STUDY ON UK OFFSHORE WIND VARIABILITY

Study on UK Offshore Wind Variability

The Crown Estate Commissioners

Report No.: L2C124303-UKBR-R-01, Issue B
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EXECUTIVE SUMMARY

The Crown Estate Commissioners (TCE) has appointed Garrad Hassan and Partners Ltd (DNV GL) to undertake a study into the variability of offshore wind speeds in UK waters. In this study, DNV GL has identified, assessed and tested options for deriving two potential industry "products":

- A robust definitive wind speed index for UK offshore wind; and,
- A new characterisation of Inter-Annual Variability (IAV) in wind speed that is specific to the UK offshore wind climate.

The aim of the study is to assess the feasibility of a reduction in Levelised Cost of Energy (LCoE) for future offshore wind projects by improving financing conditions through the provision of an improved characterisation of the long-term UK offshore wind resource. For the purpose of this study and to assess the potential reduction in LCoE, a base case scenario considering the use of a nearby meteorological station and an IAV of 6.0% has been assumed to represent the current industry standard.

DNV GL has drawn the following key conclusions from this feasibility study:

1. A regional wind speed index approach based on MERRA-2 does not offer significant advantages over the use of the nearest MERRA-2 grid cell. Using the nearest MERRA-2 grid cell as a source of long-term reference data is estimated to result in a reduction of 0.3% on LCoE compared to a base case of using an onshore meteorological station.
2. There is strong evidence to revise current industry standard assumptions of IAV for the UK offshore environment. Based on a validation against offshore measurements provided by The Crown Estate and other publically available sources of data, an IAV range of 4.0% to 5.5% is considered to be more appropriate for the UK offshore environment. This is estimated to result in a reduction in LCoE of up to 0.3% compared to a base case of using the industry standard IAV of 6.0%. When used in conjunction with the nearest MERRA-2 grid cell as a source of long-term reference data, the reduction in LCoE is estimated to be up to 0.7%.
3. A number of areas of potential further work have been identified to refine the definition and assessment of IAV across the wider global wind energy industry. For example the definition of a "year", the impact of height on IAV, and the method used to adjust IAV to represent longer periods.

The results of this study demonstrate that there is strong evidence for moving away from current industry standard assumption of 6% IAV in the UK offshore environment which will allow improvements in LCoE to be realised. Whilst this work has also identified areas of potential further study, these are considered applicable to the wider, global wind industry and not specific to the UK offshore environment. DNV GL therefore considers the results presented in this report to provide sufficient evidence to form the basis of discussions within the wind industry to revise current industry standard assumptions of IAV for the UK offshore environment.

1 INTRODUCTION

One of the facets of The Crown Estate Commissioners (TCE) as an independent commercial business is to effectively and sustainably manage the UK seabed. With the offshore wind resource in the UK being among the best in the world, this places TCE in a unique position of helping to develop and sustain the UK's energy supply and infrastructure through working with industry and government to facilitate the responsible deployment of offshore wind projects through sharing data and best practice.

The UK government has set a clear direction for the offshore wind sector to continue to drive down the Levelised Cost of Energy (LCoE) of offshore wind. This requires continued progress and development across technology, supply chain and finance domains throughout the design, procurement, construction and operation phases.

One aspect that TCE has identified as having the potential to reduce LCoE is an improved understanding of the variation of wind speeds in the UK offshore environment. This has the potential to reduce or better quantify the uncertainties in pre-construction energy production assessments, resulting in improved financing conditions.

The objective of this work is summarised as follows:

"To reduce LCoE for future offshore wind projects by improving financing conditions through the provision of an improved characterisation of the long-term UK wind resource."

TCE has appointed Garrad Hassan & Partners Ltd (DNV GL) to undertake a feasibility study into the variability of offshore wind speeds in UK waters. The study is designed to *identify*, *assess* and *test* options for deriving two potential industry "products":

- A robust definitive wind speed index for UK offshore wind; and,
- A new characterisation of Inter-Annual Variability (IAV) in wind speed that is specific to the UK offshore wind climate.

TCE has access to a unique range of offshore wind datasets across the UK offshore environment. The incorporation of these data into the design and validation of the above products is a key feature of this study.

The study has been completed in four phases, from the initial design of the products, through to validation, and considerations for potential further work.

The results of each phase are summarised in this report, which is structured as follows:

- Section 3: Phase 1 – Scoping and outline design
- Section 4: Phase 2 - Validation
- Section 5: Phase 3 – Risks and opportunities
- Section 7: Considerations

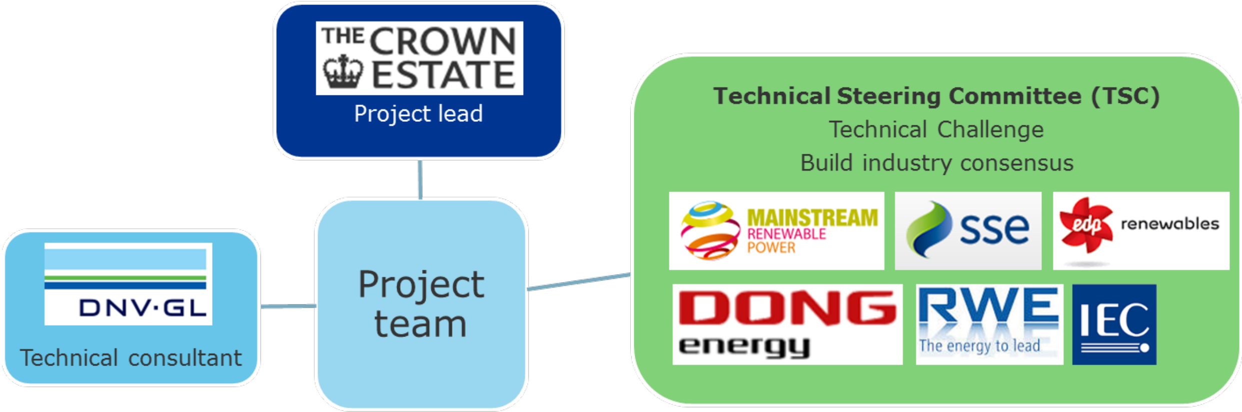
Further discussion of the background and motivation for this work is included in Section 2.

As part of the study, TCE established a Technical Steering Committee (TSC) as an advisory body to the project. Members were drawn from key UK offshore wind developers and two committee meetings were held during the course of this study to discuss the results of the work. The role of the TSC has been to:

- Challenge the work from a technical perspective to ensure it is in line with industry expectations.
- Build industry consensus on if and how the work should be implemented and utilised.

The structure of the project team is summarised in Figure 1-1.

Figure 1-1   Project team



2 BACKGROUND

2.1 Motivation

The assessment of the wind regime and energy production of a proposed offshore wind farm typically involves the consideration of wind data measurements at, or close to, the project. These measurements are undertaken using site meteorological masts and/or remote sensing devices, over short-term periods, typically with duration of a few years. A key source of uncertainty in the estimation of the wind regime and energy production of a proposed project (with a typical lifetime of 20-25 years) is the assumption that the measurement period is representative of long-term wind conditions. As a result, steps are typically taken to place the measurement period into a long-term context, through correlations with sources of long-term data, such as meteorological stations or reanalysis datasets. The availability, or unavailability, of suitable long-term reference sources offshore can be a limiting factor in deriving the long-term wind regime at a project.

Furthermore, it is known that wind speed naturally varies from one year to the next, referred to in this report as the Inter-Annual Variability (IAV) of wind speed. This is often the largest source of uncertainty in the estimation of the wind regime and energy production of a proposed project, and is therefore a key consideration when a project is going through finance. A study completed by Garrad Hassan, now DNV GL, in 1997 /1/ indicated that in the UK this wind speed variability can be defined by assuming a standard deviation of approximately 6%. This was based on a review of long-term datasets measured at onshore meteorological stations and has largely been accepted as industry standard for UK projects.

The work reported here is designed to provide an improved understanding of the variation of wind speeds in the UK offshore environment through the definition of a robust wind speed index and a new characterisation of IAV that is specific to the UK offshore wind climate. The products have the potential to reduce or better quantify the uncertainties in pre-construction energy production assessments in four areas. These are summarised in Table 2-1 below.

Table 2-1 Key uncertainty categories

Source of uncertainty	Explanation
Correlation	The uncertainty in the relationship used to describe the wind conditions between the site measurements and reference data. Assessed using the amount of scatter in the correlation and amount of data synthesised.
Representativeness of historical long-term period	The uncertainty in the assumption that the mean wind speed estimate is representative of the historical long-term. Dependent on the length of the reference dataset and the IAV of wind speed.
Consistency of reference source	The uncertainty associated with the consistency of the reference source. Dependent on the level of regional validation available, the metadata available and the nature of the long-term reference data.
Future period under consideration	The uncertainty in the assumption that the mean wind speed estimate is representative of the future period under consideration. Dependent on the future period under consideration and IAV of wind speed.

An offshore specific wind index has the potential to reduce uncertainties associated with long-term correlations by providing a more robust and geographically representative reference source. From DNV GL's experience, the derivation of a regional index can improve correlation uncertainties compared to the use of, for example, a single meteorological station. If the long-term consistency of the index can be demonstrated, this has the potential to increase the length of the data source and reduce the consistency uncertainty. Furthermore, an offshore specific characterisation of IAV might allow for standard assumptions to be revised for future offshore wind energy production assessments.

Overall, this work has the potential to reduce or better quantify uncertainties in pre-construction energy production assessments, which has a positive impact on subsequent project financing arrangements.

In addition, a small number of regional, well validated wind speed indices can be centrally stored and maintained, thereby providing a convenient, downloadable dataset and enabling consistency across the industry.

2.2 Workstreams

This study has been conducted under two separate workstreams. These are summarised in Table 2-2 along with the key technical considerations identified for each workstream.

