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ANALISI DI PRODUZIONE ENERGETICA – PARCO EOLICO MONREALE – SINTESI DEI RISULTATI

Il cliente sta sviluppando il Parco Eolico di Monreale (il “Progetto”), ed ha incaricato DNV di svolgere una analisi indipendente della risorsa eolica e produzione energetica del Progetto. I dettagli dell’analisi sono riportati nel documento 10448821-ITBO-R-08-A, emesso da DNV in data 28/09/2023. Il presente documento rappresenta invece una sintesi dei risultati riportati nel documento principale.

Descrizione del progetto

Il Progetto è costituito da 15 macchine, ed è situato a circa 45km nordovest di Cagliari, in Sardegna. DNV ha analizzato due configurazioni per il parco, riportate in Tabella 1. Le coordinate del parco sono invece riportate in Tabella 2.

Tabella 1 Caratteristiche del parco

Configurazione	Modello di turbina	Altezza mozzo [m]	Capacità installata [MW]
V162 HH125	Vestas V162 6.0MW	125.0	90.0
V163 HH113	Vestas V163 4.5MW	113.0	67.5

Tabella 2 Coordinate del parco Monreale

Turbina	Coordinate [m]	
M1	477144	4374075
M2	477461	4374455
M3	477814	4374985
M4	478282	4375658
M5	478602	4376025
M6	479003	4376403
M7	478356	4373251
M8	478968	4374308
M9	480915	4375118
M10	484464	4374355
M11	484653	4375146
M12	484644	4375735
M13	485045	4376218
M14	485653	4376505

Sistema di riferimento UTM, Datum WGS84, zona 32

Risorsa eolica

Il Cliente ha fornito dati di vento registrati da una torre anemometrica installata in sito. Le caratteristiche della strumentazione di misura sono riportate in Tabella 3.

Tabella 3 Strumentazione di misura installata in sito

Strumentazione	Inizio del periodo di misura	Fine del periodo di misura	Tipologia di sensore	Altezze di misura [m]
Mast M99	01/09/2021	30/04/2023	Anemometro	99.0, 80.0 [a], 60.0 [a], 40.0 [a]
			Banderuola	98.0, 78.0, 58.0

a. Due anemometri paralleli installati a queste altezze.

I risultati dell'analisi dei dati di vento sono riportati in Tabella 4.

Tabella 4 Risultati dell'analisi dei dati di vento

Altezza mozzo [m]	Periodo di misura [anni]	Periodo di riferimento di lungo termine [a] [anni]	Velocità di lungo termine al mast [m/s]	Velocità media di lungo termine del parco [m/s]
[redacted]				

a. Data la bassa qualità delle correlazioni con le serie di riferimento di lungo termine, nessun aggiustamento di lungo termine è stato applicato ai dati misurati in sito.

Analisi energetica

I risultati dell'analisi energetica sono riportati in Tabella 5.

Tabella 5 Sintesi dei risultati di produzione

Scenario	V162 HH125	V163 HH113
Periodo di valutazione [years]	20	20
[redacted]		

La stima di produzione netta P50 rappresenta la media di lungo termine, con probabilità di eccedenza del 50%, della effettiva produzione del parco eolico. Questo valore rappresenta la migliore stima del valor medio di lungo termine da aspettarsi per il progetto. C'è quindi una possibilità del 50% che, anche quando valutata su periodi molto lunghi, la produzione media del parco sia inferiore al valore stimato.

Fonti

/1/ “Monreale Wind Farm – Energy Production Assessment” , DNV report 10448821-ITBO-R-08-A datato 28/09/2023

MONREALE WIND FARM WIND FARM

Energy Production Assessment

Monreale Wind s.r.l.

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List of abbreviations

Abbreviation	Meaning
AGL	Above Ground Level
CFD	Computational Fluid Dynamics
ECMWF - ERA	European Centre for Medium-Range Weather Forecasts - European Reanalysis
GEOS-5	Goddard Earth Observing System Data Assimilation System Version 5
MARS	Meteorological Archival and Retrieval System
MEASNET	Measuring Network of Wind Energy Institutes
MERRA	Modern-Era Retrospective Analysis for Research and Applications
NASA	National Aeronautics and Space Administration
NCAR	United States National Center for Atmospheric Research
O&M	Operation and maintenance
RANS	Reynolds Averaged Navier-Stokes
RSD	Remote Sensing Device(s)
SRTM	Shuttle Radar Topography Mission
TSA	Turbine Supply Agreement
WAsP	Wind Atlas Analysis and Application Program
WRF	Weather Research and Forecasting

EXECUTIVE SUMMARY

Monreale Wind s.r.l. ("the Customer") retained DNV Italy S.r.l ("DNV") to complete an independent analysis of the wind regime and energy production of the proposed Monreale Wind Farm Wind Farm ("the Project").

Table 1 summarises the Project and the results of the wind resource and energy production analysis for two scenarios.

Table 1 Executive summary

[redacted]

The P90 / P50 uncertainty index indicates that the uncertainty level of this estimate is average. The mitigation measures detailed in Section 7 are recommended to reduce the uncertainty. The key contributions to the uncertainty, in addition to the natural inter-annual wind speed variability, are:

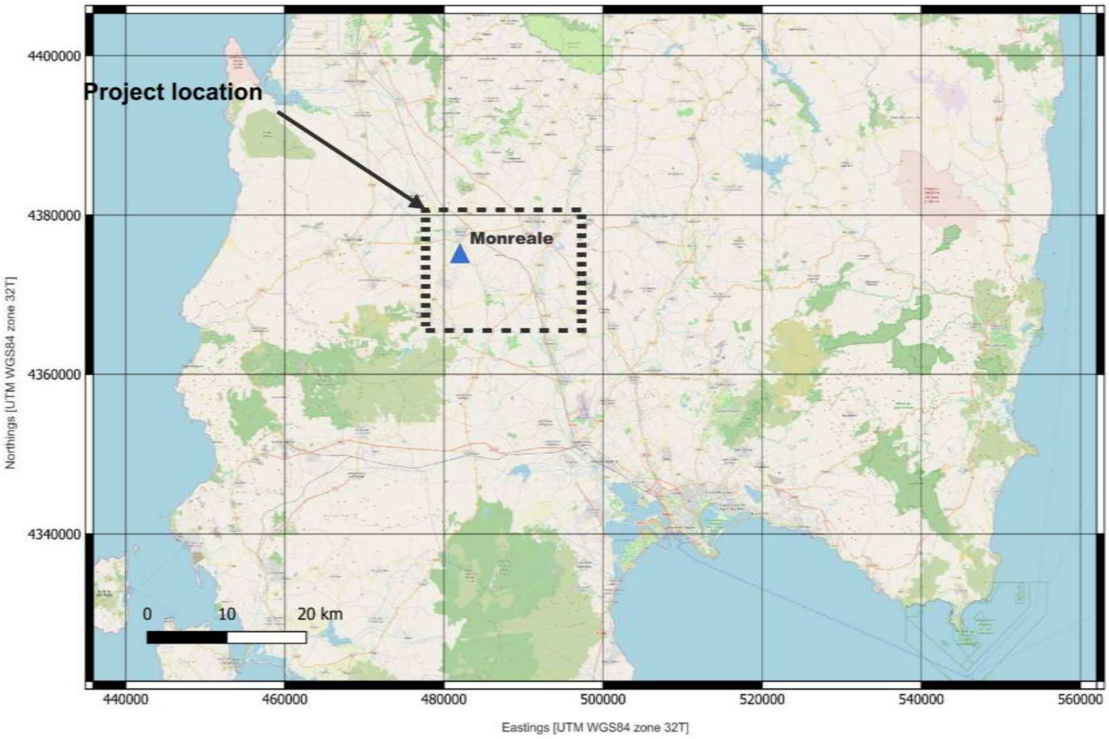
a. That most turbines are located more than 2 km from the met mast.

b. That long term adjustment was not applied due to the low quality of correlations with long-term reference sources.

1 INTRODUCTION

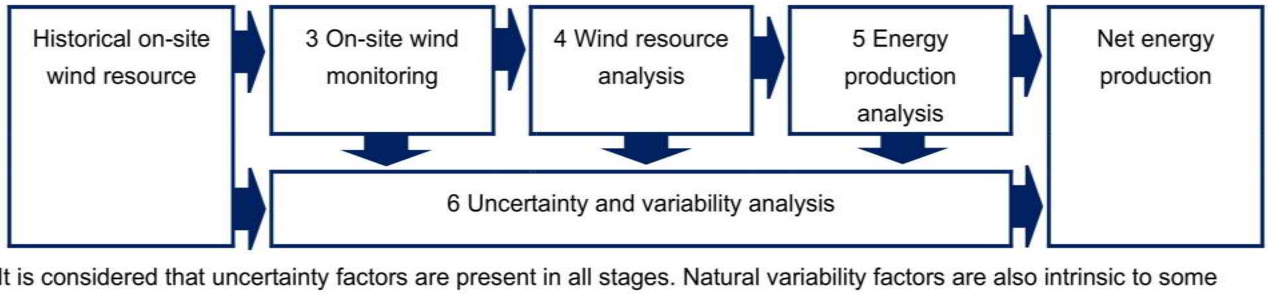
The Customer is developing the Monreale Wind Farm Wind Farm. The Project consists of 15 wind turbines and is located approximately 45 km northwest of Cagliari, in the Sardinia region of Italy, as shown in Figure 1-1.

Figure 1-1 Project location



The Customer instructed DNV to carry out an independent analysis of the wind regime and energy production of the Project for two scenarios. The results of the work are reported in this document, which has been prepared pursuant to the DNV proposal referenced L245275-ITIM-P-03-C dated 2023-05-31, and is subject to the terms and conditions contained therein.

This report presents the sequential steps that were followed to derive the wind resource at the site and the corresponding energy production, as illustrated in the flow chart below. At each stage, the method is described, and the corresponding levels of uncertainty are detailed, culminating in the combination of the individual uncertainties and variabilities, and in the wind farm net energy production profile. The main body of the report presents the results for each step, while the detailed methodology is included in Appendix E.



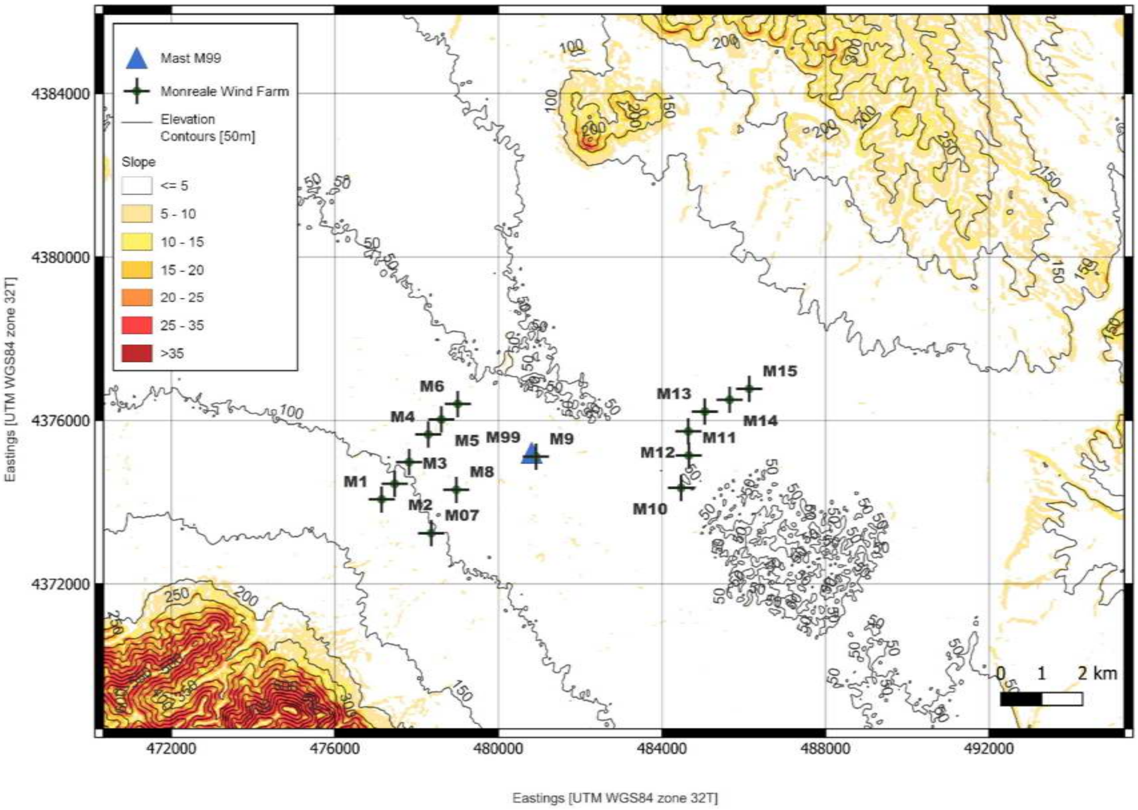
It is considered that uncertainty factors are present in all stages. Natural variability factors are also intrinsic to some stages. While variability is inherent and cannot be reduced, uncertainty factors can be reduced to normal levels through mitigation measures. Section 7 presents the DNV observations and recommendations that should be followed in order to reduce the uncertainty in the analysis to normal levels.

2 PROJECT DESCRIPTION

2.1 Site characteristics

Figure 2-1 presents a map of the site area, showing the location of the monitoring equipment for which wind data were supplied, the wind turbine layout, and areas of steep slopes close to the project site.

Figure 2-1 Map of the site area



The Project is located on a plateau of average elevation 75 m above sea level. The site is located approximately 25 km from the sea, and the surrounding area consists of mountains of elevation ranging between 200 m and 600 m above sea level. The terrain at the site is considered to be relatively complex due to mountains to the west and southwest of the site, even if there are no steep slopes within the Project area.

Based on public aerial imagery dated Jun-2023, the ground cover at the site consists predominantly of farmlands. Approximately 2 km from the site area is a settlement.

The ridge slopes on the south-west side of the plateau are covered by forest. There is a little forestry near the monitoring equipment and the proposed wind turbine locations.

2.2 Wind turbine technology and layout

The Customer instructed DNV /1/ to consider the wind turbine models shown in Table 2-1.

Table 2-1 Wind turbine model

Turbine OEM	Turbine model	Rated power [kW]	Rotor diameter [m]
Vestas	V162-6.0MW	6000	162
Vestas	V163-4.5MW	4500	163

This report presents the results for two scenarios. The wind turbine layout characteristics are presented in Table 2-2 and the coordinates for each wind turbine location are listed in Appendix D-2.

Table 2-2 Wind turbine layout

Scenario	Evaluation period [years]	Wind turbine model	Hub height [m]	Number of wind turbines	Total installed capacity [MW]
V162 HH125	20	V162 6.0MW	125	15	90.0
V163 HH113	20	V163 4.5MW	113	15	67.5

Section 5.6.1 further describes the layout.

2.3 Neighbouring wind farms

The Project is proposed within a region of wind farm development activity. The map in Figure 2-2 and the list in Table 2-3 present the information obtained by DNV from publicly available data sources regarding existing and proposed neighbouring wind farms. The known characteristics and layout of the existing neighbouring wind turbines are listed in Appendix A.

