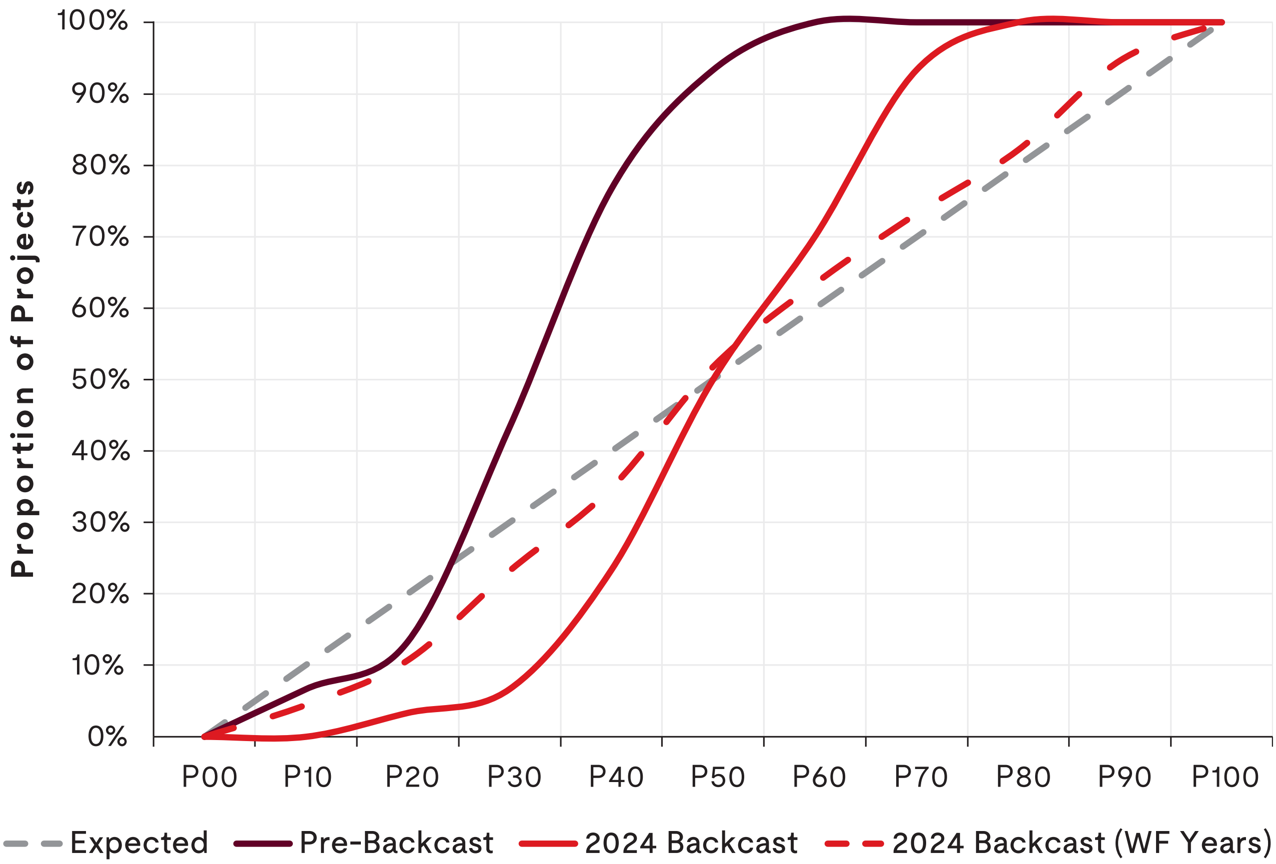

Figure 4: Proportion of projects for which the operational yield exceeds the estimated p-value of the pre-construction EPE.

UL Solutions now converges on a set of validated, offshore-specific losses that achieve a zero bias in offshore resource and energy assessments.

Methodology updates

The aim of the 2024 Backcast was to establish a set of loss methodologies specific to offshore wind energy assessment. Methods of assessing losses have been modified for offshore-specific considerations because of this backcast, including array, availability, electrical and power curve.

The assessment of other loss categories that have no offshore-specific considerations remain consistent with our existing onshore methodology, including those associated with turbine performance (sub-optimal, high wind hysteresis and inclined flow), environmental (icing, blade degradation, temperature shutdown and lighting), and curtailments (directional, environmental, and production limit/point of interconnect).

