Leading Light Wind

Attachments to Section 3

Attachment 3.1

DNV Statement of Qualifications

30 May 2023

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Subject: Capability and experience statement - DNV Energy Assessment

To whom it may concern:

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- In the United States and Canada, DNV has performed independent energy production assessments on more than 190,000 MW of proposed wind farms and approximately 70% of the installed wind capacity. DNV has conducted more than 40 GW of energy yield assessments for offshore projects worldwide. Our energy assessment reports are trusted and relied upon for most of the project-financed projects in the U.S.
- DNV has taken the lead in industry efforts to validate wind farm energy production estimates:
    - Onshore Energy Production Assessments: DNV's most recent study, based on DNV's database of more than 1,400 project-years of wind farm production, totaling 33 GW in North America, is the most comprehensive and robust analysis of its type to be published.
    - Offshore Energy Production Assessments: DNV holds industry's most comprehensive independent offshore energy assessment validation and has been involved in the offshore wind industry for more than 30 years starting with the first offshore wind projects installed in Europe and has, in diverse capacities, played a role in more than 90% of the world's offshore wind projects.
- DNV's Wind Energy Assessment team in North America has a long track record of successfully supporting wind projects through various financing and investment structures. This team of engineers, atmospheric scientists, and physicists bring a combined total of more than 150 years of relevant experience and diverse expertise in every aspect of energy assessment, including: remote sensing, micro-scale computational fluid dynamics (CFD) and mesoscale wind flow modeling, operational energy assessments, statistics, and project management.
- Extensive practical metocean measurement and analysis experience including numerous offshore energy assessments and thousands of metocean studies. DNV worked with several industry partners and the Carbon Trust to develop best practices for floating lidar systems, and these best practices have become the standards that are referenced by developers and investors. Project investors and lenders will have full confidence in the assessments by DNV for their investments which will facilitate the development of offshore wind projects.

- DNV’s CFD wind flow model includes advanced physics not present in traditional microscale wind flow models, without which it is not possible to consistently produce accurate wind speed predictions. Validation demonstrates that on average DNV reduces wind speed prediction errors by 40% relative to commonly used linear models. DNV CFD has also scored the highest among all models tested in the E.ON blind test which comprised wind flow modelling for 8 wind farm sites located across four countries: USA, UK, Spain and Sweden. The article can be found here.
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- DNV has unparalleled experience in providing technical advisory for wind energy projects, having advised on more onshore wind projects around the world than any other company.
- DNV has been at the forefront of repowering efforts in the wind industry having performed the energy assessment of about 8000 MW of operating wind farms.

Should you have any questions, please do not hesitate to contact us.

Sincerely,

On behalf of DNV

Onur Kaprol

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Attachment 3.2

Power Curve Specifications

Redacted from Public Copy

Attachment 3.3

Extended Cut-Out Feature

Redacted from Public Copy

Attachment 3.4

DNV Wind Resource and Energy Assessment Report

LEADING LIGHT OFFSHORE WIND FARM

Energy Assessment Report

Invenergy Wind Offshore LLC

Document No.: 10438873-HOU-R-01
Date: 24 July 2023
Issue: A, **Status:** Draft

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Project name:	Leading Light Offshore Wind Farm	
Report title:	Energy Assessment Report	
Customer:	Invenergy Wind Offshore LLC One South Wacker Drive, Suite 2000, Chicago, IL 60606	
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Date of issue:	24 July 2023	
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Enterprise no.: 23-2625724

Task and objective:

To complete an independent assessment of the wind climate and energy production for the Project.

Prepared by:	Verified by:	Approved by:
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Issue	Date	Reason for Issue	Prepared by	Verified by	Approved by
A	24 July 2023	Initial issue for review	E. Chénier	A. Burden	B. Williams E. Traiger

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List of abbreviations

Abbreviation	Meaning
ABL	Atmospheric Boundary Layer
AEP	Annual Energy Production
ASIT	Air-sea Interaction Tower
ASL	Above Sea Level
CFD	Computational fluid dynamics
CNR	Carrier-to-noise ratio
DNV	DNV Energy USA Inc.
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	European Centre for Medium-Range Weather Forecasts Re-Analysis (fifth generation)
FLS	Floating Lidar System
GEOS-5	Goddard Earth Observing System Data Assimilation System, Version 5
IEC	International Electrotechnical Commission
MEASNET	Measuring Network of Wind Energy Institutes
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NWS	National Weather Service
O&M	Operations and maintenance
RANS	Reynolds-averaged Navier-Stokes
RMS	Root-mean-square
SNR	Signal-to-noise ratio
TI	Turbulence intensity
VMD	Virtual Met Data
WRF	Weather Research and Forecasting

EXECUTIVE SUMMARY

Invenergy Wind Offshore LLC retained DNV Energy USA Inc. (DNV) to complete an independent assessment of the wind climate and energy production for the proposed Leading Light Offshore Wind Farm. The table below summarizes the project and the results of the wind resource and energy production analysis.

Leading Light Offshore Wind Farm executive summary – PS163

Project Summary	
Layout	Layout PS163
Turbine make and model	[redacted]
Turbine hub height [m]	
Turbine rated power [kW]	
Number of turbines	
Installed capacity[a] [MW]	
Wind Resource Summary	
Average air density [kg/m^3]	[redacted]
On-site measurement period [years]	
Long-term reference period [years]	
Average turbine hub-height wind speed [m/s]	
Energy Assessment Summary	
Evaluation period [years]	[redacted]
Gross energy [GWh/year]	[redacted]
P50 loss factors	
- Turbine interaction effects (wakes and blockage)	
- Availability	
- Electrical	
- Turbine performance	
- Environmental	
- Curtailment	
Total losses	
Effect of asymmetric production	
P50 Net Energy [GWh/year]	
P50 Net Capacity Factor[b]	
1-year P99 Net Energy [GWh/year]	
1-year P99 Net Capacity Factor	

a. [redacted]
b.

Leading Light Offshore Wind Farm executive summary – PS164

Project Summary	
Layout	[redacted]
Turbine make and model	
Turbine hub height [m]	
Turbine rated power [kW]	
Number of turbines	
Installed capacity[a] [MW]	
Wind Resource Summary	
Average air density [kg/m^3]	[redacted]
On-site measurement period [years]	
Long-term reference period [years]	
Average turbine hub-height wind speed [m/s]	
Energy Assessment Summary	
Evaluation period [years]	[redacted]
Gross energy [GWh/year]	
P50 loss factors	
- Turbine interaction effects (wakes and blockage)	
- Availability	
- Electrical	
- Turbine performance	
- Environmental	
- Curtailment	
Total losses	
Effect of asymmetric production	
P50 Net Energy [GWh/year]	
P50 Net Capacity Factor[b]	
1-year P99 Net Energy [GWh/year]	
1-year P99 Net Capacity Factor	

a. [redacted]

b.

Leading Light Offshore Wind Farm executive summary – PS165

Project Summary	
Layout	Layout PS165
Turbine make and model	[redacted]
Turbine hub height [m]	
Turbine rated power [kW]	
Number of turbines	
Installed capacity[a] [MW]	
Wind Resource Summary	
Average air density [kg/m^3]	[redacted]
On-site measurement period [years]	
Long-term reference period [years]	
Average turbine hub-height wind speed [m/s]	
Energy Assessment Summary	
Evaluation period [years]	[redacted]
Gross energy [GWh/year]	
P50 loss factors	
- Turbine interaction effects (wakes and blockage)	
- Availability	
- Electrical	
- Turbine performance	
- Environmental	
- Curtailment	
Total losses	
Effect of asymmetric production	
P50 Net Energy [GWh/year]	
P50 Net Capacity Factor[b]	
1-year P99 Net Energy [GWh/year]	
1-year P99 Net Capacity Factor	

a. [redacted]

b.

The key findings of the analysis and factors affecting the analysis results are summarized below:

1. DNV notes the following observations and opinions regarding uncertainty.
    a. [redacted]
    b. [redacted]
    c. [redacted]
2. The variation in wind speed over the Leading Light Offshore Wind Farm site was predicted using DNV's VMD mesoscale model and is consistent with measurements recorded on site. This has been accounted for in the uncertainty analysis.
3. [redacted]
4. DNV has recently undertaken a validation of its offshore wake modeling methodology using operational data from a number of offshore wind farms in North Europe. As a result of that work, DNV estimates offshore wake only turbine interaction effects using the DNV WindFarmer: Analyst Eddy Viscosity wake model with Large Wind Farm correction applied.
5. DNV has undertaken, and continues to undertake, extensive research into turbine interaction effects. Through this research, evidence suggests turbines cause lateral as well as upstream effects, which together contribute to a resistance, or blockage, on the wind flow, deflecting some of the flow above and around the wind farm. DNV has estimated the wind flow blockage effects based on the project configuration at the Leading Light Offshore Wind Farm using an empirical model based on more than 50 CFD simulations.
6. The balance of plant availability for each layout has been provided by the Customer. [redacted]
7. The electrical loss for each layout has been provided by the Customer. [redacted]
8. The potential external wake effects from neighboring projects described in Section 2.4 have been considered in this assessment. Details of the neighboring wind farms located in the BOEM lease areas OCS-A 0498, OCS-A 0499, OCS-A 532, OCS-A 0538, OCS-A 0539, OCS-A 0541, OCS-A 0542 and OCS-A 0549 have been provided by the Customer. The configurations of the other nearby wind farms in the area are not publicly available at this time. [redacted]

[redacted] The estimated loss is presented in Section 5. When additional information about these wind farms becomes available, it is recommended that the impacts of the proposed wind farms are reconsidered.

9. [redacted]

10. [redacted]

The preceding factors have all been considered in the analysis.

1 INTRODUCTION

Invenergy Wind Offshore LLC (Invenergy) retained DNV Energy USA Inc. (DNV) to complete an independent analysis of the wind regime and energy production of the proposed Leading Light Offshore Wind Farm (Leading Light). This report is issued to Invenergy pursuant to a written agreement arising from the Proposal for Energy Assessment Services 247224-HOU-P-01-E, dated 16 May 2023 and the change order 247224-HOU-CO-01-D, dated 20 July 2023.