Figure 2-2 Map of neighbouring wind farms considered in the analysis

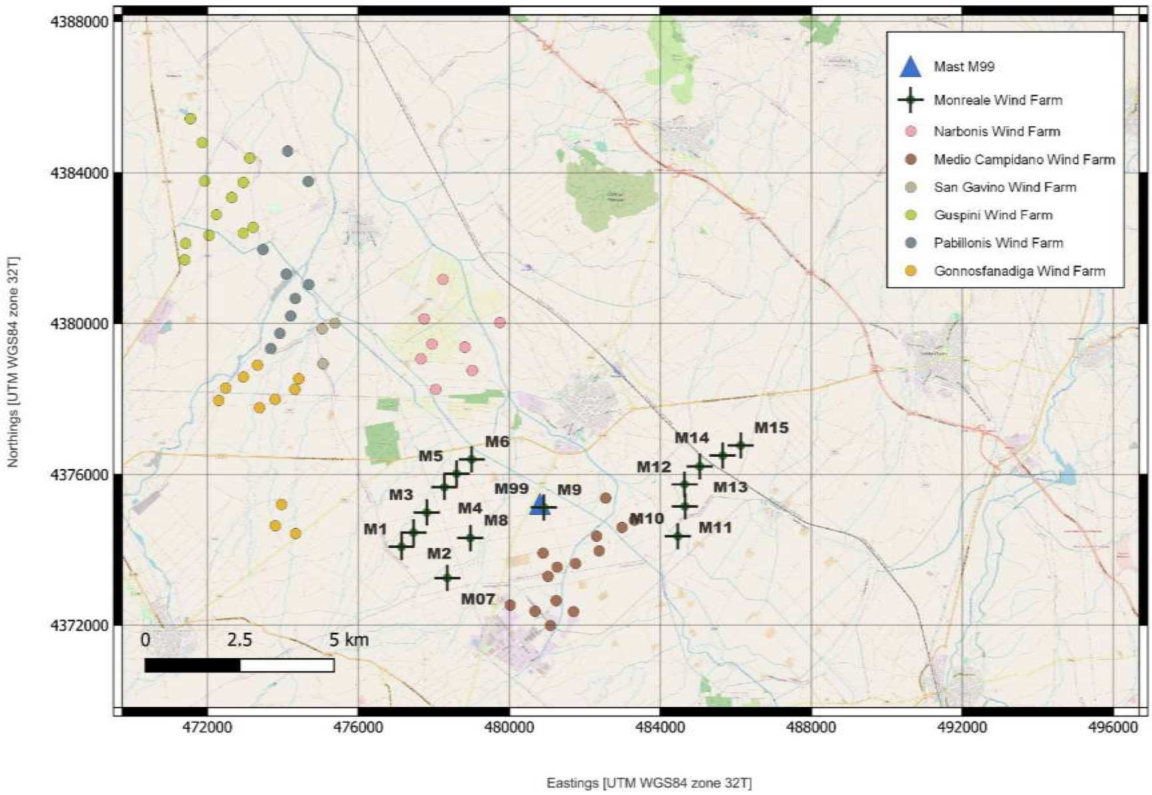


Table 2-3 Summary of existing and proposed neighbouring wind farms

Wind farm name	Approximate location	Turbine Model	Start of operation
Narbonis Wind Farm	2.0 km North	Assumed 8 x Vestas V162 6.0MW at 125 m	Proposed
Medio Campidano Wind Farm	1.1 km East	Vestas V110 2.2MW at 95 m	Dec-18
San Gavino Wind Farm	4.5 km Northwest	Vestas V90-2.0 MW at 80 m	Nov-08
Guspini Wind Farm	8.3 km Northwest	Vestas V90-2.0 MW at 80 m	Nov-08
Pabillionis Wind Farm	5.9 km Northwest	Vestas V90-2.0 MW at 80 m	Nov-08
Gonnosfanadiga Wind Farm	2.8 km West	Vestas V90-2.0 MW at 80 m	Nov-08

The impact on the energy output of the Project caused by neighbouring wind turbines was considered in this analysis. DNV considers that the data recorded by the Project measurement mast have been affected by the presence of neighbouring wind turbines of the Medio Campidano wind farm during the measurement period that was concurrent with the operation of the neighbouring wind turbines. The influence of wakes caused by neighbouring wind farms on the wind speed data recorded was estimated, and this estimate was used to adjust the mean wind speed at the mast.

It is possible that additional wind energy projects will be built in the vicinity of the Project. However, there is insufficient information available to reasonably estimate the impact of any other future developments on the Project. It is recommended that the Customer procures this information and supplies it in future updates of this work.

3 ON-SITE WIND MONITORING

Existing on-site wind resource	→	3.1 On-site monitoring equipment 3.2 On-site measurements quality control	→	Measured on-site wind resource

3.1 On-site monitoring equipment

The Customer supplied wind data recorded by the on-site measurement equipment listed in Table 3-1. Full details, panoramic views and photographs of the mounting arrangements of the monitoring equipment are presented in Appendix D.

Table 3-1 List of on-site monitoring equipment

Monitoring equipment	Measurement period start date	Measurement period end date	Wind measurement type	Measurement heights [m]
M99	Sep 2021	Apr 2023	Wind speed	99.0, 80.0 [a], 60.0 [a], 40.0 [a]
M99	Sep 2021	Apr 2023	Wind direction	98.0, 78.0, 58.0

a. Parallel anemometers installed.

3.1.1 Site mast mounting arrangements

The mounting arrangement criteria that must be fulfilled for compliance with the IEC /3/ standard is summarised in Appendix E-1.1. It is important that DNV have been able to independently verify information regarding the wind data measurement campaign, including mast measurement heights, sensor mounting configurations and mast installation positions, and also that detailed commissioning and maintenance reports are available and adequate.

At Mast M99 the mounting arrangements of the primary sensors were consistent with the recommendations of the IEC /3/. The measurements further benefited from the selective averaging process described in Appendix E-1.1, due to the presence of two parallel anemometers mounted at the same height in opposite directions.

Mast installation reports and maintenance records have been provided by the Customer/1/. The standard of documentation is good and is sufficient to ensure traceability of the instrumentation throughout the monitoring campaign.

All information concerning the configurations and instrument mounting arrangements of the mast has been assumed from maintenance reports supplied by the Customer. The mast was not inspected independently by DNV as it was not part of the scope of work. In some cases independent inspection of masts by DNV can reduce the uncertainty level of an analysis.

3.1.2 Site mast sensor calibrations

A cup-anemometer calibration should be undertaken at a MEASNET facility according to IEC 61400-12-1 Annex F as per ISO/IEC 17025. In addition to that, DNV needs to be able to establish the veracity of the measurements, including that the data provided are original, the availability of proper calibration certificates and the applicable data logger configuration files.

At Mast M99 all sensors were individually calibrated at a MEASNET facility.

The wind data supplied by the Customer are deemed to originate directly from the mast data loggers, and configuration files showing the transfer functions applied have also been supplied by the Customer. Calibration certificates have been supplied for the anemometers mounted on the masts, and DNV has ensured that these calibrations have been applied correctly in the analysis here, as described in Appendix E-1.1.

3.2 On-site measurements quality control

Wind data from the monitoring equipment supplied by the Customer have been processed and validated in accordance with DNV's standard quality control process in order to identify records which were affected by equipment malfunction and other anomalies. These records were excluded from the analysis.

3.2.1 On-site measurement consistency

Measurement consistency throughout the validated period is important, and a detailed verification was performed on potential causes for inconsistency, such as changes in the configuration, in measuring equipment, or in the interference of changing forestry height or wake effects from neighbouring wind farms.

The configuration of the mast was kept unaltered throughout the measurement campaign. The anemometers have been installed on-site for a period shorter than four years and did not reveal signs of degradation.

As described in Section 2.1, the site has a few forested areas and any changes in forestry over time are not expected to have affected the measurement campaign.

The wakes from the operational Medio Campidano wind farm neighbouring the Project area have affected the wind data recorded at the site. An analysis of the impact on the measurements was made by modelling the wake effects at the mast location using the WindFarmer: Analyst software, and the results are presented in Table 3-2. The uncertainty is higher since the affected dataset is considered and where an attempt at correcting the wake effects is made.

Table 3-2 Summary of wake affected measurements

Affected monitoring equipment	Affected dataset start date	Affected dataset end date	Impact on measurements
M99	2021-09-01	2023-04-31	1.1%

Correction factors on a directional basis have therefore been applied to the wind speeds recorded at the mast to approximately correct for this effect. The uncertainty in the accuracy of wind speed correction is considered in Section a.

3.2.2 Selection of primary data sensors

Wind resource is composed of the wind speed and wind direction, and both are derived from on-site measurements. Based on the data coverage resulting from the data quality control and consistency check procedure, as well as on being the closest measurement height to the wind turbine hub height, the measurements selected as the primary sensors for the monitoring equipment are summarised in Table 3-3.

Table 3-3 Summary of measured wind data coverage at the primary sensors

Monitoring equipment	Measurement period start date	Measurement period end date	Wind measurement type	Height	Coverage
				[m]	[%]
M99	2021-09-01	2023-04-31	Wind speed	99.0	95.4
M99	2021-09-01	2023-04-31	Wind direction	98.0	95.4

3.2.3 Measured mean wind speed

The resulting measured on-site mean wind speed at the mast is shown in Table 3-4.

Table 3-4 Summary of measured on-site mean wind speed

Monitoring equipment	Height	Period	Wind speed
	[m]	[years]	[m/s]

[redacted]

3.2.4 Site measurement uncertainties

The following table presents the measurement uncertainties estimated for the site.

Table 3-5 Summary of measured on-site mean wind speeds

Monitoring equipment	Measurement accuracy [% wind speed]
M99	1.8

Appendix E-6 provides a discussion of typical site measurement uncertainties and how they are determined. Site specific aspects of these values are:

- DNV has applied an additional uncertainty to account for the corrections to the wind speed data at Mast M99 to remove the impact of the neighbouring Medio Campidano operational turbines.
- The uncertainty is reduced due to the presence of calibrated anemometers at MEASNET accredited facilities.

4 WIND RESOURCE ANALYSIS

Measured on-site wind resource	→	4.1 Long-term wind resource extrapolation 4.2 Vertical wind resource extrapolation 4.3 Spatial wind resource extrapolation	→	Long-term hub-height wind resource at the turbine positions

The wind resource of a wind farm is described by both the long-term wind speed and by the long-term wind speed and direction frequency distribution, at hub-height, at the location of every wind turbine.

This section describes the process that is followed to derive these two components of the wind resource.

4.1 Long-term wind resource extrapolation

To reduce the uncertainty of the long-term wind resource estimate at the Project site, it is desirable that firstly a dataset from all sensors/heights on the measurement device is established for the longest possible period, in order to maximise the use of on-site wind data, and then that an adjustment is made based on quality long-term reference sources.

4.1.1 On-site data reconstruction

Sensors for which there is a longer period of valid wind data can be used to reconstruct data at the remaining sensors, and this process is described in Appendix E-1.3, for ten-minute, daily and monthly reconstruction methods. Reference sensors which are better correlated to the target sensors, such as sensors installed at different heights in the same mast, are prioritised in the reconstruction process. All correlations were quality checked as explained in Appendix E-1.5, and the results of this check were used to inform the next steps in the analysis.

However, due to the presence of only one mast at the site with the same valid data periods at all heights, the method described above did not result in an improvement in data coverage at the primary sensors, and therefore wind speed and direction data reconstruction was not employed at the mast.

4.1.2 Long-term reference data

DNV reviewed reference wind data from a list of sources, including nine MERRA-2 /4/ grid cells and nine ERA-5 /5/ grid cells closest to the Project site.

It is important that the source of reference data is consistent over the period being considered, and this was evaluated through a comparison with regional trends and statistical verifications. Where this comparison suggested an inconsistency in the reference dataset, the data prior to the inconsistency were excluded. It is also important that the wind regime for the reference data is driven by similar factors as the site wind regime. The adjustment uncertainty is influenced by the time basis used in the correlation and by the coefficient of determination R^2, which indicates the quality of the correlation to each source.

Table 4-1 summarises these factors between the monitoring equipment and the investigated reference datasets. The R^2 coefficient corresponds to the grid cell showing the most robust correlation with the mast.

Table 4-1 Correlations between each mast and reference data set

Monitoring equipment	Reference data Source	Reference data Consistent data period [years]	Correlation Concurrent data period [years]	Representative correlation coefficient R^2	Time basis for the correlation
[redacted]					

The quality of the correlations between the monitoring equipment and the reference datasets, were significantly poor for all time basis considered. For this reason, it is considered inappropriate for the representativeness of the site, and the incorporation in this assessment of these datasets would increase the uncertainty in predicting the wind regime at the site. As such, these were not considered further.

4.1.3 Adjusting on-site wind speed to the long-term

The long-term period of data is assumed here to represent the Evaluation Period. To derive the period of long-term, the first option is to consider the on-site measured data period shown in Table 3-4 to be representative of the long-term. The alternative option is to adjust the on-site data to a longer period using a reference data source. The latter alternative yields longer and more representative datasets, but also adds uncertainty factors to the analysis, due to the consistency and correlation quality issues described earlier.

To compare the uncertainty associated with the representativeness of the shorter on-site dataset and the longer adjusted dataset, the specific natural variability of the wind speed observed at this site, from year to year, due to natural climatic oscillations, must be considered. DNV determined the inter-annual variability of the wind speed based on its knowledge of the region, as well as on reference datasets and the onsite measured data. Table 4-2 presents the inter-annual variability estimated for the site.

Table 4-2 One-year wind speed inter-annual variability

Variability	Long-term wind speed [%wind speed]
[redacted]	

The inter-annual wind speed variability shown for the Project site is relatively high, and so a long period of data is considered to be required to represent the long-term wind speed at the site. However, since the correlations with the reference data are not sufficiently robust, DNV considers that the lowest uncertainty route is to consider the on-site measurement period as representative of the long term, forsaking the use of the available reference sources. It is recommended that other sources of quality reference data be evaluated.

DNV

4.1.4 Long-term mean wind speed

The resulting long-term mean wind speed estimated as at the measurement device is presented in Table 4-3.

Table 4-3 Summary of long-term mean wind speeds

Monitoring equipment	Height	Period	Wind speed
	[m]	[years]	[m/s]
[redacted]			

4.1.5 Long-term wind regime uncertainties

DNV has estimated the uncertainties associated with the derivation of the long-term hub height wind regime at each measurement device on the site. Appendix E-6.2 provides a discussion of the uncertainties and how they are determined. The uncertainties are presented in the following table.

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

Monitoring equipment	On-site data reconstruction	Reference data		Representativeness	
		Consistency	Correlation	Period of wind speed data	Wind frequency distribution
	[% wind speed]	[% wind speed]	[% wind speed]	[% wind speed]	[% energy]
[redacted]					

Since no long-term adjustment was considered due to the low quality of correlations the long-term uncertainty is mainly driven by the short period of wind speed data considered to represent the long-term.

4.2 Vertical wind resource extrapolation

Wind shear determines the variation of wind speed with height above the ground. Accurately establishing this vertical wind speed profile depends on the installation height of the wind sensors, on the period of measured wind data available, and on the complexity of the atmospheric wind flow at the site.

4.2.1 Effective historical mast measurement heights

Where obstacles to the flow, such as trees in proximity to a mast, were present during the historical measurement campaign, it is necessary to consider a potential reduction on the effective measurement height these obstacles may have caused. There is uncertainty in accurately determining the forestry height over the course of the measurement campaign, as well as on the method of displacing the atmospheric freestream to take the forestry effect into account.

As described in Section 2.1, the site has a few forested areas, and any trees present at the site were considered not to decrease the effective measurement heights at the masts.