Table 2-2 Workstreams and technical considerations

Workstream	Description	Technical considerations
A	UK offshore wind index	• Quality of correlations • Consistency of datasets • Predicted wind speed adjustments
B	Assessment of UK offshore IAV	• Long datasets required • Impact of considering longer periods in definition of IAV

3 PHASE 1 – SCOPING AND OUTLINE DESIGN

3.1 Definition of assessment zones

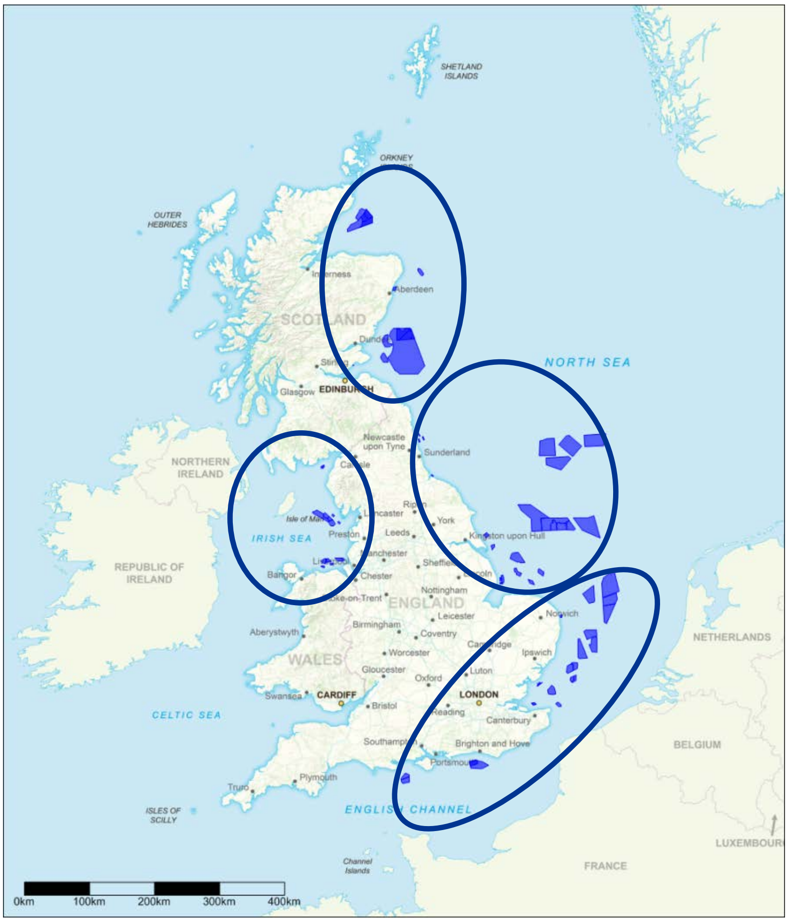
From DNV GL's experience of the wind regime across the UK offshore environment, it is considered that there is some variation in the wind variability across different regions of UK waters, due to the varying exposure of the regions to the prevailing south-westerly winds and nearby land masses.

At the outset of Phase 1 of this study, DNV GL identified four assessment zones for the derivation of wind speed indices and the assessment of IAV. These zones were selected on the basis of the main areas of offshore wind development and areas which are expected to be subject to similar wind conditions. The zones are shown in Figure 3-1 and are listed below:

- Zone 1 – Irish Sea
- Zone 2 – English Channel
- Zone 3 – North Sea
- Zone 4 – East Scotland

It is noted that DNV GL considers there to be an advantage in limiting the number of assessment zones to enable robust validation using measurements. This is considered to be a key factor in obtaining industry acceptance of the results of this study.

Figure 3-1 Assessment zones



It is noted that, during the progression of this study, DNV GL considered it appropriate to divide Zone 2 into two subzones, to account for the variation in the wind regimes along the English Channel. Furthermore, the westerly extent of Zone 2 shown in Figure 3-1 is mainly driven by the location of the Navitus Bay Wind Farm, which is no longer under development. These points are discussed further in Section 3.4.

3.2 Review of input datasets

DNV GL initially undertook a review of the sources of measured and modelled wind speed data that were available for the derivation of wind speed indices and assessment of IAV. The datasets considered are detailed in the following subsections.

3.2.1 Reanalysis data

Reanalysis datasets are multiyear, global, gridded representations of atmospheric states, which have been generated using state-of-the-art numerical weather prediction models and data assimilation techniques. Reanalyses combine model fields with observations that are distributed irregularly in space and time to produce a spatially complete, gridded meteorological dataset.

A number of reanalysis datasets are available globally, from the early NCEP-NCAR (R-1) and NCEP-DOE (R-2) datasets, to the more recent “third generation” reanalyses such as the Modern Era Retrospective-analysis for Research and Applications (MERRA) dataset produced by NASA, and ERA-Interim produced by the European Centre for Medium-Range Weather Forecasts (ECMWF).

DNV GL has been extensively using MERRA data in energy production assessments globally for nearly four years. DNV GL therefore has a solid understanding of its quality and suitability as a long-term reference, particularly in the UK region, and has been able to draw upon this previous experience for this study. Additionally, there are many active evaluations of MERRA appearing in open, peer-reviewed literature, which demonstrate that its quality is well understood. As a result, whilst it is acknowledged that there are many reanalysis datasets available, MERRA was identified as a focus point for this study. Further information about MERRA is given below.

MERRA is available from 1979 at a height of 50 m and on a global grid of 0.500 ° latitude x 0.667° longitude (~50 km), which represents a nearly five-fold increase in horizontal resolution over the R-1 and R-2 datasets. MERRA also offers a substantial increase in vertical resolution by employing 72 vertical computational layers compared to the 28 vertical levels used in R-1 and R-2. MERRA is also one of only two reanalyses that provides hourly output, and its outputs are regularly updated, lagging only about a month behind real time.

DNV GL has recently undertaken a study into the performance and consistency of MERRA data as a source of long-term reference data in the UK and Ireland /2/. As part of this review, DNV GL undertook comparisons of MERRA data with reliable long-term “ground” sources of measurements across the UK and Ireland. It was concluded that the MERRA dataset exhibits acceptable temporal consistency since January 1996, with a wind speed consistency uncertainty of 1%. Further information on consistency uncertainty is included in Section 5.2.4.

It is noted that TCE has also undertaken a validation exercise for MERRA data using UK offshore meteorological data /3/. The study concluded that strong correlations are obtained between the MERRA dataset and offshore measurements and that MERRA can be used as a semi-quantitative indicator of IAV.

During 2015 NASA announced the development of MERRA version 2 (MERRA-2), which was intended to replace and extend the MERRA dataset. In March 2016 NASA announced the discontinuation of MERRA data after February 2016, with only MERRA-2 available going forward. Given the timing of the release of the MERRA-2 dataset in relation to this study and the superior body of evidence supporting MERRA, DNV GL has investigated the use of both datasets for the purpose of this work.

MERRA-2 assimilates substantially more satellite data compared to MERRA and ERA-Interim, and is available at a slightly higher horizontal resolution of 0.500° latitude x 0.625° longitude. Based on the aforementioned investigations regarding the consistency of the MERRA dataset across the UK /2/ and further detailed comparisons between MERRA and MERRA-2 in the UK offshore environment, the long-term consistent reference period considered for the MERRA-2 dataset is also from January 1996 to the present. Further discussion on this is given in Section 3.3.

3.2.2 UK Met Office onshore meteorological stations

The UK Met Office (UKMO) operates a network of onshore meteorological stations across the UK and Northern Ireland. The meteorological stations generally comprise 10 m masts. DNV GL maintains a database of information regarding the consistency and exposure of the stations, and therefore has a good understanding of the quality of the datasets from across the network. As a result, DNV GL has identified a subset of coastal meteorological stations as a potential source of data for this study. DNV GL maintains an internal database of monthly mean wind speeds for these stations and these data have been considered in this review.

3.2.3 Offshore meteorological stations

Given the focus of this study on the wind variability of the UK offshore environment, DNV GL has also identified sources of publically available, long-term offshore measurements. The Royal Netherlands Meteorological Institute (KNMI) operates a network of onshore and offshore meteorological stations. These data are available for research and commercial uses in a number of different formats, corresponding to different levels of processing that have been applied. One data format, the “potential” wind speed data is publically available over the period 1996 to present. These data were produced as part of the KNMI HYDRA Project /4/. The potential wind speeds are derived from raw measured wind speeds by adjusting them to be representative of conditions at a standard 10 m height and with local flow effects removed. The potential wind speeds have an hourly averaging period. DNV GL has obtained the potential wind speed data for the Europlatform and K13 offshore meteorological stations located in the Dutch offshore zone, for consideration in this review.

DNV GL acknowledges that there are other sources of offshore wind measurements from other meteorological networks, for example those operated by Meetnet Vlaamse Banken /5/. It is understood that data from these networks are not publically available; as a result these data have not been included for consideration in this study.

3.2.4 Offshore masts/Lidars

TCE maintains a database of wind measurements collected from various meteorological masts, meteorological buoys and Lidar (Light Detection and Ranging) devices around the UK offshore environment.

The data are made publically available through the Marine Data Exchange website /6/ and are subject to a 2 year moratorium due to the commercial sensitivity of the datasets. TCE has supplied these datasets to DNV GL for the purpose of this study. In other instances, TCE has also provided DNV GL with wind data that are currently not in the public domain. The results presented in this report have therefore been anonymised to preserve the confidentiality of these data.

For the purpose of this study and to remain within scope, DNV GL has focussed on the datasets that have been supplied in a processed and cleaned format. Furthermore, DNV GL has only considered measurement locations with at least 12 months of data available. This has resulted in 24 datasets being available across 22 locations, over a range of measurement heights and with data periods ranging up to 8.4 years.

Whilst these datasets form the basis of the validation work undertaken in Phase 2, they have also been considered in this review for inclusion in the design of the wind indices.