Array loss

The array loss, also known as turbine flow effects, turbine interaction, or wakes and blockage, generally constitutes the largest component of overall losses in an offshore wind project and is a significant driver in EPE uncertainty. We used our primary model, the Deep Array Eddy Viscosity Wake Model (DAWM-EV), which combines the standard Eddy Viscosity model with a UL Solutions-developed boundary layer model. Previous validations of the DAWM-EV in 2012[11] (validated at two sites) and 2017[12] (validated at four sites, two onshore and two offshore) have proved robust through a benchmarking study by Orsted[13,14] 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 Offshore Backcast study, we retired that blockage model and replaced it with the Rankine Half-Body Induction Model coupled with increases to the DAWM turbine roughness settings. Further changes were made to remove the Eddy Viscosity Near Wake Filter and incorporate background roughness from landcover datasets, previously assumed a constant. An updated validation study,[15] based on offshore turbine SCADA data, meteorological data from five sites and the Orsted results, is available on request.

Backcast projects cover a large range of turbine size, project scope, and buildout scenarios with modeled array losses ranging from 9% to 23% and cases of external array effects as much as 11%. This represents an average reduction of approximately 1% on earlier backcast studies. Total Flow Effect (wake and blockage) losses for the 30 offshore projects were considered in this 2024 Offshore Backcast study.

Long wakes, or those extending beyond the DAWM-EV's valid range, are outside the validation dataset envelope but are not overlooked. While UL Solutions continues to develop physics-based engineering models to estimate turbine flow effects, long-wake modeling can be performed based on our extensive mesoscale modeling capabilities.

UL Solutions remains committed to developing, validating and providing access to its unbiased turbine flow effect models.

Availability

In offshore EPEs, UL Solutions assumes an energy-based availability. The overall availability loss category comprises turbine availability, collection and substation availability, and utility grid availability.

1. Turbine availability

Turbine availability is assumed to include contractual and non-contractual availability, site-access-related downtime impacts, any project restart lag after grid outages, and first-year loss considerations.

To estimate the magnitude of wind turbine availability, UL Solutions has relied on onshore and offshore operational data, both monthly reported and SCADA data, and industry publications on market-level metrics. Specifically, the system performance, availability and reliability (SPARTA) trend analysis reports from the U.K. Offshore Renewable Energy Catapult. The standard offshore Turbine Availability Loss will typically range from 3% to 5%.

2. Site access

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.

For offshore projects, UL Solutions bases the site access impact on the frequency of time that the significant wave height (SWH) within the project area is greater than 1.5 meters (m), with the ability to adjust the SWH threshold based on project-specific crew transfer vessel (CTV) characteristics. A higher frequency of SWH will result in increased turbine availability loss assumptions.

Significant wave height will vary based on site-specific metocean conditions, including wind speed, distance from shore, and other factors. In addition, project CTV and other access solutions may vary to suit local conditions and operational constraints. Table 1 presents indicative impacts on availability as CTV SWH limits are exceeded with increasing frequency.

UL Solutions can help you build a site access plan based on the current expectations to best represent future operating conditions for your projects.

Frequency over CTV SWH limit	Indicative availability loss impact
10%	0.4%
20%	0.9%
30%	1.5%

Table 1: Significant wave height frequency impacts on availability

3. Availability of balance of plant
This loss accounts for outages of the collection system and substation, as well as other non-turbine plant availability. Similar to turbine availability, site access considerations are included.

4. Availability of utility grid
This loss accounts for outages of the utility grid and will vary by country or region, though a typical value is 0.5%.

Electrical loss

Electrical losses are based on the electrical system design and need to be accounted for between the low-voltage terminals of the turbine (where the output is measured in a power curve test) and the revenue meter located at the point of delivery on land. Individual losses include those due to turbine transformers (as applicable), collection system cabling, offshore sub-station transformer, high voltage landfall cabling, any additional high voltage onshore cabling, and the onshore sub-station.

Table 2 lists typical losses associated with each component based on our extensive project-specific electrical loss studies database. The standard electrical loss assumption for offshore projects employing alternating current (AC) transmission is 3.8%. For direct current (DC), the landfall cable is considered negligible. However, additional losses are present in the offshore and onshore AC/DC/AC converters, as well as the onshore substation. These losses are considered 1.0% for a DC offshore assumption of 2.8%. These estimates can be refined when project-specific design information is available.