4.2.2 Wind shear profile

To extrapolate the wind speed estimates from measurement height (the extrapolation base) to hub-height (the extrapolation target), the average power law at the mast has been evaluated between all relevant measurement heights as described in Appendix E-2.1, and presented in Table 4-5.

Table 4-5 Wind shear exponents

Monitoring equipment	Measurement period	Measuring height	Hub height	Exponent of the α vertical profile used
	[years]	[m]	[m]	
M99	1.6	99.0	125	0.26
M99	1.6	99.0	113	0.25

At Mast M99 the anemometers included in the wind shear analysis are individually calibrated and are well distributed throughout the mast, and the measurement period used to determine the vertical wind speed profile is greater than one full year. The wind shear profile is considered high, although consistent with the expectations for this region of complex terrain and considered representative of the site.

4.2.3 Long-term hub-height mean wind speed

The resulting long-term hub-height mean wind speed at the mast is presented in Table 4-6.

Table 4-6 Summary of the long-term mean wind speeds at hub-height

Monitoring equipment	Height [m]	Period [years]	Wind speed [m/s]
[redacted]			

4.2.4 Vertical extrapolation uncertainties

Table 4-7 presents the vertical extrapolation uncertainties estimated for the site.

Table 4-7 Vertical extrapolation uncertainties

Monitoring equipment	Wind shear [% wind speed]
[redacted]	

4.2.5 Hub-height wind speed and direction frequency distribution

The wind speed and direction frequency distribution at the monitoring equipment locations represents how the mean wind speed is distributed by wind speed interval and by direction sector. The data period used in its composition can either be the measured data, or the compound measured and reconstructed data. The uncertainty will be lower if the reconstruction process is deemed to increase the representativeness of the wind speed frequency distribution and wind rose, without introducing a seasonal bias in these two components.

The minimum period of wind data that is required for representativeness, is determined by the future wind frequency distribution variability. Table 4-8 presents the one-year inter-annual variability of the wind speed and direction frequency distribution estimated for the Project region.

Table 4-8 One-year wind frequency distribution variability

Variability	Wind frequency distribution [% energy]
[redacted]	

Based on the future inter-annual variability of the wind speed frequency distribution, and also on the length of the wind speed and the wind direction measurements available being shorter than two full years, a seasonal bias of this distribution may be expected at M99 Mast.

Owing to the difference between the primary measurement height and the hub-height, a vertical extrapolation of the wind speed and direction frequency distribution was required. The vertical extrapolation was performed using a ten-minute time series method, as described in Appendix E-2.2. For the mast, the originally measured time series was firstly vertically extrapolated to hub-height and then used to derive the wind speed and frequency distribution at hub-height. Finally, the frequency distribution was adjusted to the long-term mean wind speed presented in Table 4-6..

The corresponding long-term hub-height wind speed and direction frequency distribution at the location of the mast is shown as a histogram in Figure 4-1 for the representative hub height of 125 m.

Figure 4-1 Wind speed frequency distribution at Mast M99 at 125 m

[redacted]

4.2.6 Hub-height ambient turbulence intensity

To derive the long-term hub-height ambient turbulence intensity at the location of the mast, the wind speed standard deviation recorded at the primary height of the mast was used in conjunction with the predicted long-term hub-height mean wind speed shown in Table 4-6. The turbulence intensity standard deviation for each 1 m/s wind speed interval of was also calculated, to estimate the representative turbulence intensity, which is presented in Table 4-9, and also illustrated in Figure 4-2 for the representative hub height of 125m.

Figure 4-2 Ambient and characteristic turbulence intensity at Mast M99 at 125 m

[redacted]

Includes turbulence intensity curves for each wind class according to IEC 61400 ed. 3.1

Table 4-9 Ambient turbulence intensity at hub-height

Monitoring equipment	Height [m]	Ambient turbulence intensity at 15 m/s [%]
[redacted]		

The representative turbulence intensity appears to be within the limits for subclass B for both hub heights. It is noted however that turbulence at specific turbine locations maybe higher based on wake effects, proximity to forestry and/or slopes. It is recommended that this is further investigated as part of a site conditions assessment.

4.2.7 Hub-height mean air density

When available, DNV used monthly historical pressure, temperature and relative humidity records from local met masts, as well as long-term measurements from nearby meteorological stations and standard lapse rate assumptions, to estimate the mean annual air density at the site. The resulting air density at the average hub elevation above sea level of all the wind farm turbines, averaged from all suitable sources, is presented in Table 4-10.

Table 4-10 Average air density at average hub-height altitude

Scenario	Average hub height altitude [m]	Average annual air density [kg/m^3]
[redacted]		

Air pressure, temperature and humidity measurements were recorded at the site for a period shorter than three years, and it is therefore possible that longer measurement periods may result in greater ranges and therefore in a variation of the site air density. Investigations by DNV using nearby meteorological stations indicate that the impact of these variations is relatively small.

4.3 Spatial wind resource extrapolation

To determine the wind resource at the location of each wind turbine, flow modelling is required to spatially extrapolate the wind resource obtained at the location of the mast.

4.3.1 Flow model

The variation in wind speed over the site was predicted using DNV's implementation of the Star-CCM+ CFD engine, which is capable of effectively simulating thermal effects within and above the atmospheric boundary layer and the associated impacts to surface layer wind regime /10/ as described in Appendix E-3.

In addition to wind data only being made available for one site mast, making it impossible to corroborate that the wind flow at the site is relatively complex. There remains some uncertainty in using a flow model such as CFD to capture the wind speed variation across such a site, due to presence of complex terrain and forestry.

Wind flow over terrain can differ greatly between higher turbulence neutral/unstable conditions to the low turbulence and temperature inversions characteristic of stable conditions, even over flat terrain. Therefore, in performing the DNV CFD wind flow modelling at the site, two CFD models have been analysed to model the two atmospheric conditions present; neutral-unstable conditions and stable conditions. The results of these two models were combined according to the proportion of time where stable conditions would be expected at the site, resulting in an improved wind flow model compared to models considering only a single atmospheric stability case. Further description of these models is given in Appendix E.

To account for the wind flow over trees, the canopy model within the CFD model has been used to model the resulting increased drag and turbulence on the wind flow.

4.3.2 Flow model setup

The flow model setup includes the topographic map, the ground cover map, and any potential reductions in wind turbine hub-height due to neighbouring forestry. Table 4-11 presents these flow model setup characteristics.

Table 4-11 Wind flow modelling setup characteristics

Site characteristic	Resulting setup in the analysis	Source
[redacted]		

As described in Section 2.1, the site has a few forested areas, and any trees currently present at the site were modelled as contributing to the terrain roughness and considered not to decrease the effective wind turbine hub-heights.

4.3.3 Flow modelling adjustments

Flow modelling accuracy must be analysed in order to assign the mast that will provide the input data to model the flow at the location of each wind turbine, to determine the need for flow modelling adjustments and also to quantify the uncertainty associated with the underlying process.

Wind data were only made available for one site mast, and therefore flow model accuracy could not be corroborated. The flow model was initiated by the wind data from the sole on-site met mast, although turbines are located more than 5 km from the site mast, thus with increased levels of uncertainties.

The wind flow modelling results, represented by the long-term hub-height mean wind speed at each wind turbine location detailed in Appendix D-2.

4.3.4 Long-term hub-height wind speed at the wind turbine positions

The average long-term mean wind speed for each Scenario is presented in Table 4-12.

Table 4-12 Average wind farm wind speeds

Scenario	Hub height [m]	Number of wind turbines	Average wind speed [m/s]
[redacted]			

4.3.5 Spatial variation uncertainties

DNV's methods for estimating spatial variation uncertainties are included in Appendix E-6.2.4. The following table quantifies this uncertainty for the project.

Table 4-13 Spatial variation uncertainties

Wind farm	Wind flow modelling input data [% wind speed]	Wind flow modelling [% wind speed]
[redacted]		

4.4 Climatic conditions at the wind turbine positions

A wide range of sites, some relatively benign, some more hostile, may be considered for the construction of wind farms. To assess the suitability of the wind turbine model to the wind farm site, the location of each future wind turbine is classified according to the predicted climatic conditions, and this class is then contrasted against the class for which the wind turbine model was designed.

The complete climatic conditions of the Project site were not estimated, as this was not part of the scope of work. It is recommended that the calculation of the climatic conditions for the location of each wind turbine, according to IEC 61400-1 /2/,, are included in the scope of DNV's work in future updates of this analysis, to assess the suitability of wind turbines to the Project site.

5 ENERGY PRODUCTION ANALYSIS

Long-term hub-height wind resource at the turbine positions	→	5.1 Turbine aerodynamic interaction effect 5.2 System availability 5.3 Electrical transmission efficiency 5.4 Wind Turbine Performance 5.5 Environmental 5.6 Curtailment	→	Long-term wind farm net energy production

The wind flow modelling results derived in the previous section were combined with the wind turbine performance parameters, as inputs to the Wind Farmer: Analyst software, in order to calculate the gross energy production at individual turbine locations. The expected gross energy production is a theoretical value to which efficiency factors should be applied to estimate the net energy production. These efficiency factors are determined below, according to the methods detailed in Appendix E-5.

5.1 Turbine aerodynamic interaction effect

Wake effects are specific to the project and result from the interaction between wind turbines belonging to the Project itself, wind turbines belonging to nearby projects that are already operational, or wind turbines belonging to nearby projects that may be built in the future.

The turbine interaction effects were calculated using the Ainslie wake model /12/, with modifications that account for Large Wind Farm interactions with the atmospheric boundary layer and the Blockage Effect caused by the geometry of the wind turbine layout. All of these are described in Appendix E-5.1.

5.1.1 Internal turbine aerodynamic interaction effect

These are the wake and blockage effects that the wind turbines within the wind farm being considered have on each other.

The minimum inter-turbine separation within the wind farm is greater than 2.0 rotor diameters. However, the magnitude of the wake losses calculated at some turbine locations is considered to be high.

5.1.2 External wake effect

These are the wake and blockage effects that the wind turbines from existing neighbouring operational wind farms have on the wind farm being considered.

DNV considers that the existing neighbouring operational wind farms are sufficiently distant such that any effects in the energy production of the Project. All neighbouring operational wind farms known to exist were considered in the wake calculations, and the resulting wake losses are considered significant.

5.1.3 Future wake effect

These are the wake and blockage effects that future wind turbines from the neighbouring wind farms which are not yet operational, may have on the wind farm being considered.

The layout and wind turbine characteristics of neighbouring wind farms to be built near the Project, were provided by the Customer , and therefore the wake effects of these wind farms, were considered in the net energy of the Project.

5.2 System availability

Wind turbines, the balance of plant infrastructure, and the electrical grid will not be available the entire duration of a project's life. The mean values for these sources are combined to estimate an overall system availability. Financial compensation that may be potentially admitted by the manufacturer, O&M suppliers or the grid operator, are not taken into account, because these do not affect the net energy actually generated.

5.2.1 Wind turbine availability

Actual wind turbine availability is project specific, and will depend on various aspects, such as, wind turbine model track record, O&M contract characteristics and duration, wind turbine manufacturer and O&M logistics, operator experience and site access conditions.

The Customer supplied /13/ a draft of the AOM5000 Service and Energy Based Availability Agreement for review. It is noted that the document provided appears to be a template, and does not contain specific references to the project, nor any figures for the warranted availability and the length of the service. Based on information supplied by Vestas /14/, it is understood that the service agreement will be in place for 20 years, with a nominal warranted availability level of 96% for year 1 and 97% from year 2 to the end of the agreement.

The exclusions presented in the documentation represent a reduction to the nominal value above and include, amongst others:

- Downtime requested by the Project owner for events such wind turbine inspections.
- Unavailability of SCADA system.
- Emergency or safety shutdown.
- Force majeure events.
- Scheduled maintenance. It is noted however that no limits to scheduled maintenance are indicated in the agreement. Based on DNV experience, it has been assumed a scheduled maintenance allowance of 60h per year.

Based on the above detailed review, DNV estimates the individual and total wind turbine availability to be as presented in Table 5-1. A detailed availability table can be found in Appendix D-2.

Table 5-1 Independent wind turbine availability review

Component	Availability [%]
[redacted]	

5.2.2 Balance of plant and grid availability

These factors cover the expected availability of the wind turbine transformers, the on-site electrical infrastructure, the substation infrastructure up to the point of connection to the grid of the wind farm, as well as the expected external grid availability.

DNV standard loss factors were assumed for balance of plant availability and for grid availability, based on DNV's experience of reviewing operational wind farms. It is known that the grid availability could significantly vary from one project to another and impact the net energy production of the wind farm. The specific characteristics of the Project grid were not considered, as this was not part of the scope of work.

5.3 Electrical transmission efficiency

Electrical losses up to the point of connection to the grid depend on the efficiency of individual components, such as wind turbine transformers, medium voltage circuit, one or more substation transformers, and the transmission line. Internal wind farm consumption is not considered in this analysis, as it is assumed that it is an operational cost and not an energy loss factor.

A DNV standard operational electrical efficiency was assumed, based on DNV's experience of reviewing operational wind farms. Details of the specific balance of plant infrastructure and grid connection point have been not reviewed, nor considered, as this was not part of the scope of work. It is recommended that an independent calculation of the electrical losses in undertaken by DNV.

5.4 Wind Turbine Performance

The Customer supplied /1/ the performance data for each wind turbine model, which include the commercial power curves, illustrated in Figure 5-1 and presented in Appendix B.

Figure 5-1 Commercial power curves supplied

[redacted]

The operational envelope that is valid for each commercial power curve supplied is shown in Table 5-2. Commercial power curves must first be adjusted to accurately represent the power curves that will actually be observed, on average, during the period in which the wind turbines will be operating at the Project site. This adjustment of the commercial power curve contemplates a generic adjustment based on wind turbine performance worldwide, and site-specific power curve adjustments based on the site climatic conditions and the blade degradation over time.

Table 5-2 Operational envelope for each commercial power curve supplied

Wind turbine model	Maximum power coefficient	Air temperature	Average air density	High-speed cut-out	High-speed cut-in
	(Cp_{max})	[ºC]	[kg/m^3]	[m/s]	[m/s]
[redacted]					

5.4.1 Generic power curve adjustment

In some cases, it may be necessary to apply a generic power curve adjustment to account for limitations with the supplied power curve.

The power curve is based on the manufacturer's calculations and exhibits a peak power coefficient, Cp, considered high but attainable for a modern wind turbine.

The supplied power curve is for an air density which is similar to the mean air density at the site. This power curve was adjusted to the predicted air density at each individual wind turbine, in accordance with the recommendations of the IEC /3/.

5.4.2 High wind speed hysteresis

To prevent the wind turbine from turning on and off continuously when the wind speeds are close to the cut-out wind speed, a hysteresis control algorithm is normally introduced in the wind turbine operation.

Based on the strategy supplied by the Customer, it was assumed that high wind speed hysteresis effectively reduces the wind turbine cut-out wind speed from 24.0 m/s to 23.0 m/s for the purposes of the energy calculation, for both turbine models.

Table 5-3 High wind speed hysteresis

Wind turbine model	High-speed cut-in [m/s]	High-speed cut-out [m/s]	Adjusted high-speed cut-out [m/s]
[redacted]			

5.4.3 Site specific power curve adjustment

The energy production calculation assumes that the commercial power curve provided represents the turbine power performance at the Project site, expressed relative to free stream wind conditions. To fulfil this assumption, adjustments to the commercial power curve are needed to correct for:

- deviations generally observed between commercial power curves and measured power curves
- deviations between measured power curves affected by the blockage effect, and power curves measured in free stream wind conditions
- deviations due to site specific atmospheric conditions.