3.2.5 DNV GL Virtual Met Data

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

In downscaling coarser resolution reanalysis datasets, mesoscale data can provide a better representation of localised conditions at a measurement location. DNV GL has therefore considered VMD in this review. It is acknowledged that there are a number of other mesoscale data products that are available; however, the consideration of these datasets was beyond the scope of this study.

3.2.6 Comparison

For each of the datasets identified in Sections 3.2.1 to 3.2.5, DNV GL undertook a high level comparison to identify which datasets were most appropriate to take forward for this study.

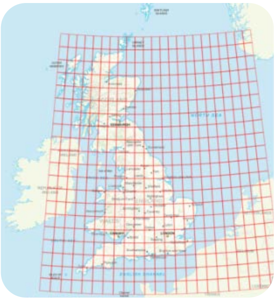
Each dataset was reviewed against a number of criteria, including the target uncertainty categories identified in Section 2.1, and other factors such as the height and spatial coverage of the datasets and whether they are publically available. It is noted that TCE has indicated a preference for non-proprietary datasets to be used in this study.

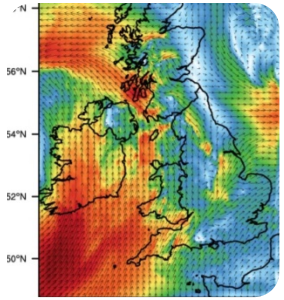
A summary of the review is given in Table 3-1.

On the basis of the comparisons, it is clear that the MERRA/MERRA-2 reanalysis datasets perform well against each of the criteria, with high quality correlations possible, a long consistent period, full spatial coverage across the UK offshore environment and public availability. These datasets were therefore identified as the most appropriate to take forward for the development of regional wind speed indices and assessment of IAV in this study.

In order to “future-proof” the results of this work, DNV GL primarily focused on the MERRA-2 dataset for the reasons discussed in Section 3.2.1. Although DNV GL has attained a larger body of direct experience with MERRA data, the technical merits of the MERRA-2 dataset and its ongoing production make it preferable according to the aforementioned ranking criteria. Due to the timing of the MERRA-2 dataset release, further investigations were conducted in order to gain comfort in MERRA-2, as discussed in Section 3.3 below.

Table 3-1 Summary of considered datasets





Criteria	MERRA / MERRA-2	Onshore meteorological stations	Offshore meteorological stations	Offshore measurements	DNV GL VMD
Correlation quality to site	Very good	Variable	Good, within close proximity to stations	Good, within close proximity to masts	Very good
Long-term period	1996 to present (20 years)[1]	Variable (~10 years)	1996 to present (~20 years)[2]	Variable (1 to 8.4 years)	1996 to present (20 years)[3]
Consistency uncertainty	~1%[1]	1%-3%	1%-3%	1%-3%	~1%[3]
Height	50 m[4]	10 m[4]	10 m[4]	Variable, up to hub height	Can be generated at hub height
Spatial coverage	Good (~50 km horizontal resolution)	Variable	Restricted to English Channel	Variable	Very good (up to ~2 km horizontal resolution)
Publically available?	Yes	No (needs to be purchased)	Yes ("potential" data)	Some (through MDE)	No (cost of modelling)

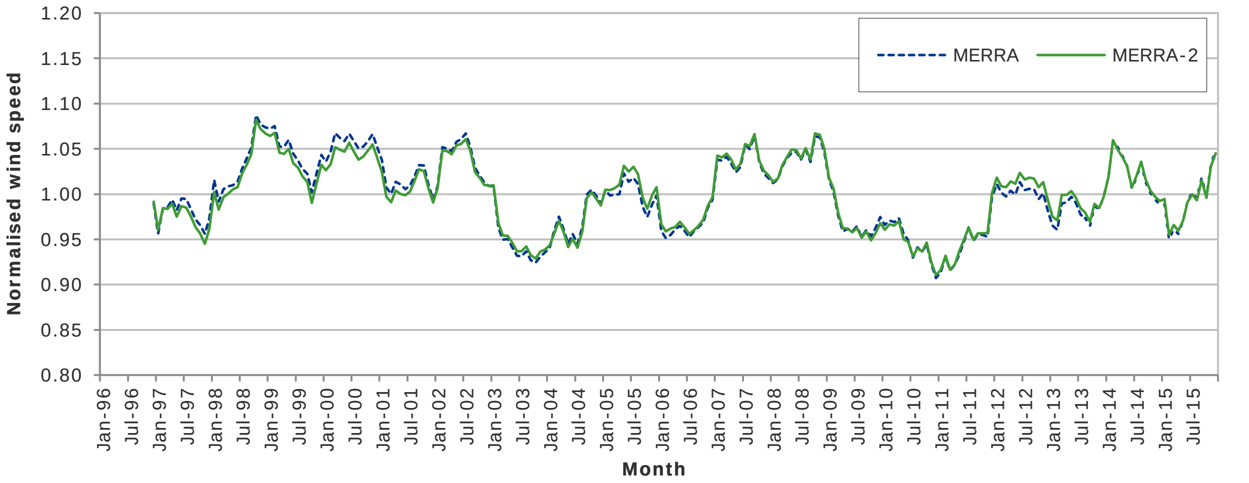
Notes:
1. Based on study reported in /2/
2. For "potential" wind speed data
3. If driven by MERRA/MERRA-2
4. Above ground level/mean sea level

3.3 Additional investigations into MERRA-2

DNV GL has extensive experience in the use of MERRA data in pre-construction energy assessments. Following the discontinuation of MERRA data in February 2016, DNV GL has been conducting global studies into the performance of MERRA-2 as a replacement to MERRA. For the purpose of this assessment DNV GL has conducted some additional investigations in order to get comfort with the performance of MERRA-2 in the UK offshore environment.

Figure 3-2 shows an example comparison of 12 month rolling averages of normalised wind speed for MERRA and MERRA-2 at a location in the UK offshore environment. It is seen that the datasets exhibit similar trends. At this location, a correlation between the monthly mean wind speeds from the MERRA/MERRA-2 datasets yields a coefficient of determination (R^2) of 0.99 indicating very good agreement. Moreover, DNV GL has undertaken correlations between MERRA and MERRA-2 across the region and has found very good agreement between the datasets.

Figure 3-2 Example comparison of MERRA and MERRA-2 data (12 month rolling averages of normalised wind speed)



DNV GL has also performed change point analyses (CPA) using the World Meteorological Organization Climate Variability and Predictability (CLIVAR) Program standard CPA method /7/, /8/. The algorithm is designed to detect multiple change points or "shifts" that exist in a data series. The analyses have been conducted for all MERRA-2 grid cells across the UK offshore environment over the period January 1996 to December 2015 assuming a 99% confidence level. No significant change points have been identified.

On the basis of these investigations, and the validation results presented in Section 4, DNV GL has gained comfort with the representativeness and consistency of the MERRA-2 dataset in the UK offshore environment. As a result, for the purpose of this study, MERRA-2 is considered consistent since January 1996 to present.

3.4 Workstream A: Derivation of wind speed indices

Following the review of the datasets available for this study, DNV GL has designed regional wind speed indices for each assessment zone on the basis of MERRA-2 data. MERRA-2 data have been obtained by DNV GL over the period January 1996 to December 2015, which was the latest period available at the inception of this study. The wind speed indices have been derived using the following methodology:

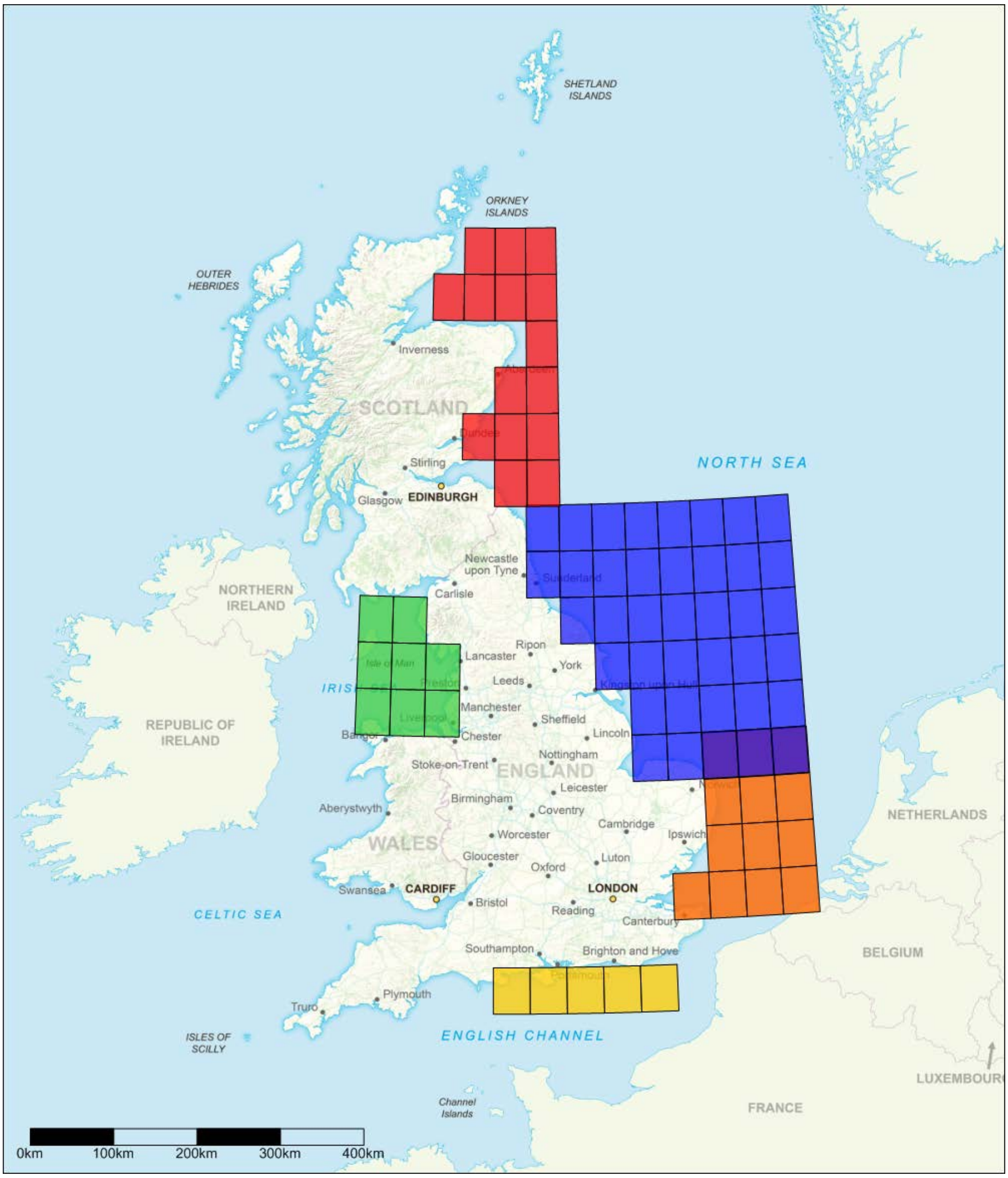
- MERRA-2 hourly wind speed data for the grid cells covering the UK offshore environment have been obtained and averaged to monthly mean wind speeds.