This report presents a description of the project site, turbine technology, and neighboring wind projects. It then describes the available measurements and analysis of the wind data followed by an evaluation of the expected project gross and net energy, as influenced by assumed losses and uncertainties. Finally, it presents DNV's observations and recommendations.

2 PROJECT DESCRIPTION

As shown in Figure 2-1, the Leading Light project is located offshore, approximately 80 km east of Atlantic City, New Jersey. The Project is located within Lease Area OCS-A 0542.

DNV has analyzed three proposed layouts, as shown in Table 2-1.

Table 2-1 Proposed layouts

Layout	Number of turbines	Turbine type	Hub height [m]
PS163	[redacted]		
PS164			
PS165			

Measurements of the wind regime have been made at six locations, using Fugro Seawatch buoys and EOLOS buoys. These are described in more detail in Section 3.

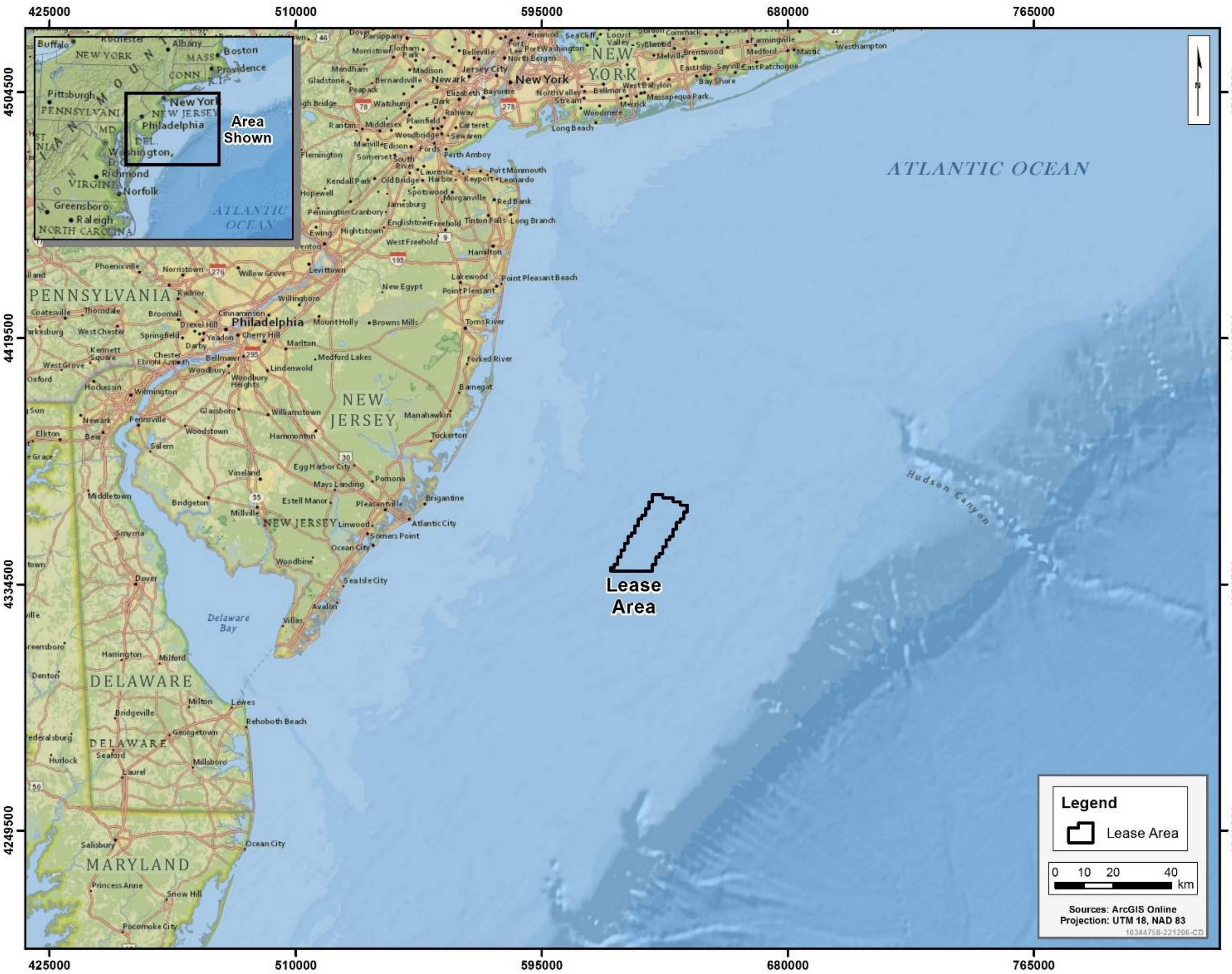

Figure 2-1 Project location

2.1 Site description

The project site is located offshore, 80 km east of Atlantic City, New Jersey. Figure 2-2 is a map of the area showing the on- and off-site measurement locations. Map of the Layouts PS163, PS164 and PS165 are presented in Figure 2-3 to Figure 2-5, showing the measurement locations and proposed turbine locations.

[redacted]

Figure 2-2 Map of the Measurement Locations

[redacted]

Figure 2-3 Map of the Leading Light Wind Farm – Layout PS163

[redacted]

Figure 2-4 Map of the Leading Light Wind Farm – Layout PS164

[redacted]

Figure 2-5 Map of the Leading Light Wind Farm – Layout PS165

[redacted]

2.2 Turbine technology

Table 2-2 summarizes the turbine configurations under consideration for the Leading Light project.

Table 2-2 Proposed turbine model parameters

Turbine	Rated power [MW]	Hub height [m]	Peak power coefficient [Cp]	Valid power curve air density [kg/m^3]
[redacted]				

The characteristics and performance data of the turbine are presented in Appendix B.

The power curve used in this analysis have been provided by Invenergy [1] . The power curve is based on the manufacturer's calculations and has been adjusted to the site density as discussed in Appendix B. The following aspects of the power curve have been considered in the energy analysis and associated uncertainties as discussed in Section 5.1.

- The peak power coefficient of the [redacted] is considered to be attainable relative to historical performance and DNV's expectations.
- [redacted]

2.3 Turbine layout

Invenergy has supplied three layouts for the Project [4] as shown in Table 2-3. The grid coordinates of the turbines are shown in Appendix D.

Table 2-3 Layout configuration

Layout	Number of turbines	Turbine type	Hub height [m]
PS163	[redacted]		
PS164			
PS165			

The following aspects of the layout are notable and have been considered in the analysis:

- [redacted]
- [redacted]

2.4 Neighboring wind farms

The Customer supplied DNV with neighboring wind farm layouts for eight lease areas with potential wind farms near the project [5]. DNV also reviewed publicly available data sources [6][7]. [redacted] The locations of Lease Areas are illustrated in Figure 2-6 to Figure 2-8, with the details of each project included in Table 2-4.

Details of the neighboring wind farms located in the BOEM lease areas OCS-A 0498, OCS-A 0499, OCS-A 532, OCS-A 0538, OCS-A 0539, OCS-A 0541, OCS-A 0542 and OCS-0549 have been provided by the Customer. The configurations of the other nearby wind farms in the area are not publicly available at this time. [redacted] The estimated loss is presented in Section 5. When additional information about these wind farms becomes available, it is recommended that the impacts of the proposed wind farms are reconsidered.

Table 2-4 Summary of neighboring wind farms

Lease Area	Project Name	Stage of development	Distance from project site	Turbine configuration
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
OCS-A 0541	Atlantic Shores Offshore Wind Bight	Proposed	Immediately west	[redacted]
OCS-A 0539	Community Wind	Proposed	Immediately north	[redacted]
OCS-A 0538	Attentive Energy	Proposed	30 km northeast	[redacted]
OCS-A 0499 & OCS-A 0549	Atlantic Shores Offshore	Proposed	30 km west	[redacted]
OCS-A 0498	Ocean Wind 1	Proposed	70 km southwest	[redacted]
OCS-A 0532	Ocean Wind 2	Proposed	60 km southwest	[redacted]
OCS-A 0537	Bluepoint Wind	Proposed	70 km northeast	[redacted]
OCS-A 0512[b]	Empire Wind	Proposed	90 km north	[redacted]
OCS-A 0544[b]	Mid-Atlantic Offshore Wind	Proposed	85 km north	[redacted]

a. [redacted]

b. Excluded from the external wake estimate due to its distance from the site and location in the non-predominant wind direction.

[redacted]

Figure 2-6 Map of Layout PS163 and surrounding projects

[redacted]

Figure 2-7 Map of Layout PS164 and surrounding projects

[redacted]

Figure 2-8 Map of Layout PS165 and surrounding projects

3 ON-SITE WIND MONITORING

3.1 Wind resource measurements

Wind resource measurements have been taken at six floating lidar systems across six locations over the period of [redacted]

The characteristics of the floating Lidar measurement campaign are summarized in Table 3-1.

Table 3-1 Met mast summary

Floating Lidar System	Buoy location	Lidar	Measurement heights [m MSL]	Measurement period	Stage maturity according to the OWA Roadmap[a]
[redacted]					

[redacted]

Full details of the history of each data source and its instrumentation are provided in Appendix C.

The standard of documentation is good and sufficient to ensure traceability of the instrumentation throughout the monitoring campaign. This has been considered in the uncertainty analysis in Section 3.3.

3.1.1 Floating Lidar System (FLS) deployments

A Stage 2 Type Verification of the EOLOS FLS-200 Buoy system against a tall offshore meteorological mast has previously been conducted at Mast Ijmuiden (MMIJ) [9] for a period of 6 months over the period March 2015 to October 2015. During this period the data recorded was compared to those recorded by Mast MMIJ. It was concluded the 'best practice' acceptance criteria and key performance indicators for accuracy were met at all comparable measurement heights. Details of this validation can be found in [9].