Component	AC (%)	DC (%)
Turbine transformers	0.7	0.7
Collection system	0.8	0.8
Substation transformers	0.3	0.3
Transmission to the POI	2.0	1.0
Total	3.8	2.8

Table 2: Offshore electrical system losses

Power curve adjustment

As a global leader in testing and advisory services, UL Solutions has extensive experience in power performance testing, both onshore and offshore. Our approach to power curve losses leverages this considerable knowledge and data to estimate power curve losses or expected deviations from warranted levels in pre-construction analyses.

We aggregate our offshore power curve data and consider site turbulence intensity and wind speed distributions when applying power curve test findings to estimate the power curve loss. Depending on the technology and number of available tests to leverage, this loss generally ranges from 0% to 2%, with an average of approximately 1% in the 2024 Offshore Backcast validation dataset.

As more test results become available, they will be incorporated into our loss models, reducing uncertainty in the estimates.

Conclusions

The 2024 Offshore Backcast study is essential for maintaining and increasing the confidence of all stakeholders in offshore wind energy estimation methods and results. Before these updates, our mean bias of 30 evaluated projects using the pre-2024 methods was 4.0%, indicating that those pre-construction energy assessment methods underestimate actual production.

As a result, UL Solutions has implemented revised methods and assumptions for array (wake and blockage), availability, electrical, and power curve adjustment losses for offshore wind projects. These changes eliminate the observed gap between pre-construction estimates and operational, reducing mean bias in the 2024 Offshore Backcast validation dataset to 0.0%.

Our experts continue to monitor the accuracy of these methods and may consider updates from time to time in response to emerging evidence.

Questions and answers

Method validation studies depend on the dataset's range of project characteristics or the validation envelope and may not cover every eventuality in future project analyses. UL Solutions presents several discussion points in Q&A format below to address this and other peripheral topics.

How do the findings of this study relate to projects outside of Northern Europe, or with more nascent turbine technology?

UL Solutions recognizes the challenges in assuming results for certain turbines in particular markets are directly translatable to other technologies or markets. Our experts address potential impacts on availability and performance for fixed foundation turbines as an increased uncertainty until the validation envelope can be extended. Turbines sited on floating platforms are assumed to have a higher availability loss relative to fixed and assessed on a case-by-case basis.

We continually strive to add projects from new regions or additional turbines to the validation dataset to bolster our pre-construction modeling assumptions.

Does the UL Solutions wake and blockage modeling methodology account for long wakes?

While the wind speed recovery downstream from a wind farm and the impact of long-range wakes on annual energy production (AEP) are challenging to validate with high certainty, it is becoming widely accepted that wakes can propagate over 50 kilometers (km) in certain stable atmospheric conditions. As used in this 2024 Offshore Backcast validation study, the DAWM-EV model extends the wake effect approximately 40 km-50 km downwind of the wind farms, sufficient to capture validation projects.

For the considerations of longer wakes, we can run additional simulations using the WRF mesoscale model, together with our wind farm parameterization, to capture the atmospheric dynamics and thermodynamics of wind farm wakes and account for thermal stability effects, which are not included in the DAWM-EV model. UL Solutions is also developing and validating the next generation of models to include in our Openwind software and pre-construction analyses (e.g., Foreman et al., 2024).

Figure 4 shows the percentage of wind speed deficit from a WRF simulation (left) and sea surface backscatter from a Sentinel-1 satellite image (right) over 22 operational wind farms in the German North Sea on June 9, 2023, at 16:00 UTC. Wind barbs are shown in white, and terrain elevation contours are shown in black on the left panel.