- Within each assessment zone, MERRA-2 monthly wind speeds have been correlated between each grid cell. The quality of the correlations was reviewed in order to examine variation in the wind regime across the zones and therefore the suitability of the grid cells for inclusion in each index. It is noted that based on this step, it was considered necessary to divide Zone 2 into two separate sub zones, in order to capture the different wind regimes found along the English Channel. As a result, the following sub zones were identified:
    - Zone 2a – English Channel
    - Zone 2b – South Coast
- Each wind speed index was created by averaging the normalised monthly wind speed at each selected grid cell. The final index was factored such that the mean of monthly means over the long-term period is unity.

The selected grid cells and spatial coverage of the regional wind speed indices are shown in Figure 3-3. Whilst consideration was given to similarity of the wind regime across the zones, the extent of the zones is largely driven by the locations of the UK Offshore wind development areas. It is noted that there is an overlap of grid cells selected for Zones 2a and 3, which can be seen in Figure 3-3. Furthermore, as discussed in Section 3.1, the westerly extent of Zone 2b South Coast is mainly driven by the location of the Navitus Bay Wind Farm, which is no longer under development. Whilst the extent of the selected grid cells could be reduced, DNV GL considers that the resulting indices are representative of the expected wind regime within the identified regions.

The final monthly wind speed indices cover the period January 1996 to December 2015 and are presented in Appendix A.

Figure 3-3 Final assessment zones (selected MERRA-2 grid cells)



Zone 1 Irish Sea Zone 2a English Channel Zone 2b South Coast Zone 3 North Sea Zone 4 East Scotland

3.5 Workstream B: Assessment of wind speed IAV

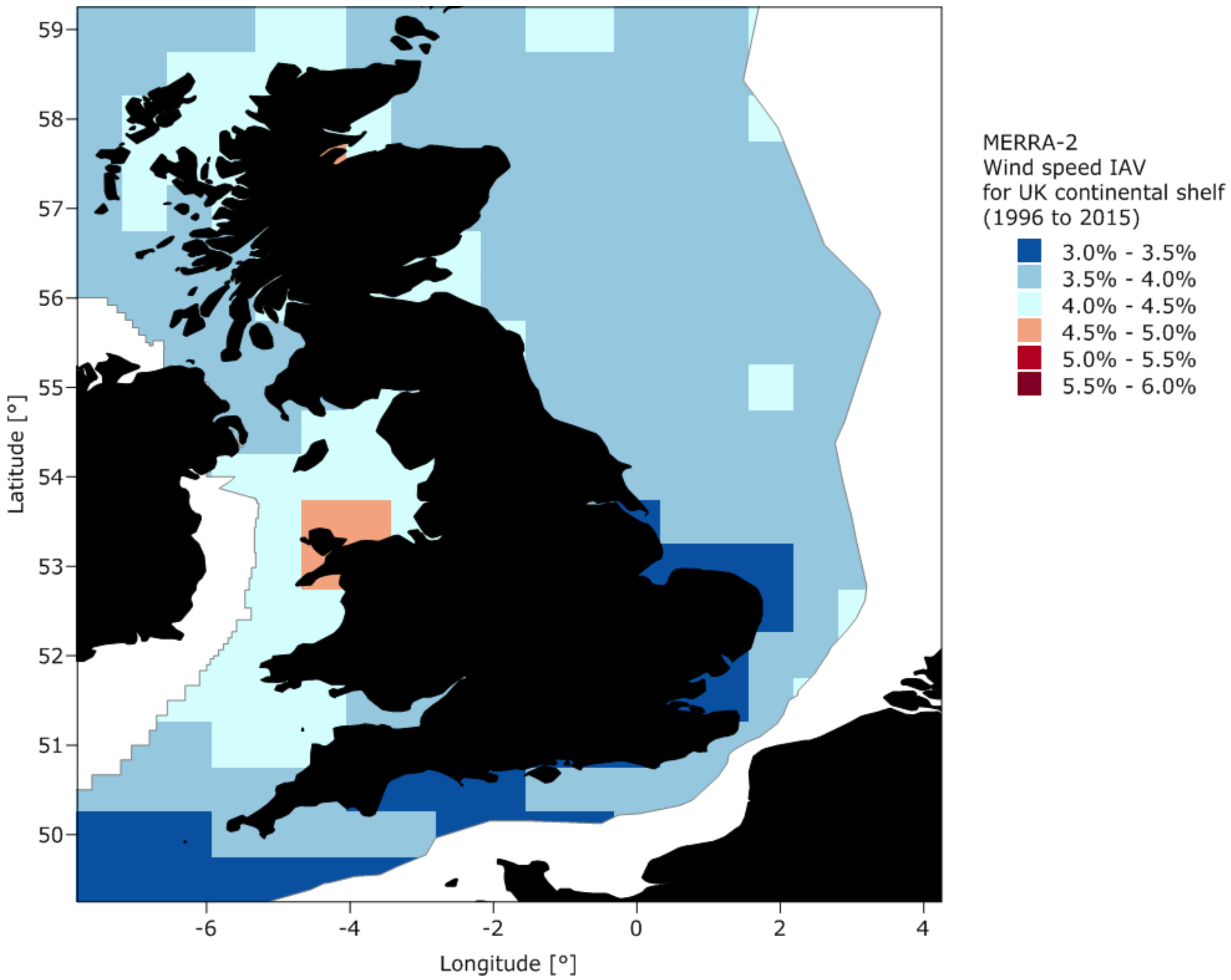
For the purpose of this study, the inter-annual variability of wind speed has been defined as follows:

$$IAV = \sigma_{ann.ws} \qquad (1)$$

where $\sigma_{ann.ws}$ is the standard deviation of annual mean wind speed, expressed as a percentage of the mean wind speed. It is noted that in order to robustly define IAV, it is desirable to have long datasets. This is driven by the assumption that inter-annual variability is normally distributed. A minimum sample threshold of 30 points (i.e. 30 years for the definition of inter-annual variability) is typically considered in statistical applications to be the minimum number of points required in order for an analysis based on a normal distribution to be valid. This derives from the Central Limit Theorem. The regional wind speed indices derived in Section 3.4 are based on a period of 20 years from 1996 to 2015. The impact of considering longer periods is discussed in Section 4.3.4.

As MERRA-2 data were identified as the most suitable source of data for this study, DNV GL initially undertook a review of the spatial pattern of IAV by MERRA-2 grid cell across the UK offshore environment. The pattern is shown in Figure 3-4 and represents the IAV of the period 1996 to 2015. It is noted that the IAV values shown in this figure are based on calendar years i.e. each annual average wind speed is derived as the average over January to December. It is seen in Figure 3-4 that the MERRA-2 IAV by grid cell ranges between 3.0% and 5.0% across the UK offshore environment based on a 20 year period, with lower IAV in the southern zones and higher IAV in the Irish Sea and east of Scotland.

Figure 3-4 Spatial pattern of IAV by MERRA-2 grid cell (1996 to 2015)



The IAV in wind speed for each assessment zone has been derived based on the regional wind speed indices derived in Section 3.4 and is presented in Table 3-2. These values are also based on calendar years over the period 1996 to 2015.

Table 3-2 Wind speed IAV by region (based on calendar years)

	Zone 1 Irish Sea	Zone 2a English Channel	Zone 2b South Coast	Zone 3 North Sea	Zone 4 East Scotland
IAV (1996 to 2015)	4.4%	3.7%	3.5%	3.7%	3.8%

It is seen that the pattern of IAV across the assessment zones is similar to that observed in Figure 3-4, with the lowest IAV for the Zone 2b South Coast, and highest IAV in Zone 1 Irish Sea. These regional definitions of IAV have been taken forward for validation, as discussed in Section 4.

As noted above, the IAV values presented in this section are based on annual means defined by calendar years. However, it is noted that the estimate of IAV can vary depending on the definition of a year; for example, if a year is defined as January to December or July to June. The impact of this is discussed further in Section 4.3. For the purpose of the validation exercise, IAV based on calendar years has been used.

Finally, within the industry there is uncertainty regarding the ability of reanalysis datasets, such as MERRA-2, to capture the observed variability in the wind, both onshore and offshore. This is a key consideration for the validation exercise conducted in Phase 2.

3.6 Phase 1 summary

Five regional monthly wind speed indices have been derived for the UK offshore environment based on MERRA-2 reanalysis data over the period January 1996 to December 2015. These wind speed indices have also been used to define the wind speed IAV in each assessment zone, based on calendar years.

The results of Phase 1 have been taken forward into the validation phase of this study as detailed in Section 4. A number of key questions have been identified under both workstreams to take forward into the validation phase.