Current industry guidance [8] recommends that independent pre-deployment verifications against a trusted reference should be undertaken as part of a wind resource assessment for lowest uncertainty. The E05 and E06 EOLOS FLS-200 Buoys underwent two-phase pre-validations, one onshore and one offshore, as reported in [10]. For the onshore validations, the units were deployed from 7 December 2018 - 18 December 2018 and the data were compared to a reference met mast. For the offshore validations, the FLSs were deployed from 12 April 2019 - 26 May 2019 and the data were compared to the Narec NOAH reference mast. [redacted] All verifications concluded that the floating Lidar systems met the minimum key performance indicators and acceptance criteria for wind speed accuracy as defined by the Carbon Trust OWA Roadmap [8].

A Stage 2 Type Verification of the Fugro Seawatch Buoy system against a tall offshore meteorological mast has previously been conducted [12]. [redacted]

The floating Lidar units were set up to record data at the heights listed in Table 3-1. The height above sea level of the Lidars has been incorporated into the heights listed in Table 3-1. All floating Lidar heights are referred to as above MSL for the remainder of this report.

The floating Lidar systems were programmed to record mean wind speed, direction and turbulence components during each ten-minute interval.

3.2 Data processing

DNV has been supplied with processed data from the [redacted]. Data from the other floating Lidar systems installed have been obtained from DNV's Resource Panorama service. The data supplied are already processed and compensated for motion using the manufacturer's algorithm; however, the processed remote sensing wind data have been subject to a further quality checking procedure by DNV to identify records which were affected by equipment malfunction and other anomalies.

[redacted] Summarized data coverage levels for the key parameters and instruments on each remote sensing device are shown in Table 3-2.

Table 3-2 Summary of site mast data coverage

Location	Lidar	Height [m]	Available period [years]	Valid period [years]	Measured wind speed [m/s]	Wind speed data coverage [%]
E05_N	[redacted]					
E05_SW						
E06_S						
L4						
L6						
[redacted]						

3.3 Site measurement uncertainties

Table 3-3 presents the site measurement uncertainty estimated for the site. Measurement locations that could potentially be used for wind flow initiation to the site have been investigated, therefore the site measurement uncertainty for the five nearest measurement locations relative to the site are presented.

Table 3-3 Site measurement uncertainties

Uncertainty category	% wind speed				
	E05_SW	E06_S	L4	L6	[redacted]
Measurement accuracy	[redacted]				

Measurement uncertainty derived for the floating Lidars is based on the IEA Floating Lidar Recommended Practices [14] considering the following components:

- Classification uncertainty – [redacted]
- Verification uncertainty – [redacted]
- [redacted]

4 WIND ANALYSIS

The analysis of the site wind regime involved several steps, which are summarized below:

- Data recorded at the site measurement location at [redacted] were correlated to each other and site measurements from [redacted] on a 10-minute basis to recover missing and historical data. These correlations were used to derive the annual wind speeds at the [redacted] location for the period from [redacted].
- Data recorded at the site measurement location at [redacted] were correlated to each other and site measurements from [redacted] on a 10-minute basis to recover missing and historical data. These correlations were used to derive the annual wind speeds at the [redacted] location for the period [redacted].
- Data recorded at the site measurement location at [redacted] were correlated to each other and site measurements from [redacted] on a 10-minute basis to recover missing and historical data. These correlations were used to derive the annual wind speeds at the [redacted] location for the period from [redacted].
- Data recorded at the site measurement location at [redacted] were correlated to each other and site measurements from [redacted] on a 10-minute basis to recover missing and historical data. These correlations were used to derive the annual wind speeds at the [redacted] location for the period [redacted].
- Data recorded at the site measurement location at [redacted] were correlated to each other and site measurements from [redacted] on a 10-minute basis to recover missing and historical data. These correlations were used to derive the annual wind speeds at the [redacted] location for the period [redacted].
- Reference data sources were correlated to the measured data at [redacted] on a daily basis. These correlations were used to derive the long-term mean wind speeds at these measurement locations for the period [redacted] at [redacted], and [redacted] at [redacted].
- In order to reference the site data to the period of [redacted] at [redacted], the adjustments determined between the FLSs and the reference data sources was applied to the mean wind speeds determined at the measurement locations for the full site period.
- Measured data recorded at the site devices were used to derive boundary layer power law wind shear exponents. The shear estimates from the nearest Lidar measurement heights were used to extrapolate the long-term mean wind regime at the measurement locations to the proposed [redacted] and [redacted] MSL hub heights.
- The hub-height wind speed and direction frequency distributions at the site devices were extrapolated from the measured data and subsequently adjusted to reflect the predicted long-term mean wind speed at each individual device.
- Wind flow modeling was carried out to determine the hub-height wind speed variations over the site.

Appendix B summarizes the wind data analysis process. Results for each step of the process are provided in the following sections.

4.1 Measurement-height wind regime

4.1.1 Site-period wind speeds

As noted in Section 3.1, data were recorded at the Leading Light site from [redacted].

In order to bring the measurement periods at the measurement locations to the longest period of record, missing and historic wind speed and direction data at the primary measurement levels of each measurement location were synthesized from neighboring Lidars, on a 10-minute directional basis. The results were synthesized and quality-checked in accordance with the methods discussed in Appendix B. The specific correlations in order of priority are presented in Table 4-1. Summaries of the regressions as well as associated statistics and graphs are presented in Appendix D.

Due to the distance of [redacted] to the turbine locations the FLS was used for synthesis only and not considered further in the analysis.

The site-period wind speeds are shown in Table 4-1, following relevant synthesis steps highlighted above. Monthly average site-period wind speeds for measurement locations are also presented in Appendix D.

Table 4-1 Site-period wind speeds

Location	Lidar	Height [m]	Reference device in order of priority	Site-period annual average wind speed [m/s]
E05_SW	[redacted]			
E06_S				
L4				
L6				
[redacted]				

4.1.2 Extension of the site period to the reference period

The inclusion of quality reference data can reduce the uncertainty in the estimate of the long-term wind regime at the site. When selecting appropriate reference data for this purpose, it is important that the reference data's wind regime is driven by similar factors as the site wind regime and the reference data are consistent over the measurement period being considered.

4.1.2.1 Reference data considered

DNV has undertaken an extensive review of the sources of reference data surrounding the Leading Light project in order to identify appropriate long-term reference stations for this analysis. Table 4-2 summarizes the stations considered while Figure 4-1 shows their proximity to the Project site.

Table 4-2 Reference data sets considered for correlation to site data

Meteorological data source	Network / model	Start date	End date[a]
[redacted]			

a. Different end dates are the result of dataset availability at the time of beginning the analysis.

[redacted]

Figure 4-1 Location of the Leading Light wind farm and potential reference data sources

Further information regarding long-term reference data sources typically used by DNV is included in Appendix C. A review of the suitability and use of these sources of data reference in the analysis is provided below.

4.1.2.2 Reference data consistency

The consistency of each source of reference data was evaluated through a comparison to the regional trends, a review of available station maintenance logs, and a statistical change point analysis.

Figure 4-2 shows a plot of seasonally-normalized 12-month moving average wind speeds for the reference data sources.

[redacted]

Figure 4-2 Reference data seasonally-normalized 12-month moving average wind speeds

[redacted]

4.1.2.3 Quality of correlation

To determine whether use of the reference data will reduce uncertainty, a correlation of daily mean wind speeds between each consistent reference station and the site was completed. The results of this analysis are summarized in Table 4-3, including only the reference sources taken forward in the analysis.

Table 4-3 Summary of correlations to site data

Device	Reference station	Coefficient of determination, R^2
E05_SW	[redacted]	
E06_S		
L4		
L6		

DNV's analysis of these results and assessment of the uncertainties in the site-period and reference-period wind speeds concludes that the method with lowest uncertainty is extending the site data to the [redacted] period available at the [redacted]

For each of the selected reference data sources, independent correlations of daily data, binned by month, were used to synthesize reference-period wind speeds at the FLSs, as described in Appendix B.2. This adjustment was applied to the remaining site masts to determine the reference period wind speeds.

The resulting estimated long-term measurement-height wind speeds at each of the measurement locations are shown in Table 4-4.

Table 4-4 Estimated measurement-height long-term wind speeds

Location	Height [m]	Long term adjustment [a]	Wind speed [m/s]
E05_SW	[redacted]		
E06_S			
L4			
L6			
[redacted]			

[redacted]

4.1.3 Measurement-height wind speed uncertainties

Table 4-5 presents the uncertainties in determining the long-term measurement-height wind speed for each of the measurement locations on the site.

Table 4-5 Long-term measurement-height wind regime uncertainties

Uncertainty category	Uncertainty sub-category	Uncertainty [% wind speed]				
		E05_SW	**E06_S**	**L4**	**L6**	[redacted]
Long-term measurement-height wind regime	On-site data synthesis	[redacted]				
	Variability of 23.3 years of data					
	Correlation to reference station					
	Consistency of reference data					
	Wind frequency distribution - past[b]					

[redacted]

Appendix B.7 provides a discussion of uncertainties and how they are determined.

4.2 Hub-height wind regime

4.2.1 Hub-height wind speed

To extrapolate the wind speed estimates from the measurement height to the [redacted] hub height, the average power law at each FLS has been evaluated between all relevant measurement heights and applied to the upper-level measurements at each FLS as described in Appendix B.3.

Table 4-6 Shear exponents and hub-height wind speeds

Device	Height [m]	Measurement heights used in shear exponent calculation [m]	Primary measurement-height wind speed [m/s]	Measured wind shear exponent	Applied wind shear exponent	[redacted] wind speed estimate [m/s]
E05_SW	[redacted]					
E06_S						
L4						
L6						
[redacted]						

[redacted]

Analysis of the shear data indicated that the seasonal and diurnal variations in the shear exponent are consistent with DNV's expectations for the region.

4.2.2 Hub-height wind speed and direction distributions

Hub-height wind speed and direction distributions were developed by extrapolating the measured wind speed data on a time series basis, as described in Appendix B.3. The frequency distributions for the measurement locations were scaled to the representative, long-term, hub-height, mean wind speed at each FLS.