Certain wind farm sites may experience wind flow conditions that materially differ from the wind flow conditions seen at simple terrain and neutral condition test sites. Where it is considered that the meteorological parameters in some areas of a site differ from those at a typical wind turbine test station, then the impact on energy production of the difference in meteorological parameters at the site compared with a typical power curve test site is estimated. The adjustment may be undertaken where atmospheric stability, turbulence, wind shear or upflow angle are considered to be materially different at the Project site than compared to that experienced at a typical test site. Based on a significant number of IEC power performance tests carried out by DNV across the globe, wind turbine performance is expected to be adversely or positively affected when high or low turbulence intensity are combined with high or low wind speed. Given the combination of wind speed and turbulence intensity present at the site, an adjustment was applied, using an empirical method calculated by DNV.

This loss factor also accounts for the average blockage effect inherent in power performance test measurements that are conducted within wind farms and not in free stream conditions.

5.4.4 Sub-optimal performance

This loss is related to failures in wind turbine sensors, which can result in power curve derating, pitch control malfunctions, or nacelle yaw misalignment.

Based on DNV's experience of reviewing operational wind farms, a standard sub-optimal performance factor was considered to take into account operational factors such as wind turbine sensor errors, and operator errors. The issues are correctable, and the loss factor value considers an average over the lifetime of the Project.

5.4.5 Turbine degradation

The performance of wind turbines can be affected by degradation of the blades and other components, which includes the accretion of dirt, which may be washed off by rain from time to time, as well as physical degradation of the blade surface such as leading-edge erosion, and other components, over prolongated operation. This is a time-dependent phenomenon which DNV models as increasing linearly, and which is increased in harsh climates or coastal areas, where salt accretion is probable. Based on historical observations for the region, icing is not expected at the site, and therefore degradation caused by icing was not considered in the analysis.

A standard turbine blade degradation efficiency of 99.9 % was therefore assumed for Year 1, reducing by 0.1 % per year until the end of the Evaluation Period. A detailed turbine degradation table can be found in Appendix D-2.

5.5 Environmental

The energy that will be generated by the Project will depend on how the wind farm will be operated during the Project lifetime. During that time, the operation may be affected by failure of the wind turbine sensors, and by curtailment strategies that mitigate impacts of high wind speeds, excessive aerodynamic loads between wind turbines, impact in the electrical grid, and noise or shadow flicker impacts in areas surrounding the site.

5.5.1 Performance degradation – icing

Numerous amounts of icing on the turbine blades can change the aerodynamic performance resulting in loss of energy. This loss and associated uncertainty distribution are typically calculated on a site-specific basis.

This loss is estimated according to the icing events observed during the wind data processing and of DNV knowledge of the icing in the region. DNV used the climatic conditions and measured icing on the cup anemometers at the site as to derive the site-specific loss related to the underperformance due to icing. No icing events were identified at the site.

5.5.2 Icing shutdown

As ice accretion gets more severe wind turbines will shut down or will not start. Icing can also affect the anemometer and wind vane on the turbine nacelle which also may cause the turbine to shut down. This loss and associated uncertainty distribution are typically calculated on a site-specific basis.

This loss is estimated according to the icing events observed during the wind data processing and of DNV knowledge of the icing in the region. DNV used the climatic conditions and measured icing on the cup anemometers at the site as to derive the site-specific loss related to the shutdowns from icing. No icing events were icing events were identified at the site.

5.5.3 Temperature derating

Turbines are designed to operate over a specific temperature range. For certain sites this range may be exceeded and, for periods when the permissible temperature range is exceeded, the power rating of the wind turbine will be reduced.

DNV used the temperature derating strategy supplied by the Customer to estimate the impact of the ambient temperature at the site, on the operation of the wind turbine model.

5.6 Curtailment

5.6.1 Wind sector management

Wind sector management is used to shut down wind turbines for some wind direction sectors, when the distance between wind turbines is particularly close, thus reducing wind turbine aerodynamic loading.

No wind sector management strategy was supplied and therefore DNV has not included any losses which may be associated with this.

5.6.2 Overcapacity curtailment

It may be necessary to curtail the output of the wind farm at certain times, and this will result in a loss of energy production. This factor also includes the time taken for the wind farm to become fully operational following grid curtailment.

No specific curtailment strategies were supplied, and this study assumes that the energy production of the wind farm will not be curtailed due to grid restrictions during the Evaluation Period.

5.6.3 Noise, visual and environmental curtailment

In certain jurisdictions, there may be requirements to shut down wind turbines during specific meteorological conditions to meet defined noise emission, shadow flicker criteria at nearby dwellings, or environmental conditions due to such aspects as birds or bats.

No specific curtailment strategies were supplied, and this study assumes that the energy production of the wind farm will not be curtailed due to noise, visual and environmental restrictions during the Evaluation Period.

5.6.4 Dynamic grid curtailment

Under some circumstances, the System Operator may require reducing the power output of a power plant below its producible level to guarantee the security and stability of the network, resulting in a loss of energy.

Assessing the impact of this grid curtailment requires a specific analysis of the local grid conditions and its expected evolution, which is beyond the standard scope of this study. Therefore, this energy loss is not being considered in the energy assessment.

5.7 Long-term wind farm net energy production

The energy loss factors derived in the preceding sections were then applied to the gross energy estimate to obtain the net energy estimate, as shown in Table 5-4. Some of the loss factors vary throughout the operational life of a wind farm, and the prediction represents the annual production expected over the Evaluation Period.

Table 5-4 Energy production summary

[redacted]

5.7.1 Uncertainty in loss factors

DNV's methods for estimating loss factor uncertainties are included in Appendix E-6.3. These uncertainties are quantified in the following table for the project.

Table 5-5 Loss factor uncertainties

Scenario	Turbine interaction [% energy]	Availability [% energy]	Electrical [% energy]	Turbine performance [% energy]	Environmental [% energy]	Curtailment [% energy]
[redacted]						

It is recommended that each of the above uncertainties are considered carefully. They can often be mitigated to some extent, especially in early years of the project, through appropriate warranty provisions. Therefore, these uncertainties should be considered in detail in combination with these provisions, for instance as part of a full technical due diligence exercise.

6 UNCERTAINTY AND VARIABILITY ANALYSIS

Long-term wind farm net energy resource Individual uncertainties and variabilities	6.1 Wind farm sensitivity curve 6.2 Total project uncertainty and variability	Net energy production

6.1 Wind farm sensitivity curve

Some uncertainty categories are quantified in wind speed terms while others are quantified on an energy basis. In order to combine all categories, all wind speed uncertainty levels are converted into energy uncertainty levels using a sensitivity curve. This curve shows how sensitive the net energy production is to changes in wind speed and is mainly dependent on the wind speed distribution and power curve of the wind turbine. For example, with a sensitivity of 1.5, a 2.0% reduction in wind speed would lead to a 3.0% reduction in net energy production. The sensitivity curve is approximately linear over small wind speed ranges but non-linear over larger wind speed ranges, and this has been accounted for in this analysis. The average calculated sensitivity ratio for the Project is shown in Table 6-1.

Table 6-1 Average sensitivity ratio

Scenario	Variation in wind speed [%]	Average sensitivity ratio
[redacted]		

6.2 Total project uncertainty and variability

The net energy prediction presented in Section 5.7 represents the long-term mean of the annual energy production of the Project with a probability of exceedance of 50 % (the P50 estimate). This value is the best estimate of the long-term mean value expected for the Project. The sources of deviation from the P50 estimate, were grouped into five main categories of uncertainty. The inter-annual variabilities, also ascertained in this report, were combined. These are tabulated below for each Scenario, and were aggregated to determine the overall energy uncertainty of the analysis. The future 1-year results are representative of a one-year average period within the Evaluation Period, while the future 10-year results are representative of the first 10 years of the Evaluation Period.

Table 6-2 Uncertainty in the projected energy output for Scenario V162 HH125

Source of uncertainty / variability	[GWh/year]	Equivalent standard deviation [%]
[redacted]		

Table 6-3 Uncertainty in the projected energy output for Scenario V163 HH113

Source of uncertainty / variability	[GWh/year]	Equivalent standard deviation [%]
[redacted]		

It is apparent that, other than the inter-annual wind speed variability, long-term wind resource extrapolation is the greatest driver of uncertainty in the analysis.

6.3 Net energy production – probability of exceedance

The various sources of uncertainty presented in Table 6-2 were then combined using a probabilistic Monte Carlo uncertainty model, assuming full independence between the sources, to create a net energy frequency distribution for the wind farm. The model generates fifty thousand predictions of wind farm energy production for each year of operation, capturing the impact of variable factors such as wind speed and project losses, providing a robust, probabilistic projection of the potential energy output of the project. The net energy production for each probability exceedance level is extracted from this distribution and is tabulated below for each Scenario.

Table 6-4 Summary of net average energy production for Scenario V162 HH125

Probability of exceedance [%]	Net energy output [GWh/year]			Average capacity factor [%]		
	1 year	10 years	20 years	1 year	10 years	20 years
[redacted]						

Table 6-5 Summary of net average energy production for Scenario V163 HH113

Probability of exceedance [%]	Net energy output [GWh/year]			Average capacity factor [%]		
	1 year	10 years	20 years	1 year	10 years	20 years
[redacted]						

Differences between P50 values for different averaging and sampling periods are usually small and result from the factors described in Appendix E-5.7.

The P90 / P50 ratio represents the uncertainty index for wind farm energy estimates; this index varies between indicative estimates with very high uncertainty, where little or no on-site data exists, and robust estimates with a very low uncertainty, where operational data exists. The uncertainty index of 0.84 and 0.86 indicate that the uncertainty for the Project is considered to be average and that mitigation is recommended.

7 OBSERVATIONS AND RECOMMENDATIONS

DNV makes the following observations and recommendations regarding this analysis:

2. The P50 net energy prediction represents the long-term mean, 50 % exceedance level, for the annual energy production of the wind farm. This value is the best estimate of the long-term mean value to be expected for the Project. There is therefore a 50 % chance that, even when taken over very long periods, the mean energy production will be lower than the value given.

3. The energy production of the wind farm assumes that some loss factors are time dependent. The results presented here assume availability levels averaged over the Evaluation Period.

4. The complete climatic conditions for the Project site were not estimated, as these were not part of the scope of work, and therefore the suitability of the wind turbine model to the Project site could not be assessed. In addition to calculating the climatic conditions for the location of each wind turbine, it is recommended that the wind turbine manufacturer approves the wind turbine model, layout, and hub height being considered for the Project, providing sufficient contractual guarantees to cover these site-specific climatic conditions. This assessment assumes that these guarantees exist, and that wind turbine performance and availability will not be adversely affected. The energy production estimates should be reviewed if this assumption is not correct.

5. A number of loss and uncertainty factors are either DNV's standard assumptions made at this stage or for which an analysis was outside of DNV's scope of work. It is recommended that the Customer considers each of these items carefully. These losses may vary materially from standard assumptions and can often be mitigated to some extent, especially in the early years of a project, through appropriate contractual provisions. These values may only be reviewed upon a detailed analysis by DNV of the documentation specific to the Project.

6. An additional uncertainty has been applied to account for the corrections to the wind speed data at Mast M99 to remove the impact of the operational Medio Campidano Wind farm.

7. The key contributions to the uncertainty level of the estimate, in addition to the inter-annual wind speed variability, are:

    a. That most turbines are located more than 2 km from the met mast.

    b. That long term adjustment was not applied due to the low quality of correlations with long-term reference sources.

8. The following mitigating actions may be added to the scope of DNV's work to reduce the uncertainty level of updates of this analysis:

    a. This energy estimate should be updated when additional on-site wind data exists.

    b. New masts should be installed at locations that are more representative of the wind turbines positions.

    c. Additional sources of reference data, such as Vortex Series data, should be considered in the analysis

    d. Measured power curves from independent tests of the performance of the wind turbine should be supplied for DNV to check that the power performance levels stated by the wind turbine manufacturer are attainable.

    e. High resolution terrain maps and up to date detailed forestry maps specifying tree height should be supplied to DNV..

8 REFERENCES

/1/ Data supplied by the Customer by dataroom and email between 2023-06-20 and 2023-07-21.

/2/ IEC 61400-1 Ed3.1: “Wind turbines – Part 1: Design requirements”, 2014.

/3/ IEC 61400-12-1 Ed2.0, “Wind turbines - Part 12-1: Power performance Measurements of electricity producing wind turbines, Annex G”, 2017.

/4/ Global Modelling and Assimilation Office (GMAO); MERRA-2; data available from Goddard Earth Sciences Data and Information Services Center (GES DISC); website at https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/

/5/ The European Centre for Medium-Range Weather Forecasts (ECMWF); ERA-5; website at https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era5.

/6/ NASA JPL. *NASADEM Merged DEM Global 1 arc second V001*. 2020, distributed by NASA EOSDIS Land Processes DAAC, downloaded from https://search.earthdata.nasa.gov/

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APPENDIX A - WIND FARM SITE INFORMATION

Table A-1 Wind farm information – Scenario V162 HH125

Wind farm	Wind turbine	Coordinates [m] WGS 84 UTM zone 32N	Wind turbine model	Hub height [m]
[redacted]				

Table A-2 Wind farm information – Scenario V163 HH113

Wind farm	Wind turbine	Coordinates [m] WGS 84 UTM zone 32N	Wind turbine model	Hub height [m]
[redacted]				

APPENDIX B - WIND TURBINE PERFORMANCE

Table B-1 Performance data for the Vestas V162 6.0MW wind turbine model

[redacted]

Source: "Document no.: 0098-0840 V05 2021-10-29 Performance Specification EnVentus™ V162-6.0 MW 50/60 Hz"

Table B-2 Performance data for the Vestas V163 4.5MW wind turbine model

[redacted]

Source: "Document no.: 0130-7822.V03 2023-06-08 Performance Specification V163–4.5 MW 50/60 Hz"