Workstream A (wind speed index for the UK offshore environment):

- Do the regional wind speed indices provide robust correlations to site measurements?
- Do the regional wind speed indices exhibit temporal consistency and can the predicted wind speed adjustments be validated using other sources of reference data?

Workstream B (Inter-Annual Variability specific to the UK offshore environment):

- How should IAV be defined?
- Is IAV derived from MERRA-2 data and the regional wind speed indices representative of measured IAV?
- Can IAV be robustly defined using 20 years? What is the impact of using a longer period?

4 PHASE 2 - VALIDATION

4.1 Validation data

The datasets considered in the validation of the wind speed indices and IAV derived in Sections 3.4 and 3.5 are shown in Figure 4-1 and described in the following sections.

Figure 4-1 Validation data sources

✚ Offshore masts/Lidars ◆ Coastal UKMO stations ● KNMI stations ▲Ofgem data

4.1.1 Offshore masts/Lidars

As discussed in Section 3.2.4, TCE has supplied DNV GL with a range of wind datasets from various meteorological masts, Lidar devices and meteorological buoys around the UK offshore environment.

DNV GL has focussed on the datasets that have been supplied in a processed and cleaned format. Furthermore, DNV GL has only considered measurement locations with at least 12 months of data available. This has resulted in 24 datasets being available across 22 locations, over a range of measurement heights and with data periods ranging up to 8.4 years.

The location of the datasets that have been used in the validation of the wind speed indices and IAV derived in Sections 3.4 and 3.5 are shown in Figure 4-1.

As some of the periods of data are confidential, DNV GL has anonymised the results presented in this report.

4.1.2 Ofgem data

DNV GL has derived monthly production data from the publically available Renewables Obligation Certificate (ROC) register maintained by Ofgem, the UK electricity and gas market regulator /9/, for all operational UK offshore wind farms. The dataset includes data from 24 wind farms (14 Round 1 projects and 10 Round 2 projects), with data available from January 2006 onwards. In addition, DNV GL has obtained high level information regarding the project characteristics (i.e. turbine model, commissioning dates) from publically available sources /10/.

It is noted that DNV GL has corrected the datasets to account for months where significant operational issues result in lower production. To do this, DNV GL has compared the actual monthly production with the expected production, based on the windiness of the period indicated by the MERRA-2 dataset. In months where the deviation is large, DNV GL has removed the monthly value and ‘synthesised’ the production based on the relationship between the wind speed and production for each wind farm. Wind farms with significant proportions of synthesised production data or less than 12 months have not been considered, resulting in 2 wind farms being excluded from the analysis. The resulting datasets have been used in the validation of the wind speed indices and IAV derived in Sections 3.4 and 3.5, and are shown in Figure 4-1.

Whilst comparisons between the regional wind indices and the synthesised production data are not entirely independent, this synthesis step is considered necessary in order to ensure reasonable production data coverage for the purpose of the validation.

It is noted that whilst DNV GL has attempted to identify and mitigate months with significant operational issues, due to the coarse temporal resolution of the data available (monthly wind farm production) it is possible that less significant operational issues were present but not identifiable. This leads to increased uncertainty in this validation dataset.

4.1.3 Onshore and offshore meteorological stations

DNV GL has also considered the onshore and offshore meteorological stations listed in Section 3.2 that were not used directly in the derivation of the wind speed indices and IAV for the purposes of the validation exercise.

DNV GL has also derived indicative “measurement-based” regional wind speed indices using the onshore and offshore meteorological stations. Where possible these have been derived over the January 1996 to December 2015 period in order to provide a direct comparison. In order to derive such a long dataset, it has been necessary to relax some of the criteria typically applied for deriving wind speed indices and include stations with short overlapping periods. Whilst this is less than ideal, the resulting indices are considered suitable for the indicative checks included in this study.

Long-term measurement based indices have been derived for Zone 1 Irish Sea, Zone 2a English Channel and Zone 3 North Sea. Measurement based indices were not derived for Zone 2b South Coast and Zone 4 East Scotland due to the lack of suitable long-term measurements in the respective zones.

4.2 Workstream A: Validation of wind speed indices

4.2.1 Correlation quality

As part of the validation of the wind speed indices, correlations were derived between the regional MERRA-2 wind speed indices and validation datasets using a monthly averaging period. Months for which the data coverage at either the validation point is less than 90% have been excluded from the correlation. DNV GL has assessed the quality of these correlations using the coefficient of determination (R^2). The average R^2 for each zone is presented in Table 4-1. Also shown in this table is the number of validation points available in each zone, for reference.

It is seen that good quality correlations are obtained between the regional MERRA-2 indices and the offshore masts/Lidars. Good quality correlations are also obtained with the wind farm production data in the regions where these data are available. These correlations are generally of lower quality than the wind speed measurements; this is a result of the production data being subject to other sources of variability such as system availability.

For comparison, DNV GL has also derived R^2 values for correlations with nearest MERRA-2 grid cell to each of the masts/Lidars. It is seen that similar or better correlations are obtained using the nearest MERRA-2 grid cell compared to the regional MERRA-2 wind speed indices. The greatest improvement is seen in Zone 3. It is considered that this may be a result of the larger size of Zone 3, and the fact that the majority of the validation points in this zone are near-shore.

DNV GL has also compared correlations with the measurement based indices derived in Section 4.1.3. It is seen that correlations between the wind datasets and the measurement based indices are generally of a similar or lower quality than the MERRA-2 regional indices.

Table 4-1 Average coefficient of determination (R^2) from monthly correlations

		Zone 1 Irish Sea	Zone 2a English Channel	Zone 2b South Coast	Zone 3 North Sea	Zone 4 East Scotland
Wind speed measurements	MERRA-2 regional index	0.97	0.96	0.93	0.93	0.97
	Nearest MERRA-2 grid cell	0.97	0.98	0.93	0.96	0.97
	Measurement based index	0.90	0.96	-	0.89	-
	Number of masts/Lidars	8	7	1	6	2
Production data	MERRA-2 regional index	0.93	0.92	-	0.89	-
	Number of wind farms	9	8	-	5	-

4.2.2 Temporal consistency

DNV GL has undertaken checks on the temporal consistency of the regional MERRA-2 wind speed indices derived in Section 3.4.

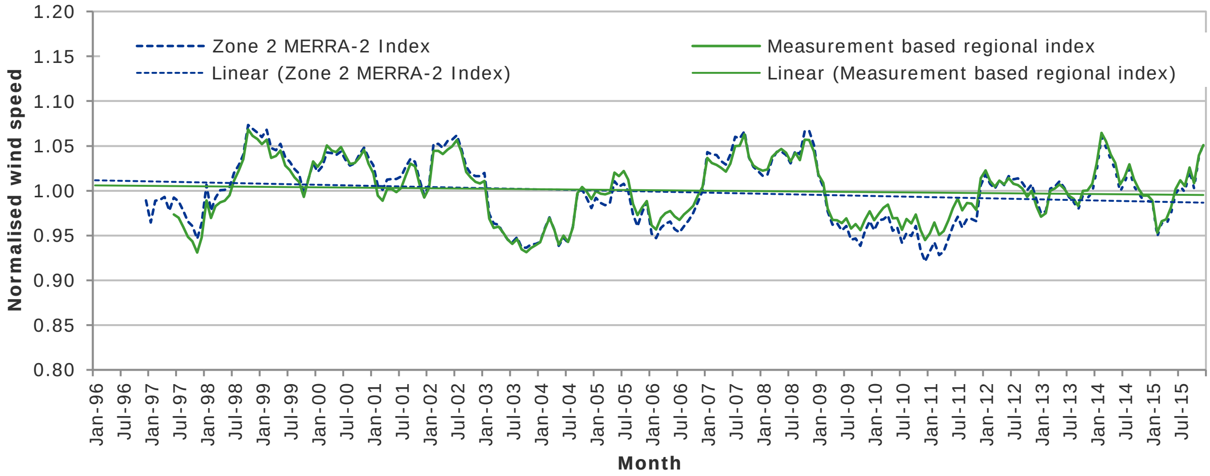
Change point analysis, using the methodology described in Section 3.3, has been conducted on the regional wind speed indices. No significant change points have been identified at the 99% confidence level.

DNV GL has also undertaken a comparison between the long-term trends predicted by the regional MERRA-2 wind indices and long-term measurements where available. Figure 4-2 presents an example comparison of 12 month rolling averages between the MERRA-2 index for Zone 2a English Channel and a measurement based index for the region derived from onshore and offshore meteorological stations. Whilst there are some deviations, it is seen that the indices exhibit similar trends over the 20 year period, giving confidence in the temporal consistency of the regional MERRA-2 wind speed index.

Similar trends were also found between the MERRA-2 regional index and measurement based index in Zone 1 Irish Sea. Larger differences were observed in Zone 3 North Sea; however, DNV GL considers that the measurement based index derived in this zone is not fully representative of the entire zone. This is because it is based on coastal meteorological stations and the zone extends a significant distance offshore. Measurement based indices are not available for Zone 2b South Coast and Zone 4 East Scotland and therefore this additional check could not be undertaken in these regions.

Any deviations in trends will impact predicted wind speed adjustments; these have been assessed in Section 4.2.3.

Figure 4-2 Comparison of 12-month rolling averages between Zone 2a regional index and a measurement based regional index



4.2.3 Wind speed adjustments

DNV GL has undertaken checks on the long-term wind speeds predicted by the MERRA-2 regional wind speed indices at the offshore validation masts/Lidars. These checks compare the wind speed adjustments predicted by the sources of long-term reference data over the 20 year period, using a monthly correlation and synthesis approach. These investigations therefore consider the impact of both the quality of the correlation and the long-term trend, as discussed in in the previous sections, on the final long-term wind speed prediction.

The comparisons are summarised in Table 4-2 below.