A representative, long-term, hub-height wind rose and wind speed histogram are shown in Figure 4-3 for E06_S. Additional representative long-term hub-height wind speed and direction frequency distributions are shown in Appendix D.

[redacted]

Figure 4-3 [redacted] Long-term hub-height frequency distribution and wind rose at [redacted]

4.2.3 Vertical extrapolation uncertainties

Table 4-7 presents the vertical extrapolation uncertainties estimated for the site. Appendix B.7.1.3 provides a discussion of vertical extrapolation uncertainties and how they are determined.

Table 4-7 Vertical extrapolation uncertainties

Uncertainty category	[% wind speed]				
	E05_SW	E06_S	L4	L6	[redacted]
Vertical extrapolation	[redacted]				

4.3 Wind regime across the site

4.3.1 Modeling

[redacted]

The initiation measurement location for each turbine is indicated in Appendix D. Through this approach, the predicted long-term mean wind speeds at each turbine at the proposed hub height were developed as shown in Appendix D. The average long-term wind speed for the wind farm portfolio as a whole was found to be [redacted] at a hub height of [redacted].

4.3.2 Spatial variation uncertainties

DNV's methods for estimating spatial variation uncertainties are included in Appendix B.7.1.4; Table 4-8 quantifies this uncertainty for the Leading Light project, given that wind speed variation is relatively low, and this is supported by VMD, resulting in lower uncertainty.

Table 4-8 Spatial extrapolation uncertainties

Uncertainty category	% wind speed
Spatial extrapolation	[redacted]

4.4 Turbulence

Post-processed turbulence intensity measurements were available at the floating Lidars of [redacted]. However, it is widely accepted that turbulence intensity measurements (TI) from Lidar devices (volume measurements) are not directly comparable to turbulence intensity measurements from meteorological masts using cup anemometers (point measurements), which is currently the wind industry standard [15].

[redacted]

5 ENERGY ANALYSIS

5.1 Gross and net energy estimates

The gross energy production at the individual turbine locations has been calculated using the WindFarmer software and the results of the wind flow modeling, together with the turbine power curve in accordance with the methodology in Appendix B.

Table 5-1 to Table 5-3 provide the aggregated results for Leading Light.

The projected net energy productions of the project shown in Table 5-1 to Table 5-3 were calculated by applying a number of energy loss factors to the gross energy production. The predictions represent the estimate of the annual production expected over the first [redacted]. Wind farms typically experience some time dependency in availability and other loss factors. A detailed definition of loss factors is included in Appendix B.6 and any time dependency considered is detailed in Appendix D.4.

Table 5-1 Energy production summary – PS163

	Layout	PS163	
	Evaluation Period	[redacted]	
	Wind Farm Rated Power		
	Gross Energy Output		
1	**Turbine interaction effects**		
1a	Internal wake and blockage effects		
1b	External wake effect		
1c	Future wake effect		
2	**Availability**		
2a	Turbine availability		
2b	Balance of plant availability		
2c	Grid availability		
3	**Electrical efficiency**		
3a	Operational electrical efficiency		
3b	Wind farm consumption		
4	**Turbine performance**		
4a	Generic power curve adjustment		
4b	High wind speed hysteresis		
4c	Site-specific power curve adjustment		
4d	Sub-optimal performance		
4e	Turbine degradation		
4f	Aerodynamic device degradation		
5	**Environmental**		
5a	Performance degradation – icing		
5b	Icing shutdown		
5c	Temperature shutdown		
5d	Site access		
6	**Curtailments**		
6a	Wind sector management		
6b	Grid curtailment		
6c	Noise, visual, and environmental curtailment		
	Total Losses (%)		
	Asymmetric production effect		
	Net Energy Output		
	Net Capacity Factor		

[redacted]

Table 5-2 Energy production summary – PS164

Layout		PS164	
Evaluation Period		[redacted]	[redacted]
Wind Farm Rated Power		[redacted]	[redacted]
Gross Energy Output		[redacted]	[redacted]
1	**Turbine interaction effects**	[redacted]	[redacted]
1a	Internal wake and blockage effects	[redacted]	[redacted]
1b	External wake effect	[redacted]	[redacted]
1c	Future wake effect	[redacted]	[redacted]
2	**Availability**	[redacted]	[redacted]
2a	Turbine availability	[redacted]	[redacted]
2b	Balance of plant availability	[redacted]	[redacted]
2c	Grid availability	[redacted]	[redacted]
3	**Electrical efficiency**	[redacted]	[redacted]
3a	Operational electrical efficiency	[redacted]	[redacted]
3b	Wind farm consumption	[redacted]	[redacted]
4	**Turbine performance**	[redacted]	[redacted]
4a	Generic power curve adjustment	[redacted]	[redacted]
4b	High wind speed hysteresis	[redacted]	[redacted]
4c	Site-specific power curve adjustment	[redacted]	[redacted]
4d	Sub-optimal performance	[redacted]	[redacted]
4e	Turbine degradation	[redacted]	[redacted]
4f	Aerodynamic device degradation	[redacted]	[redacted]
5	**Environmental**	[redacted]	[redacted]
5a	Performance degradation – icing	[redacted]	[redacted]
5b	Icing shutdown	[redacted]	[redacted]
5c	Temperature shutdown	[redacted]	[redacted]
5d	Site access	[redacted]	[redacted]
6	**Curtailments**	[redacted]	[redacted]
6a	Wind sector management	[redacted]	[redacted]
6b	Grid curtailment	[redacted]	[redacted]
6c	Noise, visual, and environmental curtailment	[redacted]	[redacted]
	Total Losses (%)	[redacted]	[redacted]
	Asymmetric production effect	[redacted]	[redacted]
	Net Energy Output	[redacted]	[redacted]
	Net Capacity Factor	[redacted]	[redacted]

[redacted]

Table 5-3 Energy production summary – PS165

Layout		**PS165**	
Evaluation Period		[redacted]	
Wind Farm Rated Power		[redacted]	
Gross Energy Output		[redacted]	
1	**Turbine interaction effects**	[redacted]	
1a	Internal wake and blockage effects	[redacted]	
1b	External wake effect	[redacted]	
1c	Future wake effect	[redacted]	
2	**Availability**	[redacted]	
2a	Turbine availability	[redacted]	
2b	Balance of plant availability	[redacted]	
2c	Grid availability	[redacted]	
3	**Electrical efficiency**	[redacted]	
3a	Operational electrical efficiency	[redacted]	
3b	Wind farm consumption	[redacted]	
4	**Turbine performance**	[redacted]	
4a	Generic power curve adjustment	[redacted]	
4b	High wind speed hysteresis	[redacted]	
4c	Site-specific power curve adjustment	[redacted]	
4d	Sub-optimal performance	[redacted]	
4e	Turbine degradation	[redacted]	
4f	Aerodynamic device degradation	[redacted]	
5	**Environmental**	[redacted]	
5a	Performance degradation – icing	[redacted]	
5b	Icing shutdown	[redacted]	
5c	Temperature shutdown	[redacted]	
5d	Site access	[redacted]	
6	**Curtailments**	[redacted]	
6a	Wind sector management	[redacted]	
6b	Grid curtailment	[redacted]	
6c	Noise, visual, and environmental curtailment	[redacted]	
	Total Losses (%)	[redacted]	
	Asymmetric production effect	[redacted]	
	Net Energy Output	[redacted]	
	Net Capacity Factor	[redacted]	

[redacted]

Table 5-1 to Table 5-3 include potential sources of energy loss that have been either assumed to be the DNV standard values or estimated for this project. The background and general basis for all loss estimates is provided in Appendix B.6. Project-specific aspects of the loss estimates which are not included in the Appendix B.6 are provided in the following bullets:

- 1a Internal wake and blockage effects – DNV has recently undertaken a validation of its offshore wake modeling methodology using operational data from a number of offshore wind farms in North [16][17]. As a result of that work, DNV estimates offshore wake only turbine interaction effects using the DNV WindFarmer: Analyst Eddy Viscosity wake model with Large Wind Farm correction and offshore specific settings applied. Classical wake models such as WindFarmer: Analyst do not consider lateral or upstream turbine interaction effects, which may also reduce the wind speeds seen by the turbines [18]. The turbine interaction blockage effect, a loss factor of [redacted] has been estimated using an empirical model based on more than 50 CFD simulations, as described in Appendix B.6.1.2. Table 5-4 shows the loss factor for each layout.

Table 5-4 Blockage loss factor

Layout	Blockage loss factor [%]
PS163	[redacted]
PS164	
PS164	

- 1b External wake effect – Wake effects of the proposed neighboring wind farms described in Section 2.4 have been calculated using the WindFarmer: Analyst Eddy Viscosity wake model with an offshore-specific Large Wind Farm correction. The wind farms located in the lease areas OCS-A 0498, OCS-A 0499, OCS-A 0532, OCS-A 0537, OCS-A 0538, OCS-A 0539, OCS-A 0541 and OCS-A 0549 have been included in the external wake model. It is noted that any turbine interaction blockage effects caused by neighboring turbines are included in 1a. When additional information about the proposed future wind farms becomes available, it is recommended that this analysis is updated to reflect the impact of the proposed turbines.
- 1c Future wake effect – It has been assumed that no future wind farms other than those considered in loss 1b will be built in the vicinity of the wind farm. When additional information pf proposed future wind farms becomes available, it is recommended that this analysis is updated to reflect the impact of the proposed turbines.
- 2a Turbine availability – DNV has made a starting assumption for the turbine availability that could be expected from the project based on the wave climate, an anticipated O&M access strategy of a SOV vessel based in New York and some assumptions regarding the reliability and track record of the turbine technology to be installed in the future, based on DNV experience.
- 2b. Balance of plant availability – [redacted]
- 3a Operational electrical efficiency – [redacted]

- 4b High wind speed hysteresis – [redacted]

  [redacted]

- 4c Site-specific power curve adjustment – It is assumed that site-specific wind flow issues related to TI which will affect the performance of the turbines are included in the TI specific power curve for the project. This loss factor includes a [redacted] loss to account for the average blockage effect inherent in power performance test measurements [20]..