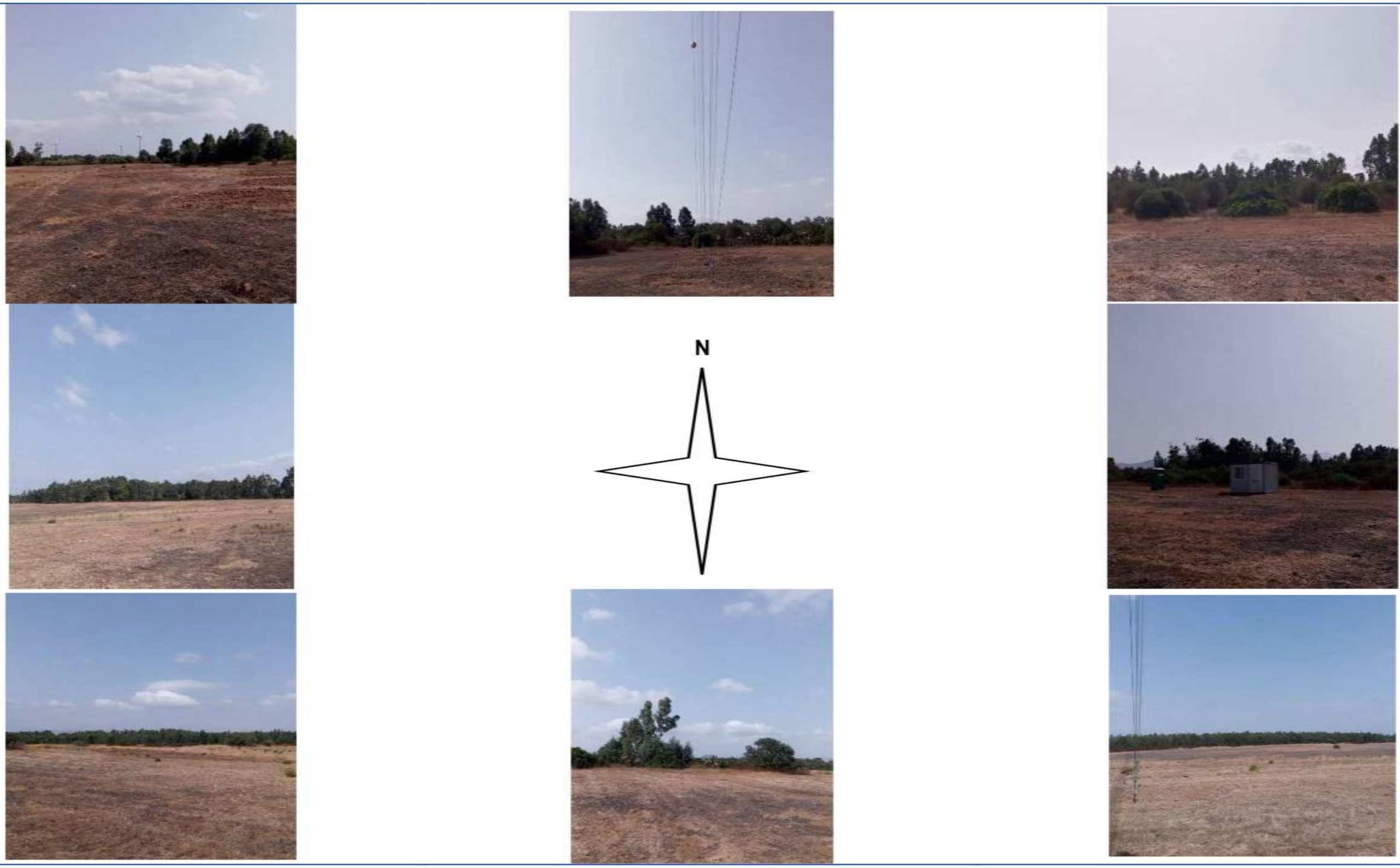
APPENDIX C - WIND DATA MEASUREMENT AND ANALYSIS

C-1 MAST M99

C-2 REFERENCE WIND DATA

C-1 Mast M99

Figure C-1 Panoramic view from the location of Mast M99



Source: Mast Installation Report, *Vestas San Gavino Monreale H100 - 04.08.2021.pdf*

Figure C-2 Mast M99 mounting arrangements

80 m

Top

80 m

60 m

60 m

78 m

58 m

40 m

40 m

Source: Mast Installation Report, *Vestas San Gavino Monreale H100 - 04.08.2021.pdf*

Table C-1 **Mast M99 configuration**

General information						
Installation date	Mast height [m]	Lattice width [cm]	Easting [m]	Northing [m]	Datum	Zone
[redacted]						

d. Following sensor calibration, wind speed records were adjusted as detailed in Appendix E-1.1.

Table C-2 List of calibration certificates

Anemometer serial number	Calibration body reference	Calibration facility
[redacted]		

Table C-3 Mast M99 data filtering and quality control

Excluded data			
The wind data have been subject to a quality checking procedure by DNV to identify records which were affected by equipment malfunction and other anomalies. The main periods for which valid wind data were not available are summarised below, together with details of the errors identified.			
Start	End	Sensors	Reason for exclusion
01/02/2022	28/02/2022	All sensors	Missing data

Selective averaging

In an attempt to minimise mast effects in the measured wind speed data, selective averaging was undertaken of the data recorded by the two parallel anemometers at 80,60 and 40 m heights. This procedure was undertaken by determining priority directions sectors for each sensor. Wind speed data recorded between 17.5 degrees and 82.5 degrees by the 80,60 and 40 m anemometer orientated to the 45° and wind speed data recorded between 197.5 degrees and 262.5 degrees by the 80, 60 and 40 m anemometer orientated to the 225° were considered to be of lower priority and were replaced by wind speed data recorded by the other anemometer. For the remaining direction sectors, wind speeds from both anemometers were averaged. This procedure resulted in a new joint wind speed time series at 80, 60 and 40 m measurement heights.

Table C-4 Directional correction factors applied to the wind speed measurements recorded at Mast M99 to remove the wake effects from the neighbouring turbines

Direction Sector [degrees]	Mast M99 2022-09-01 to 2023-04-31
[redacted]	

Table C-5 Data recorded by Mast M99

Month	Mean wind speed [m/s]	Wind speed data coverage [%]	Wind direction data coverage [%]
[redacted]			

a. Anemometers orientated to the north-east [45º].

b. Anemometers orientated to the south-west 225º].

C-2 Reference wind data

C-2.1 MERRA-2 data

DNV investigated the use of version 2 of the public MERRA data set as a reference data source. MERRA-2 data sets are produced by NASA by assimilating satellite observations with conventional land-based meteorology measurement sources using the GEOS-5.12.4 system. The analysis is performed at a spatial resolution of 2/3° longitude by 1/2° latitude. DNV procured hourly time series of two-dimensional diagnostic data, at a surface height of 50.0 m for the nine grid points nearest to the project site.

C-2.2 ERA5 data

DNV also investigated the use of the fifth generation of ECMWF atmospheric reanalyses 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 100.0 m above ground level, as well as surface air temperature and air pressure. ERA5 incorporates vast amounts of historical measurement data, including both satellite-based, commercial aircraft, and ground-based data.

APPENDIX D - WIND FARM ANALYSIS AND RESULTS

D-1 MAST LONG-TERM WIND REGIME

D-2 TIME-DEPENDENT LOSS FACTORS

D-3 ENERGY PRODUCTION RESULTS

D-1 Mast long-term wind regime

Table D-1 Long-term wind speed and frequency distribution at Mast M99 at 113.0 m

Monthly and annual mean wind speeds

[redacted]

a. Note + indicates non-zero percentage <0.005%, blank indicates zero percentage

b. Period: 2021-09-01 to 2023-04-31

Table D-2 Long-term wind speed and frequency distribution at Mast M99 at 125.0 m

Monthly and annual mean wind speeds

[redacted]

a. Note + indicates non-zero percentage <0.005%, blank indicates zero percentage

b. Period: 2021-09-01 to 2023-04-31

D-2 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 10 years 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(s) present(s) the specific values that have been assigned for each year.

Table D-3 Time-dependent loss factors

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

D-3 Energy production results

Table D-4 Individual wind turbine energy production results for Scenario V162 HH125

ID	Coordinates [a] [m]		Initiation mast	Wind turbine model	Hub height	Altitude	Mean hub height wind speed [b]	Energy output [c]	Turbine interaction effect [d]
	Easting	Northing			[m]	[m]	[m/s]	[GWh/year]	[%]
[redacted]									

a. Coordinate system is WGS 84 UTM zone 32N

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

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

d. Individual wind turbine interaction loss including wake and blockage effects.

Table D-5 Individual wind turbine energy production results for Scenario V163 HH113

ID	Coordinates [a] [m]		Initiation mast	Wind turbine model	Hub height	Altitude	Mean hub height wind speed [b]	Energy output [c]	Turbine interaction effect [d]
	Easting	Northing			[m]	[m]	[m/s]	[GWh/year]	[%]
[redacted]									

a. Coordinate system is WGS 84 UTM zone 32N

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

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

d. Individual wind turbine interaction loss including wake and blockage effects.

APPENDIX E - ANALYSIS METHODOLOGY

This chapter details the analysis methodology for a generic project. It is noted that some of the steps outlined may not have been employed in the analysis for the Project.

E-1 WIND DATA ANALYSIS PROCESS OVERVIEW

E-2 HUB-HEIGHT WIND SPEED AND DIRECTION DISTRIBUTIONS

E-3 WIND FLOW MODELLING

E-4 GROSS ENERGY OUTPUT

E-5 LOSSES AND NET ENERGY OUTPUT

E-6 UNCERTAINTY ANALYSIS

E-7 REFERENCES

E-1 Wind data analysis process overview

The analysis of the wind data involves several steps, which are summarised below:

- The raw wind speed data from the site is processed and evaluated to identify periods with missing or erroneous data due to instrument failures, icing, or other factors.
- Missing or additional wind speed and direction data at the primary anemometer and wind vane at each site mast are reconstructed from data recorded at the same mast where available, or from others on-site masts, to create a full record for the site period (site period wind speed and direction).
- The on-site measurements are correlated with the reference stations, and the results evaluated, to develop an estimate of reference period wind speeds at measurement height.
- Uncertainties in the site period wind speeds and reference period wind speeds, as well as the relationships between the two are analysed to access what wind speeds estimate the long-term wind speeds with the lowest bias and uncertainty.
- The measurement height estimate of long-term wind speeds is extrapolated to hub height using power law wind shear exponent and associated uncertainties assessed.
- Long-term hub height wind speed and direction frequency distribution estimates at each measurement location are derived using the most appropriate method based on data that have been measured, reconstructed or adjusted to the mast long-term wind speed.
- The wind regime at the proposed turbine locations is accessed using wind flow models and DNV experience and judgment.
- The uncertainties in the resulting hub-height wind speeds and frequency distribution at the turbine locations are assessed.

E-1.1 Met mast data processing and validation

Meteorological data should be provided in a raw form, preferably encrypted. Sufficient documentation should be provided to ensure the data integrity.

Meteorological data are subject to a quality checking procedure by DNV to identify records which were affected by equipment malfunction, icing, and other anomalies. These records are considered invalid and excluded from the analysis.

E-1.1.1 Calibration procedures

When calibration certificates from a Measnet-accredited facility have been supplied, DNV applies these in converting the raw data into wind speeds. For those anemometers where calibration data are not provided, DNV applies a model specific calibration.

The Otech Engineering and Svend Ole Hansen calibration facilities in Vermont, USA, prior to 1st May 2015 were not part of the MEASNET network, and DNV considers that these were not appropriate for energy production analyses. The Svend Ole Hansen calibration facilities in Copenhagen, Denmark, belong the MEASNET network.

In these cases, DNV retrospectively applies the individual anemometer calibrations and adjusts the measured wind speeds using the proposed correction factors.

E-1.1.2 Issues observed in specific sensors

All data from NRG #40 anemometers are evaluated for evidence of a problem described in a technical note from NRG issued in Spring 2008 /E1/. In this technical note, NRG described the problem, which manifests itself as intermittent under speeding or dragging. After investigation, NRG concluded that the degrading and under speeding was due to a phenomenon known as "dry friction whip". All anemometers manufactured by NRG after 1 January 2009 featured modifications aimed at reducing or eliminating the occurrence of this behaviour. The conclusions of NRG's investigation and the subsequent design changes are discussed in more detail in /E2/, presented by NRG at the AWEA annual conference in early May 2009. DNV typically examines potentially effected wind data to identify and remove periods of data affected by this issue. Any periods which are clearly affected are removed from the analysis and the additional uncertainty in the wind speeds has been included in this analysis.

Incorrectly calibrated reference temperature sensors were identified at the wind tunnel providing calibration services for the #40C anemometer. Raw temperature data collected by the miscalibrated probes resulted in incorrect anemometer calibration reports. This applies to calibration certificates issued for #40C anemometers calibrated from 24 January 2013 through 1 August 2013.

There is evidence that the behaviour of on-site Thies Classic anemometers is different from that observed in the wind tunnel /E4/. Studies show that Thies Classic anemometers record higher wind speeds than other anemometers widely used in wind measurement campaigns, and it was therefore considered appropriate to apply a 2% reduction on wind speed data recorded by Thies Classic anemometers. It is recommended that parallel wind measurements are performed using a suitable anemometer that is calibrated and mounted according to IEC criteria /E5/, in order to quantify this effect.

E-1.1.3 Agreement with the IEC 61400-12:2005 standard

An analysis of the porosity of each mast is made, and the corresponding drag coefficient value (Ct) for each mast is presented in Appendix D. Based on the recommendations of IEC /E5/ for a lattice mast, the anemometer booms must be tubular and be oriented perpendicularly to the prevailing wind direction. The Ct value is used to determine the length of the horizontal booms supporting the anemometer, in proportion to the width of the equilateral triangle that defines the cross section of the tower, so that the speed deficit is below 0.5 %. For the vertical distance between the anemometer cups and horizontal booms, it is recommended that this is equivalent to at least 15 times the diameter of the booms. It is also recommended that the vertical boom does not have a slope greater than 5 degrees, and that each sensor is be installed on separate booms with a vertical separation of at least two meters.

To minimise mast effects in the measured wind speed data, the data recorded at levels with redundant instruments are “selectively averaged”. In direct sectors where an anemometer is affected by the wake of the mast, the unaffected anemometer is selected; in direction sectors where both anemometers are valid, the measurements are averaged.

E-1.2 Remote sensing data processing and verification

In order to evaluate the quality of a remote sensing device, several parameters may be reviewed. These include:

- Carrier-to-noise ratio (CNR)
- Signal-to-noise ratio (SNR)
- Wiper count
- Availability
- Amplitude signal
- Signal level
- Noise
- Echo suppression
- Valid count or recovery rate
- Standard deviation
- Turbulence intensity
- Beam component wind speed

Of these the CNR or SNR provides vital information about the quality of the beam propagation. The CNR or SNR generally decreases with height. If a significant number of points derivate from this, it can indicate signal noise contamination.

The first order quality control is generally an automatic procedure that is carried out by the manufacturer's online software program. Data are then filtered with in-house software using following data quality tests:

- Data with poor reliability, quality, or availability are removed;
- Horizontal wind speed (0 to 60 m/s) and direction verification (0 to 360°);
- Vertical wind speed verification (between -2 and 2 m/s); and
- Horizontal and vertical standard deviation verification (<5 m/s).

Following automated data processing, all remote sensing datasets are checked manually to ensure that the results are sensible. This included an assessment of the consistency between measurement heights and consistency relative to the associated met mast anemometry, if possible.

E-1.3 Data correlation and prediction

The period of data available at the site masts can be extended through establishing relationships between two data sets, using correlations, and using these relationships to reconstruct the missing data at the site. In the correlation step, concurrent wind data from a "target" sensor and a "reference" sensor are compared. The reference sensor may be on the same mast or at a different measurement location. The reference sensor is chosen to be one for which wind records are available for the period being reconstructed. The concurrent measured wind data are then used to establish the correlation between the winds at the two locations. This correlation is then used to reconstruct data at the "target" location from the "reference" location.

The following methods are used to complete gaps or extend the period of record available at a mast.

E-1.4 Ten-minute or hourly reconstruction method

In the correlation of 10-minute or hourly data, the concurrent data are correlated by comparing wind speeds at the two locations for each of twelve 30° direction sectors, based on the wind direction recorded at the "reference" location. This correlation involves two steps:

- Wind directions recorded at the two locations are compared to determine whether there are any local features influencing the directional results. Only those records with speeds in excess of 5 m/s at both locations are used.

- Wind speed relationships are determined for each of the direction sectors using a principal component analysis (PCA) forcing the adjustment through the origin. For correlations with substantial scatter, large offsets and/or poor coverage across wind speed bins, not forcing may provide a more reliable result.