DNV GL has first compared the adjustments predicted by the regional MERRA-2 indices and nearest MERRA-2 grid cell. Across the 24 masts, the regional MERRA-2 indices predict larger adjustments at some locations and smaller adjustments at others. The average difference in the wind speed adjustments is 0.1%, indicating that the regional MERRA-2 indices produce similar long-term mean wind speed estimates to the individual MERRA-2 grid cells. However, the largest absolute difference is found to be 2.4%, which occurs at a location where the quality of the correlation is significantly different between the two datasets. The differences across the rest of the locations are within 0.8%.

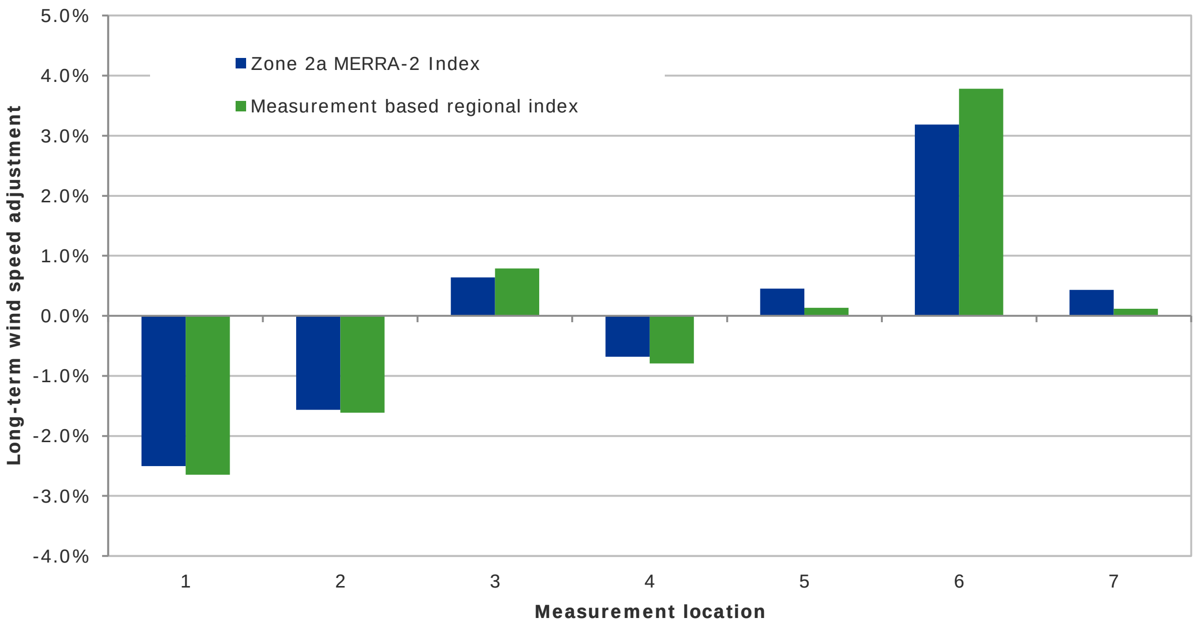
As shown in Table 4-2 DNV GL has conducted a similar comparison using the measurement based regional indices derived in Section 4.1.3. Across the masts in Zone 1, Zone 2a and Zone 3, the average difference in wind speed adjustments is 0.0%, with a largest absolute difference of 2.2%. At the location of the largest difference, the quality of the correlation is similar and high, indicating that this is a result of the differing long-term trends.

Table 4-2 Comparison of wind speed adjustments

	Difference in long-term wind speed adjustment compared to regional MERRA-2 indices				Number of masts
	Average	Average (absolute)	Maximum (absolute)	Minimum (absolute)	
MERRA-2 nearest grid cell	+0.1%	0.4%	2.4%	0.0%	24
Measurement based regional index	+0.0%	0.6%	2.2%	0.1%	21

An example of a comparison of wind speed adjustments is show in Figure 4-3 for Zone 2a English Channel for the regional MERRA-2 and measurement based indices.

Figure 4-3 Comparison of long-term wind speed adjustments predicted by Zone 2a regional index and measurement based regional index



It is noted that the level of agreement in the long-term wind speed predicted by different sources of long-term reference data can be used to inform the magnitude of the consistency uncertainty applied (see Section 5.2.4). As part of any formal wind resource and energy production assessment, DNV GL recommends that multiple sources of reference data are assessed on a site-by-site basis in order to increase confidence in the final long-term mean wind speed prediction.

4.3 Workstream B: Validation of IAV assessment

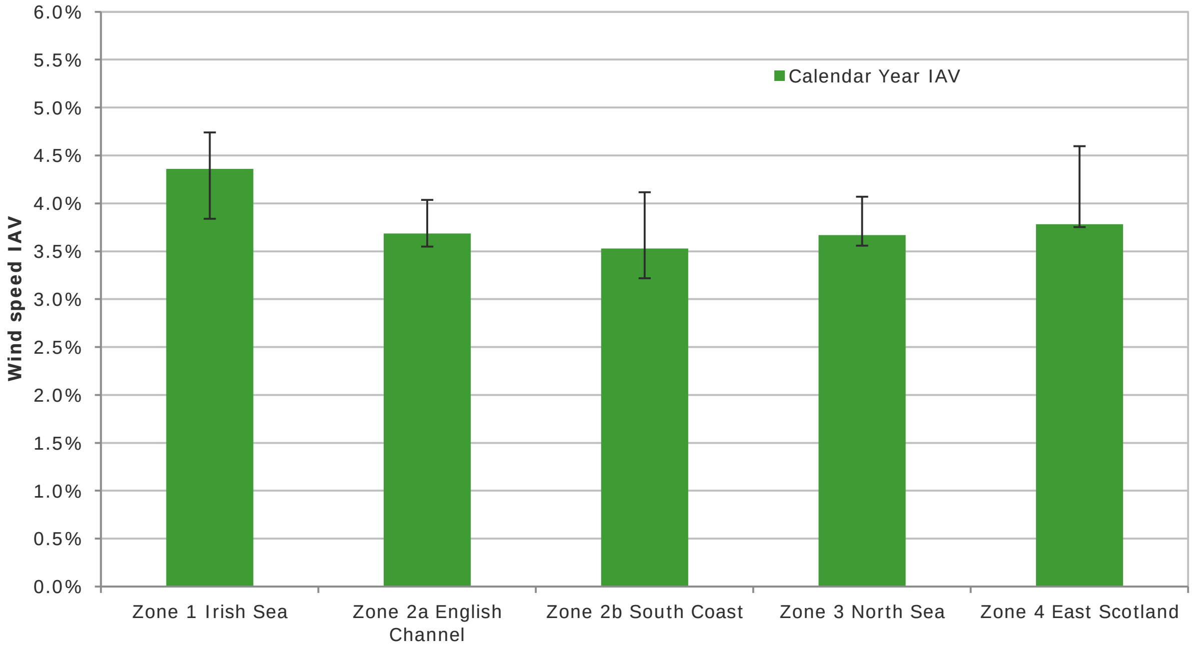
4.3.1 Definition of year

As noted in Section 3.5, the IAV values presented in this report are based on annual means defined by calendar years. However, it is noted that the estimate of IAV can vary depending on the definition of a year; for example if a year is defined as January to December or July to June.

DNV GL has investigated the sensitivity of the IAV derived when assuming different definitions of a year, by assuming different cases where the year is defined from January, February, March etc., resulting in 12 definitions of IAV for a given zone.

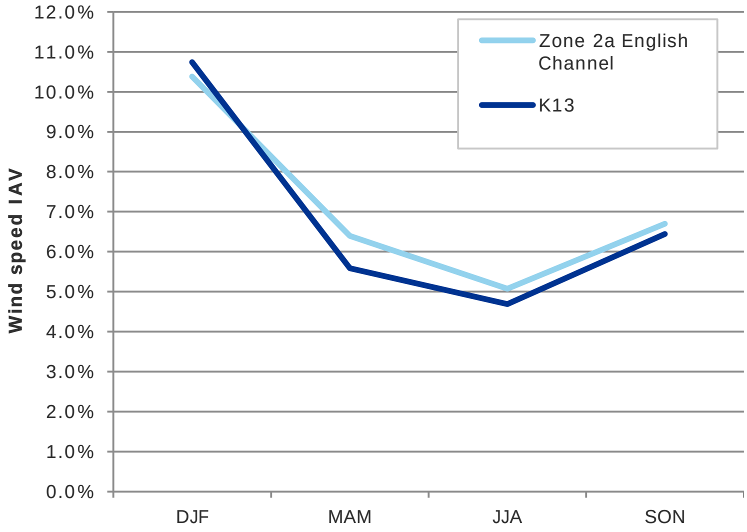
The range in IAV values across all definitions of a year is presented in Figure 4-4, as error bars around the calendar year value. It is seen that IAV can vary by as much as 0.9%.

Figure 4-4 Range of wind speed IAV for different year definitions based on regional wind speed indices



This highlights the sensitivity of the definition of IAV. It is considered that in the UK the year-to-year variations in wind speed are largely driven by year-to-year variations in the winter mean wind speed. This is seen in Figure 4-5, which shows the inter-annual variability of the seasonal means for winter (December, January, February: DJF), spring (March, April, May: MAM), summer (June, July, August: JJA) and autumn (September, October, November: SON) for the MERRA-2 index for Zone 2a English Channel. Long-term, offshore measurements are available in this zone from the KNMI K13 offshore meteorological station. Therefore the same check has been undertaken using those data and plotted for comparison, showing a similar trend.

Figure 4-5 IAV of seasonal mean wind speeds for Zone 2a East Anglia



For the purpose of the validation exercise conducted here, DNV GL has compared IAV based on calendar years. The impact of the definition of a year is identified as a technical risk that should be considered in the implementation of this work, which is discussed further in Section 5.4.

4.3.2 Wind speed IAV

DNV GL has undertaken a comparison of the IAV derived from the measured wind speed datasets and MERRA-2 regional wind speed indices using a number of approaches, as detailed below.