- 4e Blade and turbine degradation – This assumption is to account for the performance degradation of the turbine drivetrain and rotor assembly. The loss factor applied assumes that the future projects will have blade leading edge protection systems installed and that a proactive plan to manage leading edge erosion based on regular blade inspections and repair will be in place throughout the project lifetime. For future projects, it is recommended that an Independent Engineer reviews the plans to manage leading edge erosion as part of a full due diligence exercise.

- 4f Aerodynamic device degradation – [redacted]

- 5a Performance degradation – icing – [redacted]

- 5b Icing shutdown – [redacted]

- 5c Temperature shutdown – [redacted]

- 5d Site access – Site access due to the project being located offshore is accounted for as part of loss 2a – Turbine availability.

- 6a Wind Sector Management – [redacted]

- 6b Grid curtailment – [redacted]

- 6c Noise, visual, and environmental curtailment – [redacted]

5.1.1 Uncertainty in loss factors

DNV's methods for estimating loss factor uncertainties are included in Appendix B.7.2; Table 5-5 quantifies this uncertainty for the Leading Light project.

Table 5-5 Loss factor uncertainties

Uncertainty category	Uncertainty subcategory	% Energy		
		PS163	PS164	PS165
Loss factors	Wakes	[redacted]		
	Availability			
	Electrical			
	Turbine performance			
	Environmental			
	Curtailment			

a. Non-zero percentage (<0.05%)

5.2 Customer-provided consideration

[redacted] DNV's net energy estimate is detailed in Table 5-6 to Table 5-8.

Table 5-6 Energy production summary, customer-requested scenario – PS163

Layout		PS163	
Evaluation Period		[redacted]	
Wind Farm Rated Power			
Gross Energy Output			
1	**Turbine interaction effects**		
1a	Internal wake and blockage effects		
1b	External wake effect		
1c	Future wake effect		
2	**Availability**		
2a	Turbine availability		
2b	Balance of plant availability		
2c	Grid availability		
3	**Electrical efficiency**		
3a	Operational electrical efficiency		
3b	Wind farm consumption		
4	**Turbine performance**		
4a	Generic power curve adjustment		
4b	High wind speed hysteresis		
4c	Site-specific power curve adjustment		
4d	Sub-optimal performance		
4e	Turbine degradation		
4f	Aerodynamic device degradation		
5	**Environmental**		
5a	Performance degradation – icing		
5b	Icing shutdown		
5c	Temperature shutdown		
5d	Site access		
6	**Curtailments**		
6a	Wind sector management		
6b	Grid curtailment		
6c	Noise, visual, and environmental curtailment		
	Total Losses (%)		
	Asymmetric production effect		
	Net Energy Output		
	Net Capacity Factor		

[redacted]

Table 5-7 Energy production summary, customer-requested scenario – PS164

Layout		PS164	
Evaluation Period		[redacted]	
Wind Farm Rated Power			
Gross Energy Output			
1	Turbine interaction effects		
1a	Internal wake and blockage effects		
1b	External wake effect		
1c	Future wake effect		
2	Availability		
2a	Turbine availability		
2b	Balance of plant availability		
2c	Grid availability		
3	Electrical efficiency		
3a	Operational electrical efficiency		
3b	Wind farm consumption		
4	Turbine performance		
4a	Generic power curve adjustment		
4b	High wind speed hysteresis		
4c	Site-specific power curve adjustment		
4d	Sub-optimal performance		
4e	Turbine degradation		
4f	Aerodynamic device degradation		
5	Environmental		
5a	Performance degradation – icing		
5b	Icing shutdown		
5c	Temperature shutdown		
5d	Site access		
6	Curtailments		
6a	Wind sector management		
6b	Grid curtailment		
6c	Noise, visual, and environmental curtailment		
	Total Losses (%)		
	Asymmetric production effect		
	Net Energy Output		
	Net Capacity Factor		

[redacted]

Table 5-8 Energy production summary, customer-requested scenario – PS165

Layout		PS165	
Evaluation Period		[redacted]	
Wind Farm Rated Power			
Gross Energy Output			
1	**Turbine interaction effects**		
1a	Internal wake and blockage effects		
1b	External wake effect		
1c	Future wake effect		
2	**Availability**		
2a	Turbine availability		
2b	Balance of plant availability		
2c	Grid availability		
3	**Electrical efficiency**		
3a	Operational electrical efficiency		
3b	Wind farm consumption		
4	**Turbine performance**		
4a	Generic power curve adjustment		
4b	High wind speed hysteresis		
4c	Site-specific power curve adjustment		
4d	Sub-optimal performance		
4e	Turbine degradation		
4f	Aerodynamic device degradation		
5	**Environmental**		
5a	Performance degradation – icing		
5b	Icing shutdown		
5c	Temperature shutdown		
5d	Site access		
6	**Curtailments**		
6a	Wind sector management		
6b	Grid curtailment		
6c	Noise, visual, and environmental curtailment		
	Total Losses (%)		
	Asymmetric production effect		
	Net Energy Output		
	Net Capacity Factor		

[redacted]

5.3 Seasonal and diurnal distributions

The expected long-term average seasonal and diurnal variation in energy production has been approximately assessed from the available data at the project site. The long-term average seasonal and diurnal variation in air density was developed from temperature records and pressure records at [redacted] and scaled to the site-predicted long-term annual site air density. The measured wind speeds extrapolated to hub height at [redacted] were adjusted to reflect the predicted long-term mean wind speeds and monthly profiles of each site FLS.

A simulated time series of production data was produced using the time series of density, wind direction, and wind speed and the WindFarmer energy model developed for the Leading Light project.

The resulting expected seasonal and diurnal variation in energy production at [redacted] for each layout is presented in Appendix D.6 in the form of a 12-month by 24-hour (12 x 24) matrix. It is noted that the uncertainty associated with the prediction of any given month or hour of day is significantly greater than that associated with the prediction of the annual energy production. It is also noted that the results presented are inclusive of all losses. Wake and hysteresis losses have been included by month and hour. All other losses have been applied uniformly.

6 UNCERTAINTY

The main sources of deviation from the central estimate (P50) have been quantified using procedures described in Appendix B. These sources of uncertainty have been combined using a probabilistic model, assuming full independence between the sources. Additional details on this process are given below.

6.1 Inter-annual variability

Even if the central estimate was perfectly defined, wind farm energy production varies from year to year due to a number of factors, including natural variation in the wind regime, variations in system availability, and variations in environmental losses. Appendix B.7.3.2 provides a discussion of typical future wind speed variability and how it is determined. Table 6-1 presents the inter-annual variability estimated for the site.

Table 6-1 Inter-annual variability

Uncertainty category	Uncertainty subcategory	%	Unit
Inter-annual variability	Wind frequency distribution - future	[redacted]	Energy
	Inter-annual variability of the wind		Wind Speed
	Availability		Energy

6.2 Converting wind speed uncertainties to energy uncertainties

Uncertainties in the estimate of the site wind speed were described previously in this report.

Wind speed uncertainties are converted to energy uncertainties using the sensitivity ratio. The sensitivity ratio shows how sensitive the net energy production is to changes in wind speed and is dependent mainly on the wind speed distribution and power curve of the turbine. For example, with a sensitivity ratio of 1.50, a 2.0% reduction in wind speed at all FLSs would lead to a 3.0% reduction in net energy production. The sensitivity ratio is non-linear over large ranges of wind speed, which has been accounted for in this analysis. The average calculated sensitivity ratios for the Leading Light project for variations of 10% on wind speed are presented in Table 6-2.

Table 6-2 Site average sensitivity ratios

Layout option	Sensitivity ratio
PS163	[redacted]
PS164	
PS165	

6.3 Project uncertainties

A summary of the project uncertainties considered as part of this analysis are show in Table 6-3. The 1-year numbers presented are representative of any individual year in the [redacted] of the project. The 10-year numbers are representative of the first 10 years of operation.

Table 6-3 Uncertainty in the projected energy output for Layout PS163 [redacted]

Source of uncertainty/variability	[GWh/annum]			Equivalent standard deviation [%]		
Measurement accuracy	[redacted]					
Long-term measurement height wind regime						
Vertical extrapolation						
Spatial extrapolation						
Loss factors						
Inter-annual variability						
Future period under consideration	1 year	10 year	[redacted]	1 year	10 year	[redacted]
Overall energy uncertainty	[redacted]					

Table 6-4 Uncertainty in the projected energy output for Layout PS163 [redacted]

Source of uncertainty/variability	[GWh/annum]			Equivalent standard deviation [%]		
Measurement accuracy	[redacted]					
Long-term measurement height wind regime						
Vertical extrapolation						
Spatial extrapolation						
Loss factors						
Inter-annual variability						
Future period under consideration	1 year	10 year	[redacted]	1 year	10 year	[redacted]
Overall energy uncertainty	[redacted]					

Table 6-5 Uncertainty in the projected energy output for Layout PS164 [redacted]

Source of uncertainty/variability	[GWh/annum]			Equivalent standard deviation [%]		
Measurement accuracy	[redacted]					
Long-term measurement height wind regime						
Vertical extrapolation						
Spatial extrapolation						
Loss factors						
Inter-annual variability						
Future period under consideration	1 year	10 year	[redacted]	1 year	10 year	[redacted]
Overall energy uncertainty	[redacted]					

Table 6-6 Uncertainty in the projected energy output for Layout PS164 [redacted]

Source of uncertainty/variability	[GWh/annum]			Equivalent standard deviation [%]		
Measurement accuracy	[redacted]					
Long-term measurement height wind regime						
Vertical extrapolation						
Spatial extrapolation						
Loss factors						
Inter-annual variability						
Future period under consideration	1 year	10 year	[redacted]	1 year	10 year	[redacted]
Overall energy uncertainty	[redacted]					

DNV

Table 6-7 Uncertainty in the projected energy output for Layout PS165 [redacted]

Source of uncertainty/variability	**[GWh/annum]**			**Equivalent standard deviation [%]**		
Measurement accuracy	[redacted]					
Long-term measurement height wind regime						
Vertical extrapolation						
Spatial extrapolation						
Loss factors						
Inter-annual variability						
Future period under consideration	1 year	10 year	[redacted]	1 year	10 year	[redacted]
Overall energy uncertainty	[redacted]					

Table 6-8 Uncertainty in the projected energy output for Layout PS165 [redacted]

Source of uncertainty/variability	**[GWh/annum]**			**Equivalent standard deviation [%]**		
Measurement accuracy	[redacted]					
Long-term measurement height wind regime						
Vertical extrapolation						
Spatial extrapolation						
Loss factors						
Inter-annual variability						
Future period under consideration	1 year	10 year	[redacted]	1 year	10 year	[redacted]
Overall energy uncertainty	[redacted]					

The results of the probabilistic simulation of net energy production are summarized in Table 6-9 to Table 6-11.