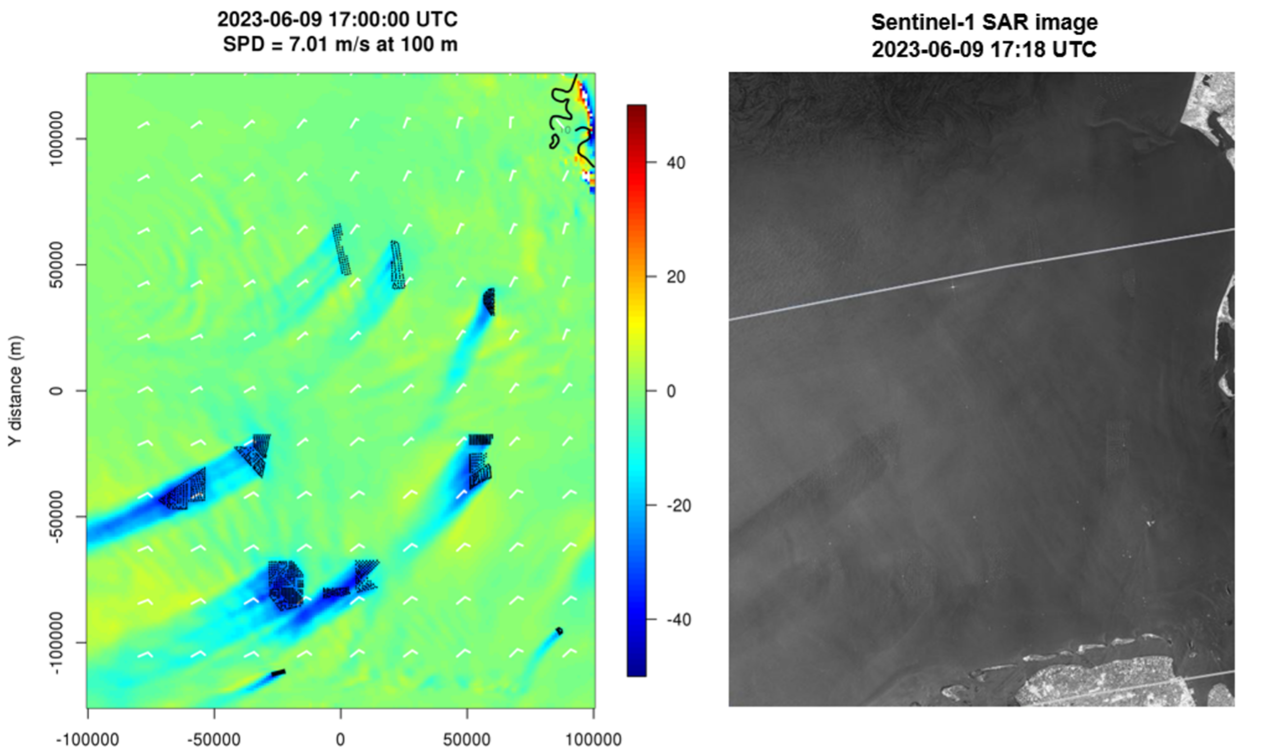

Figure 4: Wind speed deficit (%) from a WRF simulation (left) and sea surface backscatter from a Sentinel-1 satellite image (right).

Are cumulative wake effects from clusters addressed?

UL Solutions is committed to continuously improving and investigating novel wake model developments and making them available. Several projects in the 2024 Offshore Backcast validation dataset are subsets of larger clusters, with external wake impacts exceeding 10%. In addition, WRF modeling solutions can account for the cumulative cluster effects propagating further downstream.

What do you do when you don't have reliable or consistent wave data for site access assessments?

We modeled ERA5 (the European Centre for Medium-Range Weather Forecasts' fifth-generation atmospheric reanalysis) SWH data to measure SWH data at locations around North America and Northern Europe at the 2023 American Clear Power Association Resource and Technology Conference. This analysis supports the ERA5 SWH parameter in the absence of or to augment measured SWH data for the purpose of characterizing site conditions and other conditions related to offshore wind energy development and operation.

Is the 200-m grid resolution in your wind flow modeling sufficient in all cases?

UL Solutions has performed detailed analysis[16] on a range of spatial grid resolutions (50 m, 200 m and 1 km) for offshore wind flow modeling. The 50 m grid size is more typical of onshore projects but could still be used offshore with smaller domain sizes.

We found that the 200 m and 50 m grid sizes performed similarly in the validation dataset and that this trend extended to North American project areas. 1 km grids can also be used, bypassing the WindMap microscale model. However, with 1 km grids, the difference between the 50 m and 200 m grids becomes slightly more significant. UL Solutions recommends not running 1 km grids for projects within 10 km-20 km of the shore or in more complex wind flow regimes with wind direction changing around coastal features.

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