In order to minimise the influence of localised winds on the wind speed relationship, the data are screened to reject records where the speed recorded at the "reference" location falls below 3 m/s or an equivalent level at the "target" location. The directionally averaged wind speed relationship is used to adjust the 3 m/s wind speed level for the "reference" location to obtain this equivalent level for the "target" location, to ensure unbiased exclusion of data. The wind speed at which this level is set is a balance between excluding low winds from the analysis and still having sufficient data for the analysis. The level used excludes only winds below the cut-in wind speed of a wind turbine which do not contribute to the energy production.

The result of the analysis described above is series of wind speed relationships, each corresponding to one of twelve direction sectors. These relationships are used to factor the wind data measured at the "reference" mast location, thereby obtaining reconstructed wind data for the period of missing data at the "target" mast location.

To retain as much measured data as possible, the reconstructed wind data are only used to fill in gaps in the measured data series.

E-1.5 Correlation check

To check the quality of a correlation between the reference and target, the concurrent measured and reconstructed wind data at the target are compared. If the energy content of the reconstructed time series is similar to the energy content of the measured time series, the data are considered well correlated. In case the two are not similar, the correlation is reconsidered, and alternative options are investigated.

E-1.6 Daily reconstruction method

In the correlation of daily wind speeds, only wind speed data are correlated, and not the wind direction data. For this reason, this method is used to estimate the long-term wind speeds but not the frequency distributions. The concurrent daily mean wind speeds are compared in one of two ways:

- If there is a seasonal trend between the target and reference, the daily correlation can be divided into 12 separate correlations, based on the calendar month. In this “Daily-by-Month” method, 12 separate correlations are established.
- If there is no seasonal trend, or less than a year of concurrent data, a single “all-data” daily correlation is derived.

The result of the analysis described above is either a single correlation slope and offset or a set of twelve correlation slope and offset values, each corresponding to one of twelve calendar months. These slope and offset values are applied to the wind data measured at the “reference” mast location, thereby obtaining reconstructed daily wind data for the period of missing data at the “target” mast location.

The long-term mean wind speeds at the location of the site masts are derived using measured data and reconstructed data. The frequency distribution is derived from the measured and reconstructed data for the on-site period and adjusted to the long-term wind speed.

E-1.7 Monthly reconstruction method

In the correlation of monthly wind speeds, only wind speed data are correlated, and not the wind direction data. For this reason, this method is used to estimate the long-term wind speeds but not the frequency distributions. The concurrent monthly mean wind speeds are compared, in order to establish a single correlation slope and offset. These slope and offset values are applied to the wind data measured at the “reference” mast location, thereby obtaining reconstructed monthly wind data for the period of missing data at the “target” mast location.

The long-term mean wind speed at the location of the site masts is derived using measured data and reconstructed data. The frequency distribution is derived from the measured and reconstructed data for the on-site period and adjusted to the long-term wind speed.

E-1.8 Wind speed and frequency distribution de-seasoning method

In order to avoid the introduction of seasonal bias into estimates of the annual mean wind speed, as well as wind speed and direction distributions from seasonally uneven data coverage, the following procedure is followed:

- The mean wind speed or distribution for each month is determined from the average of all valid data recorded in that month, over the period. This is taken as the monthly mean, thereby assuming that the valid data are representative of any missing data.
- The mean of the monthly means (weighted by the number of days in a month) is taken, in order to determine the annual mean (“mean of means”).

E-1.9 Impact of trees

Where obstacles to the flow, such as trees in proximity to a mast or turbine, are present, it is necessary to consider these trees as not only roughness elements, but also as obstacles, in the wind flow model. In this regard, the following methodology has therefore been adopted, for both evergreen and deciduous trees, as well as palm trees:

1. Areas of forestry and land cover have been analysed to establish both the location and height of trees. It is considered that areas of representative forest height greater than 5 m vertically displace wind flow to the same extent. For areas of representative forest height below 5 m, it is considered that the displacement of the flow is reduced, and in these cases the presence of this forest is considered through profiling of the project area roughness.

2. For the mast and turbine locations, an effective reduction in the hub height has been estimated to account for the influence of trees as an obstacle to the wind flow. The selection of these heights is based on the effective flow displacement height of the trees, the proximity of the mast or turbine to the trees, and the frequency of occurrence of the relevant wind directions. The following relationship is used to find the effective flow displacement height for each direction sector at each mast and turbine location:

   $d = d_{tree} - D/50$

   where d is the effective flow displacement height;

   d_{tree} is the flow displacement height of the surrounding trees; and

   D is horizontal distance from surrounding trees.

3. By weighting each sector's effective flow displacement height by the frequency of winds in each sector, a weighted displacement height is calculated for each individual site mast and turbine.

4. The current forest cover found at the site with a 50 m turbine site clearing is assumed in the analysis.

E-2 Hub-height wind speed and direction distributions

E-2.1 Shear power law

The boundary layer power law shear exponents at the site masts are derived from the available measurements. The power law relates the ratio of measured wind speeds, U_1/U_2, to the ratio of the measurement heights, z_1/z_2, using the wind shear exponent, α, as follows:

$$\frac{\overline{U}(z_1)}{\overline{U}(z_2)} = \left(\frac{z_1 - d}{z_2 - d}\right)^{\alpha}$$

where α is power law wind shear exponent;

$\bar{U}$ is the mean wind speed;

z is the height above ground level; and

d is the effective flow displacement height, if any.

The boundary-layer power law shear exponent was derived for each mast location using the ratios of measured concurrent wind speed data recorded at multiple measurement heights, following the exclusion of wind speed data below 3 m/s.

E-2.2 Time series shear method

The boundary-layer power law shear exponent is derived between two measurement heights for each ten-minute, or hourly, time step. A time series of wind speed at the target hub-height is calculated by extrapolating the upper measurement height using the instantaneous boundary-layer power law shear exponent. These exponents are then used to extrapolate the measured data recorded in the main sensors to the rotor hub-height. For cases where instantaneous shear exponent values are not available, generic values are used for the date and time of record. The Mean of Monthly Means procedure is used to avoid the introduction of bias into the annual mean wind regime prediction from seasonally-uneven data coverage at each mast as discussed in Appendix E-1.8, thereby resulting in the measured frequency distribution at hub-height.

E-2.3 Directional shear method

The relationship between two, or more, heights on a mast is established for each of twelve 30° direction sectors, using the technique described in Appendix E-1.7. These relationships are used to derive the boundary-layer power law shear exponent in each of the twelve direction sectors, which are then used to extrapolate data recorded at the upper measurement height to the target hub-height, on a directional basis.

The annual average wind speed frequency and direction distributions at measurement height are determined from the site period wind speed data using the mean of monthly means approach described in Appendix E-1.8. The resulting distributions are then scaled to the predicted long-term hub height wind speed(s). This method is employed when data recorded is affected by shadow of the measurement mast.

E-2.4 Annual shear method

The relationship between two, or more, heights on a mast is established using the concurrent mean of monthly means technique described in Appendix E-1.8. These relationships are used to derive the boundary-layer power law shear exponent, which is then used to extrapolate data recorded at the upper measurement height to the target hub-height.

E-3 Wind flow modelling

Project wind speed is typically modelled using either the WAsP model or a CFD model, as described in the following sections. Other models may be applied in cases where significant errors are either already apparent or expected from these models. These models may be exposure-based models, experience-based models or other models that DNV expects will reduce uncertainty or bias in the results. The primary output from the models is a set of wind speed ratios between the initiating masts and other masts (or turbine locations) for each of twelve 30° direction sectors. For any given pair of masts, a prediction error is determined for each direction sector, then a root-mean-square (RMS) of the twelve prediction errors is performed, weighted by the directional frequency distribution, in order to calculate an overall directional speed-up error.

E-3.1 WAsP approach

In order to calculate the variation of mean wind speed over the site, the computer wind flow model, WAsP 10.2 is used. Details of the model and its validation are given by Troen e Petersen /E7/.

The inputs to the model are maps of the topography and surface roughness length of the site terrain and surrounding area. A digital map of an area extending at least 10 km from the site, in all directions, is normally used, and the inputs for this project are listed in Section 2 of the main body of the report. Although the domain size is much larger than the area of the site itself, such an area is necessary, since the flow at any point is dictated by the terrain several kilometres upwind.

Wind flow is affected by the roughness of the ground. The surface roughness length of the site and surrounding area has been estimated, as detailed in Section 2 of the main body of the report, following the Davenport classification /E8/.

The wind flow calculations are carried out for 30 degree steps in wind direction corresponding to the measured wind rose and results were produced as speed-up factors relative to the mast location for a grid encompassing the site area.

To determine the long-term mean wind speed at any location, the speed-up factor for each wind direction is weighted with the measured probability previously derived for the mast location. All directions are then summed to obtain the long-term mean wind speed at the required location.

E-3.1.1 Forestry representation within the WAsP approach

When there are areas of forestry on the proposed wind farm site, it is necessary to consider the effect of these obstacles on the wind flow model /E6/. DNV has developed and validated a forestry modelling approach to be used when modelling the wind flow using WAsP /E9/.

For forestry a flow displacement of equal height is assumed for trees over 5 m in height. Forestry less than 5 m in height is assumed to not cause a flow displacement and is modelled as a terrain roughness only.

For each mast and turbine location, an effective reduction in the measurement or hub height is estimated to account for the influence of trees as an obstacle to the wind flow. The selection of these heights is based on the displacement height of the trees, the proximity of the mast or turbine to the trees and the frequency of occurrence of the relevant wind directions.

Where appropriate, an indicative energy loss factor profile is derived to account for the changes in forestry over the period of operation of the wind farm that is being evaluated due to expected tree growth or felling. This profile does not include the effect of future variability in wind conditions considered. However, the wind variability is considered in the uncertainty analysis.

E-3.2 DNV freestream CFD modelling

The DNV CFD methodology produces simulations of the Atmospheric Boundary Layer (ABL) for wind power applications; it is based around STAR-CCM+, a commercial computational fluid dynamics (CFD) software package. The CFD software solves the time averaged equations of mass and momentum conservation. An energy conservation equation is also solved when modelling atmospheric stability. The DNV CFD methodology has been validated for a number of academic cases and well over 100 real wind farm sites /E7/. These studies show that on average the DNV CFD method offers substantially improved wind speed predictions as compared with WAsP.

The CFD approach requires significantly more computational resource than a classical WAsP analysis, as the calculations are significantly more complex. A flow domain is created and defined by a set of boundary conditions which control the air flows in and out of the domain. A 3D mesh is created within the domain and the conservation and turbulence equations are solved at each discrete point on the mesh. Due to this construction, the model is subject to discretization errors and can only evaluate wind from a single direction at a time. Hence, a separate simulation is undertaken for a number of directions, typically in intervals of 6 to 25 degrees, depending on the direction and direction frequency at the site. The results are averaged to derive 30-degree direction sector speed-ups from the masts to the turbine locations. These speed-ups are then combined with the measurement-based wind resource at each mast to predict the wind resource at each turbine location.

The turbine and mast locations are at least 10 km away from the edge of the computational domain for each calculation. The horizontal spacing of the mesh near points of interest is 12.5 to 50 m, depending upon the complexity of the local terrain. Mesh independence studies have shown that such tight mesh spacing is necessary to resolve flows at microscale.

For sites where atmospheric stability significantly affects wind speeds, DNV employs a stability-enabled CFD analysis. The spatial variation of wind speed over topography is often very different during stable atmospheric conditions as compared to unstable conditions. Traditional wind flow models that assume a neutral atmosphere can provide reasonable predictions of unstable and near-neutral flows, but the predictions of stably stratified flows are comparatively poor. Thus, the stability-enabled CFD analysis, includes two sets of CFD calculations: a neutral CFD analysis to represent unstable and near-neutral flows and a stable CFD analysis, which directly models buoyancy effects, to represent stable flows. The results from the two sets of calculations are combined to produce an overall wind flow model for the site. Extensive validation has demonstrated that the stability-enabled CFD analysis provides significantly improved wind speed predictions at sites where stability effects are important /E8/.

E-3.2.1 Forestry representation within the DNV freestream CFD approach

Where appropriate, the CFD model used by DNV includes a canopy model designed to reproduce within the Reynolds-averaged Navier-Stokes (RANS) simulations the turbulence generation and aerodynamic drag associated with forestry and can therefore model the resulting flow perturbation /E11/. Canopy model source terms are added to the governing equations within the volume occupied by the forestry, i.e., between ground level and the approximate height of the canopy, as described in /E12/ and /E13/. Inputs to the canopy model include tree height, coefficient of drag, and foliage density of the forestry. At the current stage, flow modelling in forestry is a topic of active research in the wind energy industry and the presence of site forestry increases the level of uncertainty compared to flow modelling on sites with less significant vegetation.

E-3.3 Vortex FARM© approach

Where appropriate, the Vortex FARM© wind speed map was used to predict the variation in wind speed over the site. This is a validated mesoscale model based on the WRF model, developed at NCAR. The input source of raw reanalysis data is the ERA-5 dataset. The output map is obtained through mesoscale wind flow modelling for the Project area with a maximum size of 500 km2. Topography data comes from the Shuttle Radar Topography Mission (SRTM) and land cover data is obtained from the ESA Global Land cover product.

E-4 Gross energy output

The gross energy production is the energy production of the wind farm obtained by calculating the predicted free stream hub height wind speed distribution at each turbine location and the manufacturer-supplied turbine power curve. In defining the gross energy output, it is assumed that there are no wake interactions between the turbines and no energy loss factors are applied. This calculation undertaken within the WindFarmer computational model /E14/, /E15/ includes adjustments to the power curve to account for differences between the predicted long-term annual turbine location air density and the air density to which the power curve is referenced.

E-5 Losses and net energy output

Net energy output is estimated by deducting expected losses from the gross energy output estimated. DNV uses a standard detailed set of six energy loss factors which aims to ensure that all potential sources of energy loss are considered by the relevant parties. For some projects certain loss factors will not be relevant in which case an efficiency of 100% is assumed. Additionally, some losses may only be sensibly estimated when comprehensive information is available from a project and review of such documentation is within the scope of DNV's work. To add clarity for the reader around the level of detail considered, DNV has three categories of loss estimates used in Energy Assessments. These are:

- DNV Standard: These are values that DNV has estimated are appropriate for typical projects in the region of the world in which a project is located. There may be regional difference in this estimate.
- Project Specific: These are values for which DNV has made a project specific estimate based on data supplied such as wind, terrain or wind turbine technology data. The basis of this estimate is provided in the body of the report.
- Not Considered: These are values for which making estimate has either not been included in the Scope of Work DNV has been authorised to complete or relevant information was not provided by the Customer.

The loss factors used to estimate the derivation of the wind farm net energy output prediction are described below. For each loss factor a general description of the loss, its typical values, and associated uncertainties are given.

E-5.1 Turbine interaction modelling

Wind turbines extract kinetic energy from the wind and downstream there is a wake from the wind turbine where wind speed is reduced. As the flow proceeds down-stream there is a spreading of the wake, and the wake recovers towards free stream conditions. The wake effect is the aggregated influence on the energy production of the wind farm which results from the changes in wind speed caused by the impact of the turbines on each other.

When modelling the interaction of turbines within a wind farm, wake models used within the wind industry generally only consider the reduction of wind speeds downstream of a turbine. There is evidence however that turbine interaction also includes 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. Consequently, the first-row turbines may produce less than they each would operating in isolation.

E-5.1.1 WindFarmer approach

Where appropriate, these turbine interaction effects are calculated using the WindFarmer computational model. The eddy viscosity model within WindFarmer is employed using a site-specific definition of the turbulence intensity as an input, combined with a Large Wind Farm Wake Model developed by DNV /E14/, /E15/, /E16/.