Table 6-9 Summary of project net average energy production for Layout PS163

Probability of exceedance	[redacted]
10%	
50%	
75%	
90%	
95%	
99%	

Table 6-10 Summary of project net average energy production for Layout PS164

Probability of exceedance	[redacted]
10%	
50%	
75%	
90%	
95%	
99%	

Table 6-11 Summary of project net average energy production for Layout PS165

Probability of exceedance	[redacted]
10%	
50%	
75%	
90%	
95%	
99%	

7 OBSERVATIONS AND RECOMMENDATIONS

DNV makes the following observations and recommendations regarding this analysis:

1. DNV notes the following observations and opinions regarding uncertainty.

   [redacted]

2. The variation in wind speed over the Leading Light Offshore Wind Farm site was predicted using DNV's VMD mesoscale model and is consistent with measurements recorded on site. This has been accounted for in the uncertainty analysis.

3. [redacted]

4. DNV has recently undertaken a validation of its offshore wake modeling methodology using operational data from a number of offshore wind farms in North Europe. As a result of that work, DNV estimates offshore wake only turbine interaction effects using the DNV WindFarmer: Analyst Eddy Viscosity wake model with Large Wind Farm correction applied.

5. DNV has undertaken, and continues to undertake, extensive research into turbine interaction effects. Through this research, evidence suggests turbines cause lateral as well as upstream effects, which together contribute to a resistance, or blockage, on the wind flow, deflecting some of the flow above and around the wind farm. DNV has estimated the wind flow blockage effects based on the project configuration at the Leading Light Offshore Wind Farm using an empirical model based on more than 50 CFD simulations.

6. [redacted]

7. [redacted]

8. The potential external wake effects from neighboring projects described in Section 2.4 have been considered in this assessment. Details of the neighboring wind farms located in the BOEM lease areas OCS-A 0498, OCS-A 0499, OCS-A 532, OCS-A 0538, OCS-A 0539, OCS-A 0541, OCS-A 0542 and OCS-A 0549 have been provided by the Customer. The configurations of the other nearby wind farms in the area are not publicly available at this time. [redacted]

[redacted] The estimated loss is presented in Section 5. When additional information about these wind farms becomes available, it is recommended that the impacts of the proposed wind farms are reconsidered.

9. [redacted]

10. [redacted]

8 REFERENCES

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APPENDIX A – Wind turbine data

Table B-1 Turbine data for the [redacted]

[redacted]

Table B-2 Turbine data for the [redacted]

[redacted]

APPENDIX B – Analysis methodology

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

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B.2.1.1 [redacted]

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B.6.1.1 [redacted]

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B.6.1.2 [redacted]

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[redacted]	[redacted]
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B.6.1.3 [redacted]

[redacted]

B.6.1.4 [redacted]

[redacted]

B.6.1.5 [redacted]

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[redacted]

B.6.2.1 [redacted]

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B.6.2.2 [redacted]

[redacted]

B.6.2.3 [redacted]

[redacted]

[redacted]

[redacted]

B.6.3.1 [redacted]

[redacted]

B.6.3.2 [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

B.6.4.1 [redacted]

[redacted]

B.6.4.2 [redacted]

[redacted]

B.6.4.3 [redacted]

[redacted]

B.6.4.4 [redacted]

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B.6.4.5 [redacted]

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B.6.4.6 [redacted]

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B.6.5.1 [redacted]

[redacted]

B.6.5.2 [redacted]

[redacted]

B.6.5.3 [redacted]

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B.6.5.4 [redacted]

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B.6.6.1 [redacted]

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DNV

B.6.6.2 [redacted]

[redacted]

B.6.6.3 [redacted]

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B.7.1.1 [redacted]

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B.7.1.1.1. [redacted]

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B.7.1.2.2. [redacted]

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B.7.1.3 [redacted]

[redacted]

B.7.1.4 [redacted]

[redacted]

[redacted]

B.7.2.1 [redacted]

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[redacted]

B.7.2.2 [redacted]

[redacted]

B.7.2.3 [redacted]

[redacted]

B.7.2.4 [redacted]

[redacted]

B.7.2.5 [redacted]

[redacted]

B.7.2.6 [redacted]

[redacted]

[redacted]

B.7.3.1 [redacted]

[redacted]

B.7.3.2 [redacted]

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[redacted]

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[redacted]

B.7.3.3 [redacted]

[redacted]

APPENDIX C – Wind data measurement and analysis

C.1 E05_N floating Lidar device
C.2 E05_SW floating Lidar device
C.3 E06_S floating Lidar device
C.4 [redacted] floating Lidar device
C.5 L4 floating Lidar device
C.6 L6 floating Lidar device
C.7 Device data coverage summary
C.8 Reference wind data

C.1 E05_N floating Lidar device

Buoy 2 floating Lidar device configuration

Site name	Leading Light	Elevation [m]	Eastings [m]	Northings [m]	Coordinate system	Datum	Zone
Device name	E05_N	0	695058	4426856	UTM	WS84	18N
Installation date	2019-08-12						

Device description	
Device Model	EOLOS FLS-200
Lidar Type	ZephIR ZX300M
Scan Heights [m MSL]	20, 40, 60, 80, 100, 120, 140, 160, 180, 200
Averaging Period [min]	10

Note that the location given above is the initial deployment location. There was occasional movement of the device throughout the deployment period, but given the scale of the movements relative to the distance from the shore and the resolution of the wind maps which were used to model flow variation over the area, these changes in location were not considered to have a significant impact on the analysis and the location above has been used in the analysis.

C.2 E05_SW floating Lidar device

Buoy 2 floating Lidar device configuration

Site name	Leading Light	Elevation [m]	Eastings [m]	Northings [m]	Coordinate system	Datum	Zone
Device name	E05_SW	0	621173	4371530	UTM	WS84	18N
Installation date	2022-01-28						

Device description	
Device Model	EOLOS FLS-200
Lidar Type	ZephIR ZX300M
Scan Heights [m MSL]	20, 40, 60, 80, 100, 120, 140, 160, 180, 200
Averaging Period [min]	10

Note that the location given above is the initial deployment location. There was occasional movement of the device throughout the deployment period, but given the scale of the movements relative to the distance from the shore and the resolution of the wind maps which were used to model flow variation over the area, these changes in location were not considered to have a significant impact on the analysis and the location above has been used in the analysis.

C.3 E06_S floating Lidar location

WHOI ASIT Lidar device configuration

Site name	Leading Light	Elevation [m MSL]	Eastings [m]	Northings [m]	Coordinate system	Datum	Zone
Device name	E06	0	634944	4378580	UTM	WGS84	18N
Installation date	2019-09-04						

Device description	
Device Model	EOLOS FLS-200
Lidar Type	ZephIR ZX300M
Scan Heights [m MSL]	20, 40, 60, 80, 100, 120, 140, 160, 180, 200
Averaging Period [min]	10

Note that the location given above is the initial deployment location. There was occasional movement of the device throughout the deployment period, but given the scale of the movements relative to the distance from the shore and the resolution of the wind maps which were used to model flow variation over the area, these changes in location were not considered to have a significant impact on the analysis and the location above has been used in the analysis.

[redacted]

C.5 L4 floating Lidar location

Buoy floating Lidar device configuration Buoy floating Lidar device configuration

Site name	Leading Light Wind	Elevation [m]	Eastings [m]	Northings [m]	Coordinate system	Datum	Zone
Device name	WS201	0	579270	4339650	UTM	WGS84	18N
Installation date	2021-05-14						

Device description	
Device Model	Fugro Seawatch
Lidar Type	ZephIR ZX300M
Scan Heights [m MSL]	4, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 250
Averaging Period [min]	10

Note that the location given above is the initial deployment location. There was occasional movement of the device throughout the deployment period, but given the scale of the movements relative to the distance from the shore and the resolution of the wind maps which were used to model flow variation over the area, these changes in location were not considered to have a significant impact on the analysis and the location above has been used in the analysis.

C.6 L6 floating Lidar location

Buoy floating Lidar device configuration

Site name	Leading Light Wind	Elevation [m]	Eastings [m]	Northings [m]	Coordinate system	Datum	Zone
Device name	WS200	0	591504	4347464	UTM	WGS84	18N
Installation date	2019-12-29						

Device description	
Device Model	Fugro Seawatch
Lidar Type	ZephIR ZX300M
Unit Serial no.	ZX899M
Scan Heights [m MSL]	4, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 250
Averaging Period [min]	10

Note that the location given above is the initial deployment location. There was occasional movement of the device throughout the deployment period, but given the scale of the movements relative to the distance from the shore and the resolution of the wind maps which were used to model flow variation over the area, these changes in location were not considered to have a significant impact on the analysis and the location above has been used in the analysis.

C.7 Device data coverage summary

Figure D-1 and Figure D-2 summarize data coverage by wind speed and wind direction. Sensor labels indicate the mast, instrument type, height, and orientation.