Meteorological station datasets

Given the offshore focus of this study and the need for long datasets in the derivation of IAV, DNV GL has first compared the IAV derived from the KNMI offshore meteorological stations identified in Section 3.2.3. Data at these stations has been considered over the period July 1996 to December 2015, although it is noted that there are short periods of data missing at each station. The IAV derived at the stations and corresponding MERRA-2 regional index is compared in Table 4-3 below. The IAV has been derived over matched periods and filtered for years with less than 90% coverage.

It is seen that there is reasonable agreement between the measured IAV and index IAV; at both locations agreement is within 0.5%. The index IAV is higher at K13 and lower at Europlatform.

The differences seen may be a result of the use of a regional index to derive the IAV rather than a “site-specific” definition. As a further check, DNV GL has derived IAV based on the nearest MERRA-2 grid cell to each location; the results are also presented in Table 4-3. The agreement is better at Europlatform and slightly worse at K13. This result, albeit from a limited validation dataset, indicates that the level of agreement between MERRA-2 IAV and measured IAV varies by location.

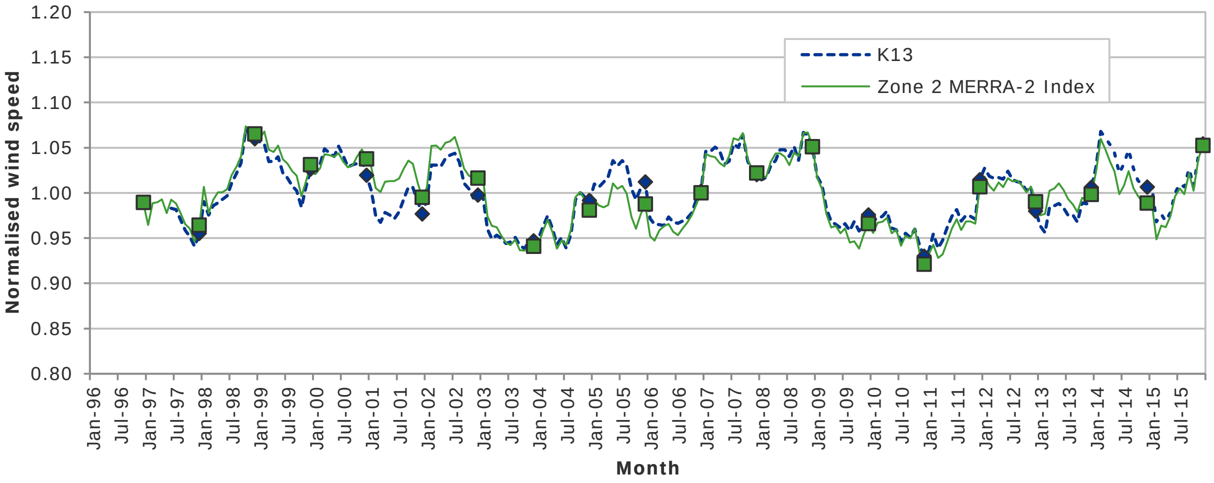
The average difference between the index IAV and measured IAV over the two measurement locations is +0.05%, with the index IAV being slightly higher. However, it is noted that there is not a sufficient number of points to draw a firm conclusion.

Table 4-3 Comparison of IAV at KNMI stations

	K13	Index Zone 2a English Channel – matched K13	MERRA-2 nearest grid cell to K13 – matched K13	Europlatform	Index Zone 2a English Channel – matched Europlatform	MERRA-2 nearest grid cell to Europlatform – match Europlatform
IAV (calendar year)	3.5%	3.8%	3.9%	4.2%	3.7%	4.2%

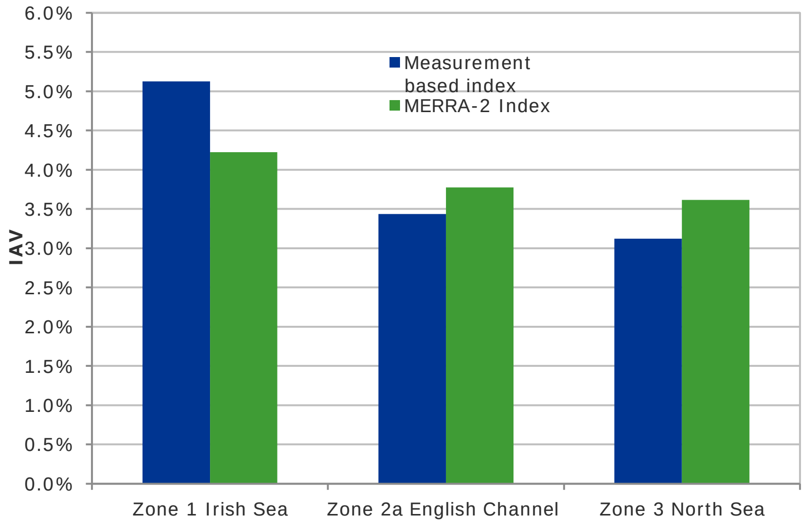
A visual comparison of the 12 month rolling average normalised wind speeds at K13 and the regional wind index is given in Figure 4-6.

Figure 4-6 12 month rolling averages at K13



DNV GL has also compared the MERRA-2 regional wind index IAV, with the measurement based indices derived in Section 4.1.3. This comparison is presented in Figure 4-7. Again, the coverage of the datasets has been matched and filtered for years with less than 90% coverage. This comparison indicates that the MERRA-2 index IAV is lower than the measured IAV in Zone 1 Irish Sea, and slightly higher in Zone 2 and Zone 3. The average difference across the zones is -0.03%, with the MERRA-2 index IAV overall being slightly lower.

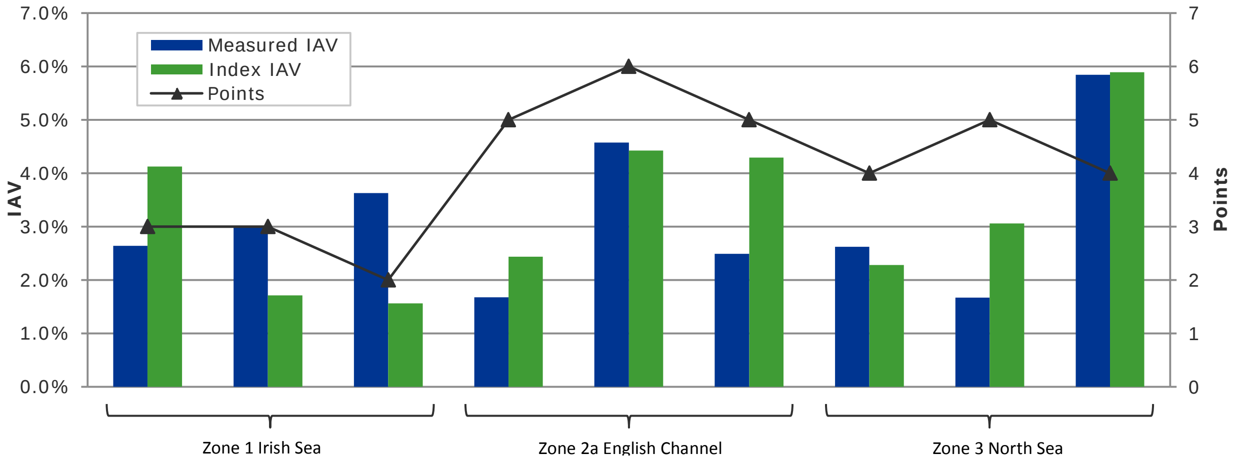
Figure 4-7 Comparison of IAV with measurement based indices



Offshore masts/Lidars

DNV GL has identified 9 of the offshore masts/Lidars with periods of wind data exceeding 4 years. The measured IAV has been derived for the measurements and indices for matched periods, for years with greater than 90% coverage. These are compared in Figure 4-8. It is noted that due to missing data periods, there are a reduced number of points in some of the comparisons. Given the high uncertainties associated with deriving IAV on a low number of points, this should be taken into consideration in the interpretation of the results. Furthermore, it is noted that no comparison has been possible for Zone 2b South Coast and Zone 4 East Scotland, as the measured periods are not sufficient for the derivation of IAV.

Figure 4-8 Comparison of IAV at masts/Lidars



In Figure 4-8 it is seen that there is no systematic tendency for the IAV derived from the MERRA-2 regional indices to be higher or lower than measured IAV. Overall the difference is +0.2%, with the IAV derived from the MERRA-2 indices being higher.

DNV GL has investigated the impact of 'synthesising' missing periods at the masts in Zone 1 Irish Sea, using correlations with the nearest MERRA-2 grid cell to improve data coverage at these locations. The inclusion of these data improves the overall agreement between the measurements and regional wind speed indices to +0.1%. It is further seen that there appears to be a tendency for the MERRA-2 regional indices to predict lower IAV than measurements in Zone 1 Irish Sea. It is acknowledged that this is not entirely independent comparison as the MERRA-2 data has been used to improve the data coverage; however, it is considered a useful high level check at locations where data coverage is low.