When the inter turbine spacing is below a distance equivalent to two rotor diameters, the Closely Spaced Turbine wake model /E29/, which is also part of WindFarmer, may also be employed.

The WindFarmer approach to turbine interaction losses also considers the Blockage Effect Estimator Tool (BEET).

E-5.1.1.1 The Blockage Effect Estimator Tool (BEET)

An alternative to site-specific CFD simulations is the use of the BEET. From a set of basic inputs, the BEET tool outputs a correction factor formulated to offset blockage-related bias in wakes-only models. This fast-running model has been trained on output from CFD results from a range of generic wind farms simulated on flat terrain. Comparisons between the BEET model and CFD results at a number of real wind farms indicate that it is capability of providing a reasonable estimate of what a site-specific CFD analysis would predict in many situations. However, there are some situations where there is elevated risk that the BEET output will depart from that of DNV CFD analysis:

- It does not consider wind direction in the analysis. The impact of blockage is generally less sensitive to direction than wakes, but it is not insensitive to direction. The uncertainty of BEET predictions is, thereby, likely to be higher at sites with unidirectional or bi-directional wind roses.
- The generic wind farm results behind the BEET predictions correspond to flat sites and coherent, consistently spaced layouts. A limited number of checks indicate that the tool is nevertheless capable of providing reasonable estimates in complex terrain and/or irregular layouts, but we do not expect that to always be the case.
- Not set up to distinguish between multiple wind farms
- Limited in its ability to handle site-specific atmospheric stability conditions.
- The CFD results behind the BEET tool correspond to onshore-like meteorological conditions. We now have preliminary results suggesting that the blockage corrections could be larger at offshore sites, where the atmospheric boundary layer is in general thinner.

This list describes situations where the uncertainty of the BEET calculation is elevated relative to other situations. A site-specific CFD analysis can reduce uncertainty in such situations.

E-5.1.2 DNV CFD modelling of the turbine interaction effect

Where appropriate, the Project wind farms are simulated in a numerical environment using DNV's implementation of Siemens StarCCM+ CFD engine /E17/. The three-dimensional simulation domain is based on DNVs tailored steady-state RANS model with k-ε turbulence closure, that has been successfully applied and validated for freestream atmospheric wind flow simulations at more than 200 wind farms around the world, as described by Corbett et al. /E18//E19/.

The solver equations and the inflow boundary conditions are customised and enabled to simulate thermal effects within and above the atmospheric boundary layer. This customised model is described in detail by Bleeg et al. /E20//E21/.

The top boundary condition of the domain is a slip wall set to a constant potential temperature. The inflow atmospheric boundary layer profiles of velocity, potential temperature, and turbulence quantities derived from a combination of similarity theories and precursor simulations /E20/.

The lower boundary of the domain is defined using a digital terrain model (DTM) and/or by publicly available data. For the ground boundary condition, the model uses a standard wall function approach based on the classic law-of-the-wall. The standard wall functions were modified to account for aerodynamic surface roughness as defined in the ground coverage map.

The computational domain is covered with an unstructured mesh. The horizontal base mesh resolution varies from 2.5 m to 200 m, depending on the proximity to points of interest. Finer vertical mesh resolution within a progressive prism layer that spans from 0 meters up to 1800 meters above ground level (AGL) is also implemented in order to capture the thermal gradients within atmospheric boundary layer. Mesh independence studies were conducted to confirm mesh convergence.

The base CFD is then extended to simulate the presence and operation of wind turbines. To achieve that, actuator disks are used to represent the turbines within the CFD numerical domain, as described by Bleeg et al. /E22/.

These actuator disks consist of extra refined cubic mesh cells with edge lengths equal to 5% of the turbine rotor diameter (20 cells across the rotor diameter and 5 cells across the disk thickness). The axial and tangential body forces applied to the cells derive from power and thrust coefficient (C_t) curves provided for the analysis.

The sales power curves are functions of the freestream wind speed (U_∞) at each turbine location. More specifically, (U_{disk}). is equivalent to the horizontal wind speed component at hub height that would be observed without the presence of the given wind turbine. Unlike in most analytical wake models, (U_∞) cannot be readily determined within a continuous three-dimensional RANS wind farm simulation, especially because of the upstream influence of the turbine rotors. The performance curves (power, C_t and rotor speed) are thus converted to be a function of a different quantity: the average axial velocity over the rotor's swept area (U_{disk}). This quantity can be readily determined from within the RANS simulations and, in addition, better represents the influence of the local flow on power and thrust.

A subset of single-turbine CFD simulations is carried out to convert the performance curves to functions of (U_{disk}). for each turbine model. Each simulation corresponding to a different hub-height wind speed. In these simulations, the inlet U_∞. values are known, and actuator disk forces are thereby set according to curves specified as functions of U_∞. After each solution, the corresponding mean value of U_{disk}) is recorded. The outcome of this procedure is a set of curves (power, C_t, and rotor speed) specified as functions of U_{disk}).

The wind farm CFD simulations are then set up using these performance curves and actuator disks that are configured to precisely represent each turbine geometry. Three different sets of numerical simulation cases are calculated:

Case "a": All selected wind turbines are operating.

Case "b": Only one selected turbine is operating in isolation. Neighbouring turbines are stationary.

Case “c”: No wind turbines are operating (this is equivalent to a freestream simulation).

The numerical simulation cases (“a,b,c”) are repeated considering a number different inlet wind directions at 5 degree intervals for a selection that encapsulates the most frequent wind direction sectors for the site. A constant inlet reference wind speed vertical profile is considered, which spans from 0m to 17000 m AGL.

Simulations in case “b” are repeated for different turbines operating in isolation until numerical convergence is achieved. This is measured by ensuring that numerical residuals were down to the order of 1e-3. The horizontal mean velocity component is also monitored at all turbine positions in order to ensure numerical convergence.

Finally, post processing procedures are carried out with all directional simulations in order to extract the following scalar results, shown in Table 8-1.

Table 8-1 Scalar variables extracted from numerical simulations

$U_{\infty-C_t}\left[\frac{m}{s}\right]$	U_∞ $interpolated\ from\ Ct\ performance\ curve\ as\ a\ function\ of\ U_{disk}.$
$U_{\infty-P}\left[\frac{m}{s}\right]$	U_∞ $interpolated\ from\ Power\ performance\ curve\ as\ a\ function\ of\ U_{disk}.$
Ct_{disk}	$C_t\ interpolated\ from\ performance\ curve\ as\ a\ function\ of\ U_{disk}.$
$Power\ [W]$	$Power\ interpolated\ from\ performance\ curve\ as\ a\ function\ of\ U_{disk}.$
$Rotor\ speed\ table\ \left[\frac{rad}{s}\right]$	$Rotor\ speed\ interpolated\ from\ performance\ curve\ as\ a\ function\ of\ U_{disk}.$
$Rotor\ speed\ VD\ \left[\frac{rad}{s}\right]$	$Rotor\ speed\ from\ virtual\ disk.$

a. Note: U_∞ is the wind speed that would be used to look up the OEM power curve.

The extracted variables are then processed for all directional CFD simulations in order to calculate the aerodynamic loss factors for each wind farm. In this study aerodynamic effects refer to the combined effect of wind turbine wake and blockage (flow induction) zones.

These aerodynamic loss factors are estimated both in % wind speed, using the variable $'U'_{\infty-P}$', and also in % energy using the variable $'Power'$. These are only valid for the wind directions and inlet wind speeds that were considered for the CFD numerical simulations. Additional post processing steps were used to integrate these results over all possible wind speed and wind direction levels, thus extrapolating the aerodynamic loss factors to represent long-term conditions.

The software Wind Farmer: Analyst /12/ (WFA) is then used to extrapolate CFD loss factors for the long-term wind resource conditions. In order to achieve that, the following steps are carried out:

Step 1: A wake loss table from the Wind Farmer results is created, where the wake loss is a function of wind speed (in increments of 0.5 m/s) and direction sector (30 degrees wide).

Step 2: The CFD results are taken to calculate an integrated average of the wakes-only loss and simulated wind speed over 12 sectors. The outputs are two vectors with 12 elements (each element corresponds to a wind direction sector). One vector is for average freestream wind speed. The other vector is for average wakes-only loss.

Step 3: The vectors are compared with the Wind Farmer table and come up with a new 12-element vector. This time the elements correspond to a scale factor. If the scale factor were to be multiplied for a given sector by the Wind Farmer wakes-only losses for that sector, the wakes-only loss for the sector interpolated at the average CFD-simulated freestream wind speed would match the sector-average CFD prediction.

Step 4: Those scale factors are applied to the Wind Farmer results so that the resulting table represents a CFD-predicted wakes-only loss table. The table matches CFD at the wind speeds where CFD was run and the variation in the loss with wind speed is based on the Wind Farmer predictions.

The CFD calculations are repeated for different inlet wind directions. The calculations are also repeated for a subset of cases where all turbines were operational (case “a”), where only one turbine operates in isolation (case “b”), and where all turbines are shut down (case “c”).

By subtracting the mean wind speed field calculated for cases “a” (wind farm operating) from the ones calculated for cases “c” (freestream), it is possible to isolate the effect of the wind turbines in the atmospheric wind flow. Wind turbine results are then grouped into individual wind farms.

In some instances, individual wind turbines can present an energy gain as output of wind farm CFD simulations, i.e., an interaction loss adjustment factor higher than 100%, indicating that some wind turbine positions are benefited with a more advantageous wind exposure when new neighbouring wind turbines are simulated. It is important to highlight that such energy gains are usually very low and cause a marginal impact on overall results.

E-5.1.3 Turbine interaction effect internal

This is the effect that the wind turbines within the wind farm being considered have on each other.

E-5.1.4 Turbine interaction effect external

This is the effect that the wind turbines from neighbouring wind farms (if any), assumed by DNV to be operational on the date of this assessment, have on the wind farm being considered. These are calculated in the same way as internal turbine interaction effects.

E-5.1.5 Future turbine interaction effect

This is the effect that the wind turbines from neighbouring wind farms (if any), which are assumed by DNV not to be operational on the date of this assessment, but which may be built in the future, have on the wind farm being considered. The effect of these may be estimated and taken into account if sufficient information is available.

E-5.2 Availability

Wind turbines, the balance of plant infrastructure, and the electrical grid will not be available the entire duration of a project’s life. Three sources of availability losses are discussed below. The mean values for these sources are combined to estimate an overall system availability.

E-5.2.1 Wind turbine availability

This factor defines the expected average turbine availability of the wind farm over the time period considered. Various measures of availability are discussed within different documents and contracts within the industry. For the purposes of energy assessments, DNV measures availability based on the percentage of time when the wind is between the turbine cut in and cut out wind speeds and the turbines are available to produce electricity. This definition of availability is referred to as “wind-in-limits” availability.

In cases where the operation and maintenance contracts, or the guarantees, include energy production values and not as “wind-in-limits”, the availability estimate is undertaken in order to best reflect the proportion of energy that is not generated due to the unavailability of the wind turbines, and in these cases, a conversion of time to energy is not required.

DNV standard analysis therefore use a downtime to energy conversion factor of 1.0, meaning that that a wind farm available for 97% of the time between cut-in and cut-out wind speeds captures 97% of the available energy. In most cases, DNV has found this relationship to be accurate when using a wind-in-limits definition of availability; however for regions where DNV expects this could materially bias the results, a project-specific value is calculated.

An adjustment to the contractual availability value to reflect the standard contractual availability exclusions provided by the wind turbine supplier is also considered. These exclusions include factors such as conducting preventive maintenance of the wind turbine, unwinding of cables, and operating outside the usual parameters. This is a generic value but which takes into account DNV's experience with the specific wind turbine model in the market where the wind farm is developed.

E-5.2.2 Balance of Plant (BoP) availability

This factor defines the expected availability of the turbine transformers, the on-site electrical infrastructure, and the substation infrastructure up to the point of connection to the grid of the wind farm. It represents, as a percentage, the factor which needs to be applied to the gross energy to account for the loss of energy associated with the downtime of the balance of plant.

E-5.2.3 Grid availability

This factor defines the expected grid availability for the wind farm in mature operation. This factor relates to the grid being outside the operational parameters defined within the grid connection agreement as well as actual grid downtime. This factor also accounts for delays in the wind farm coming back to full operation following a grid outage. It represents, as a percentage, the factor which needs to be applied to the gross energy to account for the loss of energy associated with the downtime of the grid. Typical reasons for this downtime include grid preventive maintenance, failures and associated repair time, and outages related to construction.

E-5.3 Electrical transmission efficiency

There will be electrical losses experienced between the low voltage terminals of each of the wind turbines and the wind farm point of connection, which is usually located within a wind farm switching station.

E-5.3.1 Operational electrical efficiency

Electrical losses represent the difference between energy measured at each wind turbine and energy measured at the project substation (or other point where energy is metered for transaction purposes). Actual losses will depend on the efficiency of the transformers used at the facility, collection system wire sizing, and internal parasitic consumption "behind the meter" in very low wind conditions. This is presented as an overall electrical efficiency and is based on the long-term average expected production pattern of the wind farm.

E-5.3.2 Wind farm consumption

This factor defines the electrical efficiency due to the electrical consumption of the non-operational wind farm due to transformer no load losses and consumption by electrical equipment within the turbines and substation. For most wind farms this value is set to 100% and this impact on wind farm energy production is considered as a wind farm operational cost rather than an electrical efficiency factor. However, for some metering arrangements it may be appropriate to include this as an electrical efficiency factor rather than an operational cost and therefore this factor is available to apply if warranted.

E-5.4 Turbine performance

In an energy production calculation, a power curve supplied by the turbine supplier is used within the analysis. It is usual for the supplied power curve to represent accurately the power curve which would be achieved by a wind turbine on a simple terrain test site, assuming the turbine is tested under an IEC power curve test. The actual performance of the turbine may vary from the supplied power curve as a result of different factors, which are discussed below. These factors, considered together, represent the overall turbine performance efficiency.

E-5.4.1 Generic power curve adjustment

For certain turbine models there may be reason to expect that the supplied power curve does not accurately represent the power curve which would be achieved by a wind turbine on a simple terrain site under an IEC power curve test. In such a situation a power curve adjustment is applied. This may be thought of as estimating that a turbine would not meet the turbine sales power curve in an IEC power curve test on a simple terrain turbine test site.

E-5.4.2 High wind hysteresis

Most wind turbines will shut down when the wind speed exceeds a certain limit. High wind speed shut down events can cause significant fatigue loading. Therefore, to prevent repeated start up and shut down of the turbine when winds are close to the shutdown threshold hysteresis is commonly introduced into the turbine control algorithm. Where a detailed description of the wind turbine cut-in and cut-out parameters are available this is used to estimate the loss of production due to high wind hysteresis by repeating the analysis using a power curve with a reduced cut-out wind speed. If such information is unavailable, then an estimate is made based on DNV experience with similar turbines in similar environments.

E-5.4.3 Site-specific power curve adjustment

Certain wind farm sites may experience wind flow conditions that materially differ from the wind flow conditions seen at simple terrain and neutral condition test sites according to the IEC. Where it is considered that the meteorological parameters in some areas of a site differ from those at a typical wind turbine test station, then the impact on energy production of the difference in meteorological parameters at the site compared with a typical power curve test site is estimated. The adjustment may be undertaken where atmospheric stability, turbulence, wind shear or upflow angle are considered to be materially different at the wind farm site than that which is experienced at a typical test site.