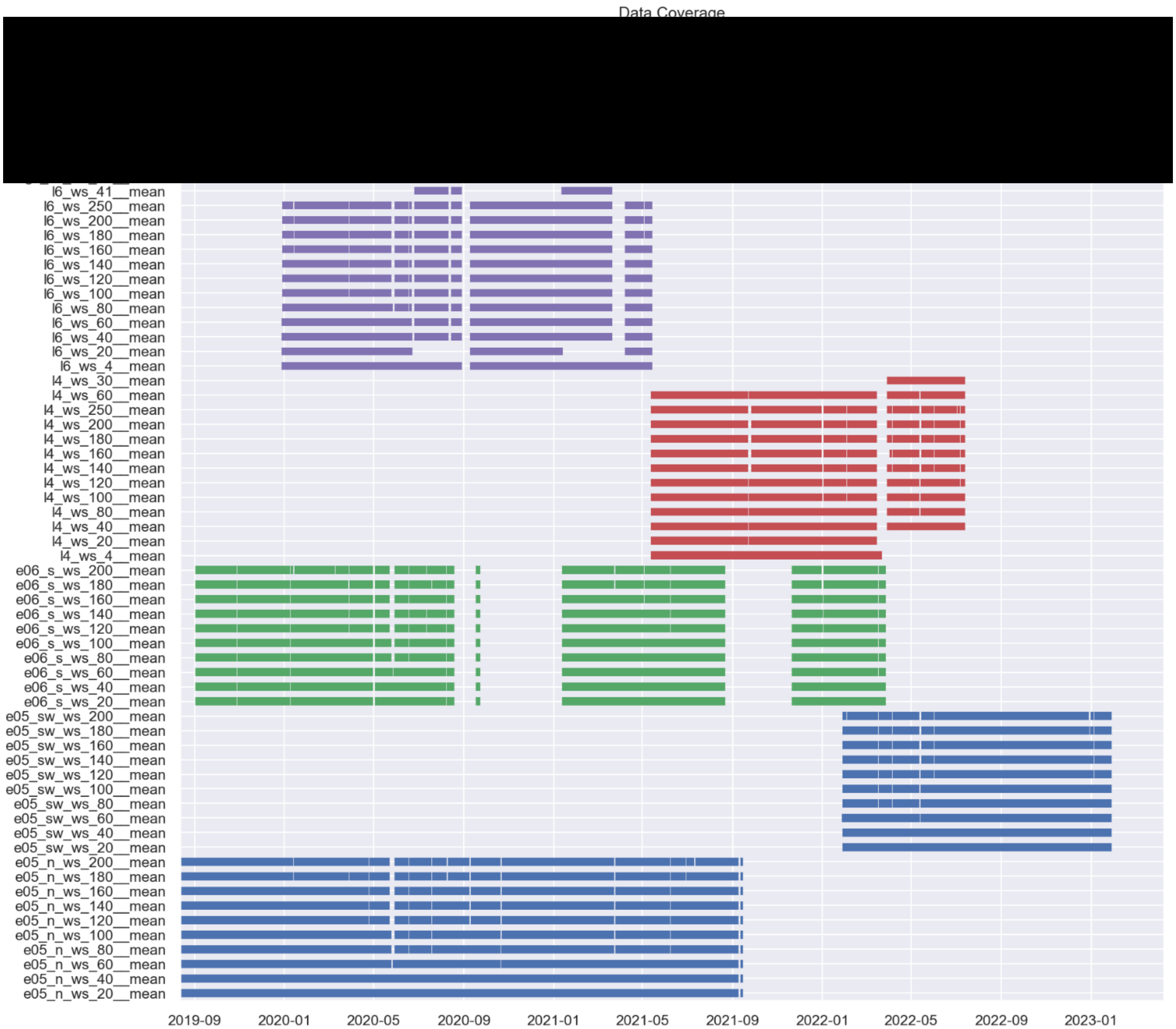

Figure D-1 Wind speed data coverage

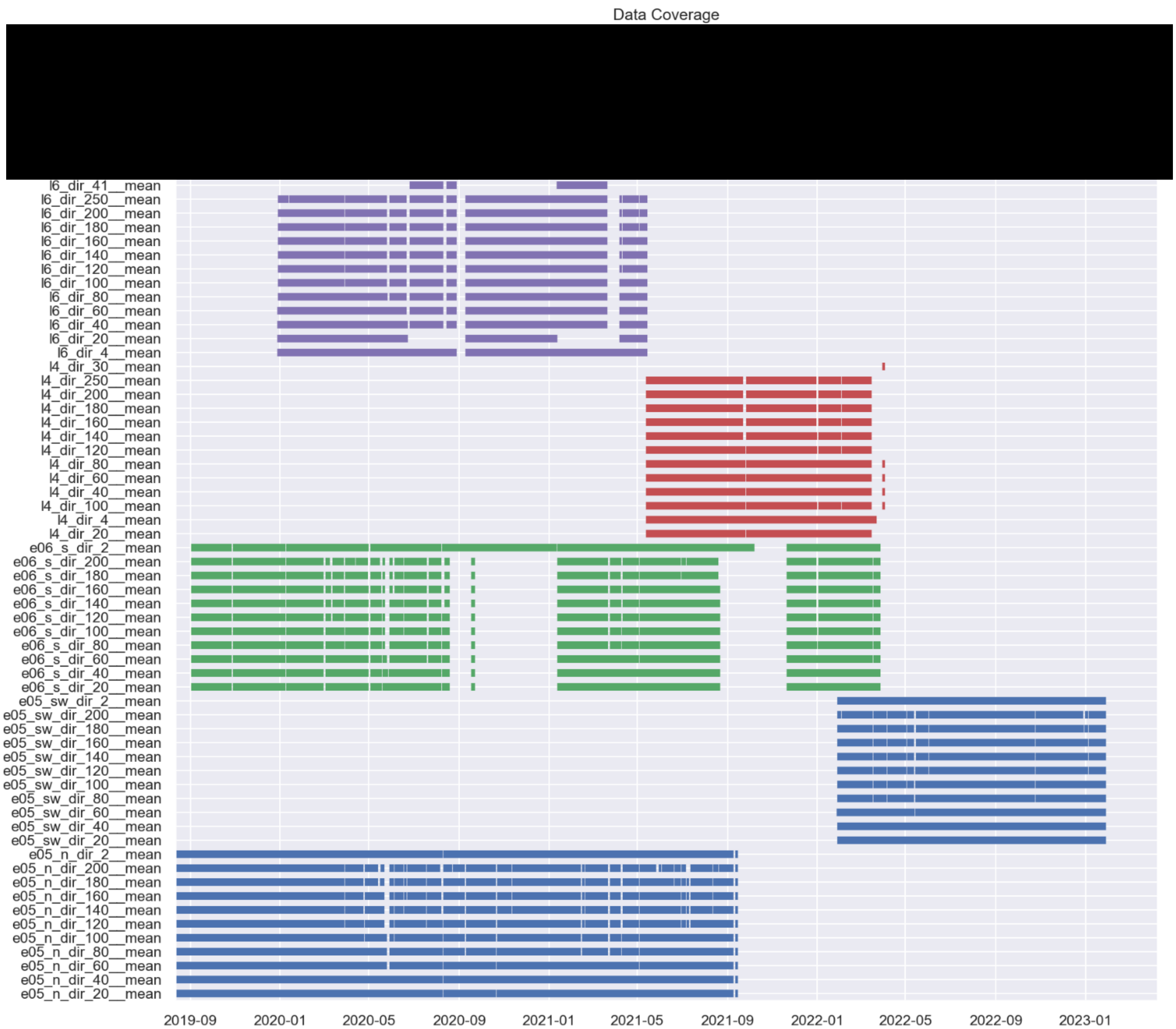

Figure D-2 Wind direction data coverage

C.8 Reference wind data

C.8.1 MERRA-2 data

The Modern Era Retrospective-analysis for Research and Applications, Version 2 (MERRA-2) data set has been produced by the National Aeronautics and Space Administration (NASA) by assimilating satellite observations with conventional land-based meteorology measurement sources using the Goddard Earth Observing System, Version 5.12.4 (GEOS-5.12.4) atmospheric data assimilation system. The analysis is performed at a spatial resolution of 0.625° longitude by 0.5° latitude. DNV typically procures hourly time series of two-dimensional diagnostic data, at a surface height of 50 m [C-1] for suitable grid cells near the project site.

C.8.2 ERA5 data

ERA5 is the fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate. It provides data at a considerably higher spatial and temporal resolution than its predecessor ERA-Interim: hourly analysis fields are available at a horizontal resolution of 31 km and include wind data at 100 m above ground level, as well as surface air temperature and air pressure. ERA5 incorporates vast amounts of historical measurement data, including satellite-, commercial aircraft-, and ground-based data [C-2][C-3].

C.8.3 Virtual Met Data

The DNV Virtual Met Data (VMD) is developed from a mesoscale-model-based downscaling system that provides high-resolution long-term reference time series data for any location in the world. DNV VMD is primarily based on the Weather Research and Forecasting (WRF) Model, a mesoscale model developed and maintained by a consortium of more than 150 international agencies, laboratories, and universities. VMD is driven by a number of new high-resolution inputs, such as MERRA-2, global 25 km resolution 3-hourly and daily analyses of soil temperature and moisture, sea surface temperature, sea ice, and snow depth. A sophisticated land surface model predicts surface fluxes of heat and moisture to the atmosphere, reflected shortwave radiation, and longwave radiation emitted to the atmosphere. Data are typically produced as a virtual hourly time series on a 2 km horizontal resolution grid, centered on the subject wind farm site at the location of a met mast on the site.

C.8.4 References

[C-1] National Aeronautics and Space Administration, MERRA-2, MDISC, https://disc.sci.gsfc.nasa.gov/mdisc/, MERRA-2 tavg1_2d_slv_Nx: 2d, 1-Hourly, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4 (M2T1NXSLV), 1980-present.

[C-2] European Centre for Medium-Range Weather Forecasts, “ERA5 data documentation,” https://confluence.ecmwf.int/display/CKB/ERA5+data+documentation

[C-3] Copernicus, “Climate reanalysis,” https://climate.copernicus.eu/products/climate-reanalysis

C.8.5 Tables of monthly reference data

Table C-1 Wind speed statistics at [redacted]

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Jan	[redacted]																							
Feb	[redacted]																							
Mar	[redacted]																							
Apr	[redacted]																							
May	[redacted]																							
Jun	[redacted]																							
Jul	[redacted]																							
Aug	[redacted]																							
Sep	[redacted]																							
Oct	[redacted]																							
Nov	[redacted]																							
Dec	[redacted]																							
Annual	[redacted]																							

Table C-2 Wind speed statistics at [redacted]

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Jan	[redacted]																							
Feb																								
Mar																								
Apr																								
May																								
Jun																								
Jul																								
Aug																								
Sep																								
Oct																								
Nov																								
Dec																								
Annual																								

APPENDIX D – Wind farm analysis and results

D.1 Correlations

Table E-1 Correlation of wind speed between [redacted]

[redacted]

[redacted]

Figure E-1 Correlation of wind direction between [redacted]

Table E-2 Correlation of wind speed between [redacted]

[redacted]

[redacted]

Figure E-2 Correlation of wind direction between [redacted]

[redacted]

Figure E-3 Correlation of wind speed between [redacted]

[redacted]

Figure E-4 Correlation of wind speed between [redacted]

[redacted]

Figure E-5 Correlation of wind speed between [redacted]

[redacted]

Figure E-6 Correlation of wind speed between [redacted]

D.2 Site-period wind speeds

Table E-3 Site-period wind speeds [m/s]

Month	[redacted]
January	[redacted]
February	[redacted]
March	[redacted]
April	[redacted]
May	[redacted]
June	[redacted]
July	[redacted]
August	[redacted]
September	[redacted]
October	[redacted]
November	[redacted]
December	[redacted]
Annual	[redacted]

Values include data synthesized from other site FLS.

D.3 Mast long-term wind regime

Table E-4 [redacted] long-term wind speed and frequency distribution at [redacted]

Monthly mean wind speeds			
Monthly	**Wind speed [m/s]**	**Valid wind speed data [months]**	**Valid direction data [months]**
January	[redacted]		
February			
March			
April			
May			
June			
July			
August			
September			
October			
November			
December			
Annual			

[redacted]

Wind speed and direction frequency distribution

Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	No Direction	Total [%]
0	[redacted]													
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
11														
12														
13														
14														
15														
16														
17														
18														
19														
20														
21														
22														
23														
24														
25														
26														
27														
28														
29														
30														
30+														
Total [%]														
Mean Speed														

Note: '+' indicates non-zero percentage <0.005%, blank indicates zero percentage

Table E-5 [redacted] long-term wind speed and frequency distribution at [redacted]

Monthly mean wind speeds			
Monthly	**Wind speed [m/s]**	**Valid wind speed data [months]**	**Valid direction data [months]**
January	[redacted]		
February			
March			
April			
May			
June			
July			
August			
September			
October			
November			
December			
Annual			

[redacted]

Wind speed and direction frequency distribution

Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	No Direction	Total [%]
0	[redacted]													
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
11														
12														
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20														
21														
22														
23														
24														
25														
26														
27														
28														
29														
30														
30+														
Total [%]														
Mean Speed														

Note: '+' indicates non-zero percentage <0.005%, blank indicates zero percentage

D.4 Time-dependent loss factors

The results presented in the main text of this report represent annual average energy production values for a wind farm averaged over the first [redacted] of operation. However, for some wind farms there will be loss factors which change over time such as the availability of the wind farm and the influence of trees (if any). The following table presents the specific values that have been assigned for each year.

Table E-6 Time-dependent loss factors

Year	Turbine availability (2a)	Turbine degradation (4e)
	[%]	[%]
[redacted]		

Turbine availability calculation

For the purposes of this analysis, DNV has made the following preliminary assumptions to derive a starting assumption for the turbine availability loss profile (loss category 2a):

a) Projects with similar project characteristics and wave and wind conditions present similar availabilities in other regions in comparison with those experienced in the North Sea. Based on this assumption, the projected turbine availability is therefore based on North Sea experience. DNV considers this to be a reasonable starting assumption for projects in other regions in the absence of a more detailed project specific review of the O&M access strategy and metocean conditions at the site, as this is supported by previous experience and extensive modelling performed by DNV.

b) Turbine reliability varies according to the wind speed conditions at site, therefore, sites with lower wind speeds will present better turbine reliability than sites with higher wind speeds. This is based on recent studies using real industry data [D-1].

c) The project operates or is to operate with an optimal number of technicians, therefore values are only representative when the number of staff is well planned.

d) Main component replacements are performed using a Jack-Up vessel with an average lead time to get to the site of 45 days. This is the typical expected value based on operational experience in the North Sea, however this is expected to be different in the future and in different markets.

e) Turbine reliability is based on experienced turbine manufacturers therefore only valid for projects considering models from offshore experienced turbine suppliers. If the project is considering newer turbine models the validity of this projection is to be regarded with caution and a project specific review is recommended.

Based on these assumptions, DNV has estimated an indicative starting assumption for turbine availability for the following project characteristics:

Table D-7 Turbine availability loss assumptions

Project characteristic	Value assumed for modelling	Source of assumption
Distance to O&M port [nautical miles]:	[redacted]	DNV
Mean long-term wind speed at hub height [m/s]:	[redacted]	DNV
Mean long-term significant wave height [m]:	[redacted]	DNV
Assumed Drive Train Concept:	[redacted]	DNV
Ramp up expected [in increase of %]:	[redacted]	DNV
Ramp up period [in years]:	[redacted]	DNV
Period evaluated [in years]:	[redacted]	Customer
Access strategy expected:	[redacted]	Customer

DNV has selected these values based on high-level assumptions. It is expected that these assumptions will change as the projects are developed further and a commercially available turbine model is identified for the site. At this later stage of the project, it is recommended that the estimated turbine availability for the project should be updated.

D.4.1 References

[D-1] Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines, Carroll et al, https://pure.strath.ac.uk/portal/files/44298789/Carroll_etal_WE_2015_Failure_rate_repair_time_and_unscheduled_O_and_M_cost_analysis_of_offshore.pdf, University of Strathclyde, first published 6 August 2015.

D.5 Energy results

Table E-8 Energy results, Layout PS163 ([redacted])

Turbine	Turbine model	Hub height [m]	Initiation device	Easting[a] [m]	Northing[a] [m]	Elevation [m]	Long-term wind speed at hub height[b] [m/s]	Energy output[c] [GWh/ annum]	Turbine interaction loss factor[d] [%]
[redacted]									

[redacted]

[redacted]

a. Co-ordinate system is UTM 18N, NAD83.

b. Wind speed at the location of the turbine, not including wake effects.

c. Individual turbine output figures include all wind farm losses.

d. Individual turbine wake loss including all turbine interaction effects (wakes and blockage).

Table E-9 Energy results, Layout PS164 ([redacted]

Turbine	Turbine model	Hub height [m]	Initiation device	Easting[a] [m]	Northing[a] [m]	Elevation [m]	Long-term wind speed at hub height[b] [m/s]	Energy output[c] [GWh/ annum]	Turbine interaction loss factor[d] [%]
[redacted]									

[redacted]

[redacted]

a. Co-ordinate system is UTM 18N, NAD83.
b. Wind speed at the location of the turbine, not including wake effects.
c. Individual turbine output figures include all wind farm losses.
d. Individual turbine wake loss including all turbine interaction effects (wakes and blockage).

Table E-10 Energy results, Layout PS165 ([redacted]

Turbine	Turbine model	Hub height [m]	Initiation device	Easting[a] [m]	Northing[a] [m]	Elevation [m]	Long-term wind speed at hub height[b] [m/s]	Energy output[c] [GWh/ annum]	Turbine interaction loss factor[d] [%]
[redacted]									

[redacted]

[redacted]

[redacted]

a. Co-ordinate system is UTM 18N, NAD83.

b. Wind speed at the location of the turbine, not including wake effects.

c. Individual turbine output figures include all wind farm losses.

d. Individual turbine wake loss including all turbine interaction effects (wakes and blockage).

D.6 Seasonal and diurnal variation

Table E-11 Relative hourly and monthly energy production as a percentage, Layout PS163

Hour	Energy production[a] [%]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	[redacted]											
0100												
0200												
0300												
0400												
0500												
0600												
0700												
0800												
0900												
1000												
1100												
1200												
1300												
1400												
1500												
1600												
1700												
1800												
1900												
2000												
2100												
2200												
2300												
All												

a. Only wake and hysteresis losses have been included in the calculation.

Table E-12 Relative hourly and monthly energy production as a percentage, Layout PS164

Hour	Energy production[a] [%]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	[redacted]											
0100												
0200												
0300												
0400												
0500												
0600												
0700												
0800												
0900												
1000												
1100												
1200												
1300												
1400												
1500												
1600												
1700												
1800												
1900												
2000												
2100												
2200												
2300												
All												

a. Only wake and hysteresis losses have been included in the calculation.

Table E-13 Relative hourly and monthly energy production as a percentage, Layout PS165

Hour	Energy production[a] [%]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	[redacted]											
0100												
0200												
0300												
0400												
0500												
0600												
0700												
0800												
0900												
1000												
1100												
1200												
1300												
1400												
1500												
1600												
1700												
1800												
1900												
2000												
2100												
2200												
2300												
All												

a. Only wake and hysteresis losses have been included in the calculation.

ABOUT DNV

We are the independent expert in assurance and risk management. Driven by our purpose, to safeguard life, property and the environment, we empower our customers and their stakeholders with facts and reliable insights so that critical decisions can be made with confidence. As a trusted voice for many of the world's most successful organizations, we use our knowledge to advance safety and performance, set industry benchmarks, and inspire and invent solutions to tackle global transformations.