E-5.4.4 Sub-optimal performance

Previously discussed performance losses are relative to the sales power curve, which assumes that the turbine controls are optimally configured and maintained. In DNV’s experience there are material performance deviations from the optimal power curve due to software or instrumentation issues which cause the machines to not reach their intended power curve or operate in a non-optimal way and it takes time and considerable focus to ensure wind turbines continuously operate as they should. In order to capture these effects, a typical loss factor of 1.0% of annual energy production is assumed for the life of the project.

E-5.4.5 Turbine blade degradation

The performance of wind turbines can be affected by degradation of blades and other components. This includes the accretion of dirt, which may be washed off by rain from time to time, as well as physical degradation of the blade surface such as leading edge erosion, and other components, over prolongated operation. This is a time dependent phenomenon which DNV GL models as increasing linearly at a rate of 0.1% per year for 20 years, resulting in an average 0.5% and 1% loss over 10 and 20 years respectively. In hash climates (mainly dry climates or coastal areas where salt accretion is probable), these values are increased 0.3 % to account for the reduced frequency with which precipitation will periodically clean the blades. The latter value is however highly dependent on the cleaning strategy planned for the wind farm, access to water and dedicated staff for the purpose. Values can be reviewed as part of a full due-diligence process if detailed information become available.

E-5.5 Environmental

The following environmental influences on project performance are considered in a standard DNV analysis. The environmental loss consists of several subcategories as discussed below. The product of the subcategory losses represents the overall environmental loss estimate.

E-5.5.1 Performance degradation –icing

Small amounts of icing on the turbine blades can change the aerodynamic performance of the machine resulting in loss of energy. This loss and associated uncertainty distribution are typically calculated on a site-specific basis.

E-5.5.2 Icing shutdown

As ice accretion gets more severe wind turbines will shut down or will not start. Icing can also affect the anemometer and wind vane on the turbine nacelle which also may cause the turbine to shut down. This loss and associated uncertainty distribution is typically calculated on a site specific basis.

E-5.5.3 Temperature shutdown

Turbines are designed to operate over a specific temperature range. For certain sites this range may be exceeded and for periods when the permissible temperature range is exceeded the turbine will be shutdown. For such sites an assessment is made to establish the frequency of temperatures being outside the operational range and the correlation of such conditions with wind speed. From this the impact on energy production is estimated. This loss and associated uncertainty distribution is typically calculated on a site specific basis.

E-5.5.4 Site access

Severe environmental conditions can influence access to more remote sites which can impact availability. An example of this might be an area prone to severe snow drifts in winter. As the impact on energy will be dependent on the Operation and Maintenance arrangements a factor will only usually be included where DNV has reviewed the operations and maintenance arrangements for the wind farm. This loss is typically calculated on a site-specific basis if considered.

E-5.5.5 Tree growth / felling

For wind farm sites located within or close to forestry or areas of trees the impact of how the trees may change over time and the effect that this will have on the wind flow over the site and consequently the energy production of the wind farm must be considered. The impact of future felling of trees, if known, may also need to be assessed. This loss is typically calculated on a site-specific basis.

E-5.6 Curtailments

Some or all of the turbines within a wind farm may need to be shut down, or their energy output curtailed, to mitigate issues associated with turbine loading, export to the grid or certain planning conditions. If sufficient information is available about any proposed wind farm curtailment strategies, then these losses can be calculated on a site-specific basis.

E-5.6.1 Wind sector management

Turbine loading is influenced by the wake effects from nearby machines. For some wind farms with particularly close machine spacing, it may be necessary to shut down certain turbines for certain wind conditions. This is referred to as wind sector management and will generally result in a reduction in the energy production of the wind farm. This loss is typically calculated on a site-specific basis.

E-5.6.2 Overcapacity curtailment

Within certain grid connection agreements, it may be necessary to curtail the output of the wind farm at certain times. This will result in a loss of energy production. This factor also includes the time taken for the wind farm to become fully operational following grid curtailment.

E-5.6.3 Dynamic grid curtailment

Under some circumstances, the System Operator may require reducing the power output of a power plant below its producible level to guarantee the security and stability of the network, resulting in a loss of energy.

This type of curtailment occur in real-time system operation and its causes can either be system-wide (for example, excess generation in low demand periods) or due to local technical grid constraints. Such technical grid constraints can be defined as any circumstance or event derived from the generation and grid operation that might affect or compromise the security, quality or reliability of the grid and the power supply.

Assessing the impact of this grid curtailment requires a specific analysis of the local grid conditions and its expected evolution, which is beyond the standard scope of this study. Therefore, this energy loss is not being considered in the energy assessment.

E-5.6.4 Noise, visual and environmental curtailment

In certain jurisdictions there may be requirements to shut down turbines during specific meteorological conditions to meet defined noise emission, shadow flicker criteria at nearby dwellings, or environmental conditions due to such aspects as birds or bats. This loss is typically calculated on a site-specific basis.

E-5.7 Effect of asymmetric distributions

The effect of changes in wind speed, whether through variability or deviations from the mean, has an asymmetric impact on project production because of the non-linear relationship of wind speed to energy. At high wind speeds the power curve flattens, so an increase in wind speed results in little or no increase in energy. At lower wind speeds the power curve is steep so a small change in wind speed results in a larger change in energy. Thus, when wind speed variability risk is converted to production risk, the resulting distribution is asymmetric, with a P50 (median) value that is less than the average. This difference is considered here.

Additionally, some of the uncertainty distributions applied to the loss factors described above are asymmetric in nature and some are truncated to prevent modelling of impossible conditions (losses less than zero). To the extent loss factors are simply asymmetric, the effect of the asymmetry is captured in uncertainty analysis, as well as the P50, as described above.

Differences between the P50 values for different averaging and sampling periods result from three factors:

1. The wind speed to energy sensitivity curve, combined with inter-annual wind speed variation, results in an asymmetric production distribution; the asymmetry in this distribution is decreased when the sampling period is increased (for example, considering the Evaluation Period average versus the 1-year average).
2. The project availability for a single year is modelled as a Weibull distribution with a standard deviation of 3%. This non-normal distribution gives a different P50 result when sampled over several years compared to a single year.
3. Consideration of time-dependent losses such as turbine degradation results in different losses, for differing averaging periods, resulting in different net energy predictions.

These factors combine to create differing 1-year and Evaluation Period production predictions. The combined impact of these factors is captured by the “asymmetric production effect”, whose magnitude is usually small.

E-6 Uncertainty analysis

The uncertainty in the net energy estimate provides a metric to determine the downside and upside production risk of a project over a specified time period. The inputs into the uncertainty analysis include uncertainties around the wind speed inputs and modelling, uncertainty around the energy loss factors, and the inter-annual variability of production. These inputs, as well as the site-specific wind speed sensitivity, are combined to generate a probability distribution for annual project net energy production using a propriety Monte-Carlo uncertainty model.

Almost all uncertainty factors can be described by a Gaussian distribution (a symmetrical distribution), in which the standard deviation is determined as explained in the following sections. The wind speed uncertainty factors are converted into asymmetric distributions due to the nonlinearity of the project sensitivity curve. Some of the uncertainties are truncated to be more representative of real operational circumstances, preventing, for example, that the value of electrical efficiency exceeds 100 %. As the combination of frequency distributions is performed in a probabilistic manner and not as an arithmetic sum, the model allows for uncertainty categories whose distributions are not Gaussian, but that fit best to a Weibull distribution.

E-6.1 Wind speed uncertainty

There is uncertainty in the wind speeds estimated due to a variety of factors described below. Uncertainties are estimated as a percentage of the mean wind speed, except where noted, and are assumed to be normally distributed. The uncertainty values referenced below and elsewhere in the report represent one standard deviation.

E-6.1.1 Measurement accuracy

There is an uncertainty associated with the accuracy of the wind speed measurements. The value of uncertainty depends on the calibration and the mounting arrangements of the instruments. For an anemometer a figure of between 1.5% and 2.25% is typically estimated to account for these uncertainties and to include an allowance for second order effects such as over-speeding, degradation, air density variations, and additional turbulence effects. For a remote sensing device that has undergone an appropriate verification a figure of between approximately 2% and 4% is typically estimated. These estimates typically includes instrument accuracy, Measurement interference, and consistency of measurement, as described below.

E-6.1.1.1 Instrument accuracy

An uncertainty of 1.75% on wind speed is typical for anemometers calibrated in a Measnet facility. An uncertainty of 2.25% is typical for non-calibrated anemometers. Multiple independent measurements of wind speed at the same height on a measurement device reduce the overall uncertainty. Typically, this benefit is a reduction of between 0.2% and 0.5%.

An instrument accuracy uncertainty estimated for remote sensing measurements is based on a range of factors such as how accurately measurements from the device can replicate those of a conventional cup-anemometer, whether the device has undergone a classification according to the IEC /3/ the outcomes of that classification, the complexity of the terrain in which the device is deployed, and whether flow curvature corrections have been applied to the measurements.

E-6.1.1.2 Measurement interference

Some uncertainty is associated with the effects of mounting anemometers on towers; even when mounted according to industry-standard procedures, small speed-up and slow-down effects are seen on measurements on tubular towers and lattice towers. DNV estimates the measurement interference uncertainty based on observations during the site visit, a review of the documentation of the mounting arrangements on the towers, and a review of the data.

A measurement interference uncertainty for remote sensing data is based on the potential impact of the following:

- Subtle echoes from nearby trees (that were not captured in the filtering process, sodar only);
- Complex flow; and
- Changes in the sodar/lidar settings.

E-6.1.1.3 Consistency of measurement

Poor data recovery and poor documentation make it difficult to confirm the consistency of a measurement. When substantial periods of data are missing or removed due to icing, equipment malfunction and other issues, there is additional uncertainty in the measurement. There is also uncertainty associated with the quality of the documentation of the met masts and instrumentation. This uncertainty is estimated based on our review of the data, information from any site visit, documentation and the data recovery percentages.

E-6.2 Long-term measurement height wind regime

E-6.2.1 On-site data reconstruction

DNV estimates the uncertainty on the relationships used to describe the wind conditions between the mast locations based on the strength of the correlations and the amount of data reconstructed.

E-6.2.1.1 Consistency of reference data

The uncertainty associated with the consistency of the reference data is assigned based on the level of regional validation available, the metadata available for the data, and the nature of the long-term reference data, i.e. ground station with documented traceability or various forms of virtual metrological data.

The agreement of multiple reference data sources, particularly when they are from different networks, reduces the risk of an undetected consistency change impacting the site wind speeds.

E-6.2.1.2 Correlation to reference station

DNV estimates the uncertainty on the relationships used to describe the wind conditions between the site measurements and reference data based on the strength of the correlations and the amount of data reconstructed.E-6.2.1.1

E-6.2.1.3 Representativeness of period of data

The uncertainty associated with how well the period of record represents the long-term wind conditions is estimated by dividing the inter-annual variability by the square root of the number of years of data used in the analysis.

E-6.2.1.4 Wind frequency distribution - past

The wind frequency distribution varies from year to year such that for a given annual mean wind speed the energy production may be higher or lower than expected due to a more or less favourable distribution of wind speeds. For example, the frequency of high-wind cut-outs varies; a year with several intense storms may record substantial time at wind speeds above the turbine cut-out speed, thereby increasing the overall average wind speed but not increasing the energy production. This category represents the uncertainty on the distribution measured over the period of data collection at the site and is estimated as a percent of energy. DNV estimates this uncertainty as 2% divided by the square root of the number of years of on-site data used to produce the frequency distribution.

E-6.2.2 Vertical extrapolation

There is some uncertainty as to whether the measured shear values represent the wind shear above the upper measurement height. To estimate uncertainty associated with vertical extrapolation, DNV evaluates the accuracy of the shear measurement, magnitude of the extrapolation, shear magnitude, representativeness of the masts and heights, and shear variation through the year. Additionally, the consistency of shear between the towers, available information concerning atmospheric stability, and the measurement configurations can influence the vertical extrapolation uncertainty.

E-6.2.3 Input data accuracy

The flow model input data package consists of the topographic map, the land cover map and the position and height of obstacles to the flow as windbreaks, and its accuracy has an impact on wind flow modelling accuracy. These input data must be valid both for both the historical period in which the wind measurements were performed, as well as for the future period when the project will be in operation. The uncertainty attributed to this factor depends on the accuracy with which these input data represent reality.

E-6.2.4 Spatial extrapolation

This uncertainty represents the uncertainty in the ability to extrapolate from the measurement locations to the wind turbine locations. DNV estimates this uncertainty based on the wind flow models' ability to cross-predict wind speeds at measurement locations, the differences in wind speeds at met masts, how representative the measurement locations are of turbine locations, in the reliability of the model inputs, variations in ground cover, and the complexity of the wind flow at the site.

E-6.3 Loss factor uncertainty

E-6.3.1 Wakes

Uncertainties on wakes are modelled as a normal distribution centred on the median estimate. The standard deviation of the distribution depends on site specific conditions but is typically between 25% and 35% overall wake effect.

E-6.3.2 Availability

The uncertainty in project availability is considered as a variability and it is described further in Appendix E-6.4.3.

E-6.3.3 Electrical

To acknowledge the uncertainty on this estimate, a normal distribution is assumed with a standard deviation of 10% of the total electrical loss, so a loss of 2.5% would have an uncertainty of 0.25 %.

E-6.3.4 Turbine performance

The uncertainty on this overall turbine performance loss estimate is modelled as a normal distribution with a typical standard deviation of between 2% and 3%. The magnitude of this uncertainty depends on the confidence DNV has in the turbine's ability to achieve the claimed level of performance. Turbines with a body of evidence supporting the claimed performance level, through measured power curves, for instance, will have a lower uncertainty.

E-6.3.5 Environmental

The uncertainty on the overall environmental loss estimate is typically modelled as a normal distribution with a standard deviation of 10% of the loss.

E-6.3.6 Curtailment

The uncertainty on the overall curtailment loss estimate is typically modelled as a normal distribution with a standard deviation of 10% of the loss.

E-6.4 Inter-annual variability

E-6.4.1 Wind frequency distribution variability - future

This category represents the year-to-year variability in energy due to changes in the wind speed distribution and air density. DNV typically estimates this value to be 2.0% on energy.

E-6.4.2 Inter-annual variability of the wind speed

The inter-annual variability of project wind speed represents the expected range of variation in annual average wind speed from year to year.

The inter-annual variability accounts for uncertainty on one-year wind speed and is an input in the uncertainty model. DNV typically use data from long term reference stations as well as its knowledge of the region when estimating this value, which typically is 6 % /E28/.

On longer time scales, there is some related uncertainty associated with whether or not the true long-term mean wind speed will occur during that period due to the year-to-year variations in wind. Over many years, wind variations tend to average out such that the long-term uncertainty is less than the one-year variability. For example, the Evaluation Period uncertainty can be estimated by dividing the inter-annual variability by the square root of the number of years in the Evaluation Period.

Year-to-year variations in wind speed result from a variety of phenomena, potentially including climate change. DNV has researched the literature regarding the impact of climate change on wind speeds and concluded that while available modelling tools are predicting material changes in some atmospheric characteristics such as temperature, no similar pattern is apparent with regard to wind speeds. The majority of models predict small changes which are well within the historic inter-annual variability and there is no agreement among models regarding the direction of any changes.

E-6.4.3 Availability variability

The inter-annual variability in project availability is modelled as a Weibull distribution with a standard deviation of 3%. This variability refers to the availability of the system and records the availability of the wind turbine, the substation and electrical grid.

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