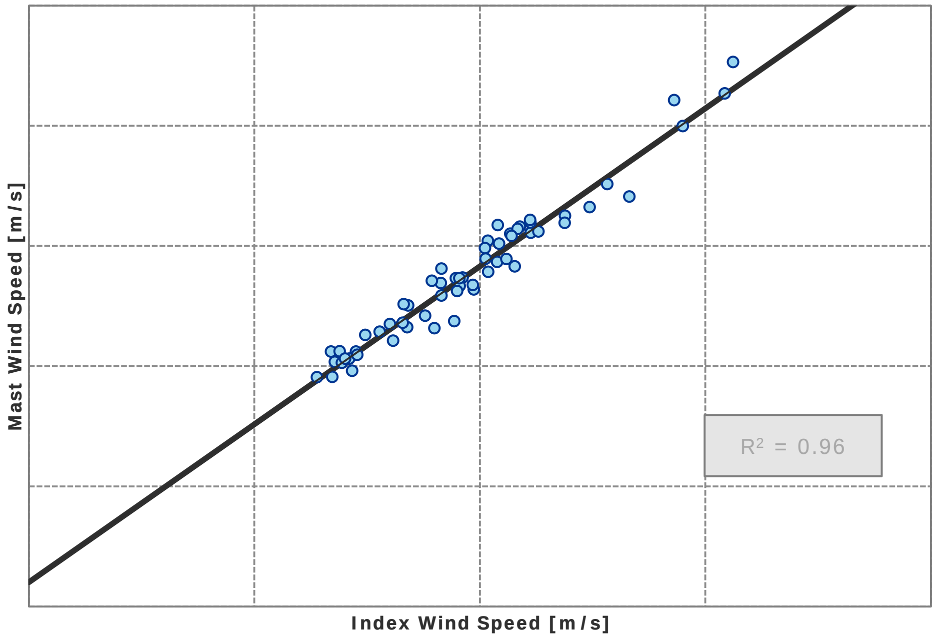
Correlation offsets

In order to further investigate the relationship between the regional indices and the site measurements, DNV GL has reviewed the slope and offset from correlations between the regional wind speed indices and site measurements.

The MERRA-2 regional indices have been correlated to the 24 offshore mast/Lidar datasets on a monthly basis. An example is given in Figure 4-9 below, which has an offset of +0.61 m/s. The axis values have been removed from this plot in order to preserve the anonymity of these data. The average offset from the correlations across the datasets is found to be +0.9 m/s. All correlations have a positive offset. This result indicates higher variability in the MERRA-2 regional indices than seen in the measurements, although this finding is sensitive to the quality of the correlation. An average offset of 0.9 m/s corresponds to approximately 10% of the mean wind speed of the measurement locations. This result indicates that the variability in the MERRA-2 indices is of the order of 10% higher than the variability in the measurements. This is in reasonable agreement with the other results seen in this section.

DNV GL considers that further investigation would be beneficial to establish whether and how this observation can be accounted for in the definition of IAV. This is discussed further in Section 5.4.

Figure 4-9 Example monthly correlation and linear regression fit



Impact of wind shear

The MERRA-2 regional wind speed indices have been derived using the surface dataset at 50 m above ground level/mean sea level. Typical hub heights for offshore projects in the UK are in the region of 100 m above mean sea level. As a result, consideration has been given to whether the IAV predicted by the MERRA-2 regional indices at 50 m is representative of typical offshore hub heights.

DNV GL has investigated this by reviewing the inter-annual variation in wind shear at an offshore measurement location where data were available at two heights; at approximately 50 m and 80 m. The power law shear exponent between these heights has been derived on a time series basis, and 12 month rolling averages have been plotted alongside 12 month rolling averages of wind speed in Figure 4-10. The axis values have been removed from this plot in order to preserve the anonymity of these data. It is seen that there is a relationship, with a tendency for higher shear in years where the average wind speed is high, and lower shear in years where the average wind speed is low. This may be a result of higher sea surface roughness during higher wind speeds leading to higher wind shear. This indicates that wind speed IAV is higher at 80 m than 50 m; however, due to the short period of data available it is not possible to compare the wind speed IAV at the two heights and draw firm conclusions.

Figure 4-10 12 month rolling averages of power law shear exponent (alpha) and wind speed at one location

It is noted that the measurements used in the validation of IAV in this section represent range of heights, from meteorological stations with measurements made at 10 m, up to measurement heights that are close to typical offshore turbine hub heights. The differences in heights may therefore account for some of the differences seen in the comparisons undertaken here. DNV GL has attempted to identify trends between height difference and the differences observed in the comparisons reported in this section; however, no clear trend is observed. This has been identified as a potential area for further investigation, as discussed further in Section 5.4.

4.3.3 Production IAV

DNV GL has also undertaken a comparison of the IAV derived from the Ofgem production datasets and MERRA-2 regional wind speed indices.

To provide a fair comparison, DNV GL has converted the MERRA-2 regional wind speed indices to production indices for each site. The IAV comparisons presented in this section are therefore not directly comparable to the wind speed based comparisons presented in Section 4.3.2. To achieve this, DNV GL has assumed a representative wind speed to energy sensitivity ratio based on the turbine model at each site /10/ and a representative mean wind speed. The assumed sensitivity ratios range from 1.1 to 1.4.

Furthermore, DNV GL has assumed that the Ofgem production datasets contain other sources of variability, such as variability in the system availability and the shape of the wind speed frequency distribution. To account for this, DNV GL has “added” these additional sources of variability to the MERRA-2 regional wind speed indices. Based on DNV GL experience, system availability can be assumed to have inter-annual variability of 3% and the frequency distribution to have an inter-annual variability of 2%. Both are defined in terms of energy.

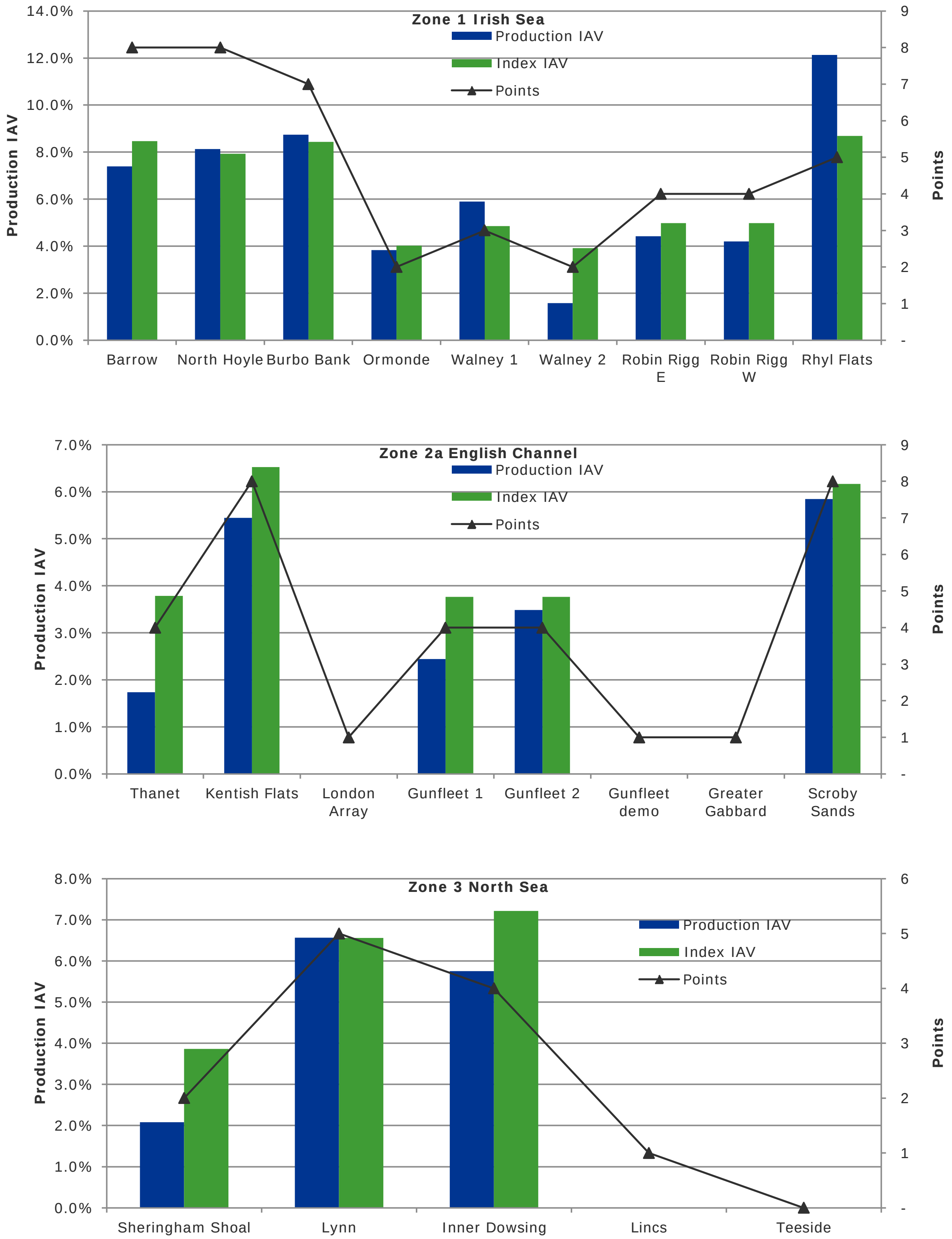
The resulting production indices have been used to derive IAV for periods matching the Ofgem production datasets for calendar years. IAV has not been defined where only 1 year of data or less is available. The IAV is compared in each region where production data is available in Figure 4-11.

It is seen that there is a range in the level of agreement, with very good agreement seen at some locations, such as North Hoyle and Lynn, and worse agreement at other locations such as Rhyl Flats. By region, better agreement is found in Zone 1 Irish Sea, with an average difference between measured production IAV and the index production IAV of +0.4% (index production IAV being higher). The average differences in Zone 2a English Channel and Zone 3 Irish Sea were larger, at +1.0% and +1.1%, respectively. Across all locations, the average difference in production IAV was found to be +0.5%. Taking into consideration wind speed to energy sensitivity ratios assumed above and the uncertainties in therein, this is broadly in line with the comparisons of wind speed IAV described in Section 4.3.2.

It is noted that there is elevated uncertainty in this comparison due to the following:

- High level input data available from Ofgem;
- High level assumptions made to convert the wind speed indices to production;
- Adjustments made to correct for significant operational issues and the potential for issues that have not been detected due to the coarse temporal resolution of the data;
- Adjustments made to factor in other sources of variability, such as system availability and the shape of the wind speed and direction frequency distribution.

Figure 4-11 Comparison of production IAV at operational projects



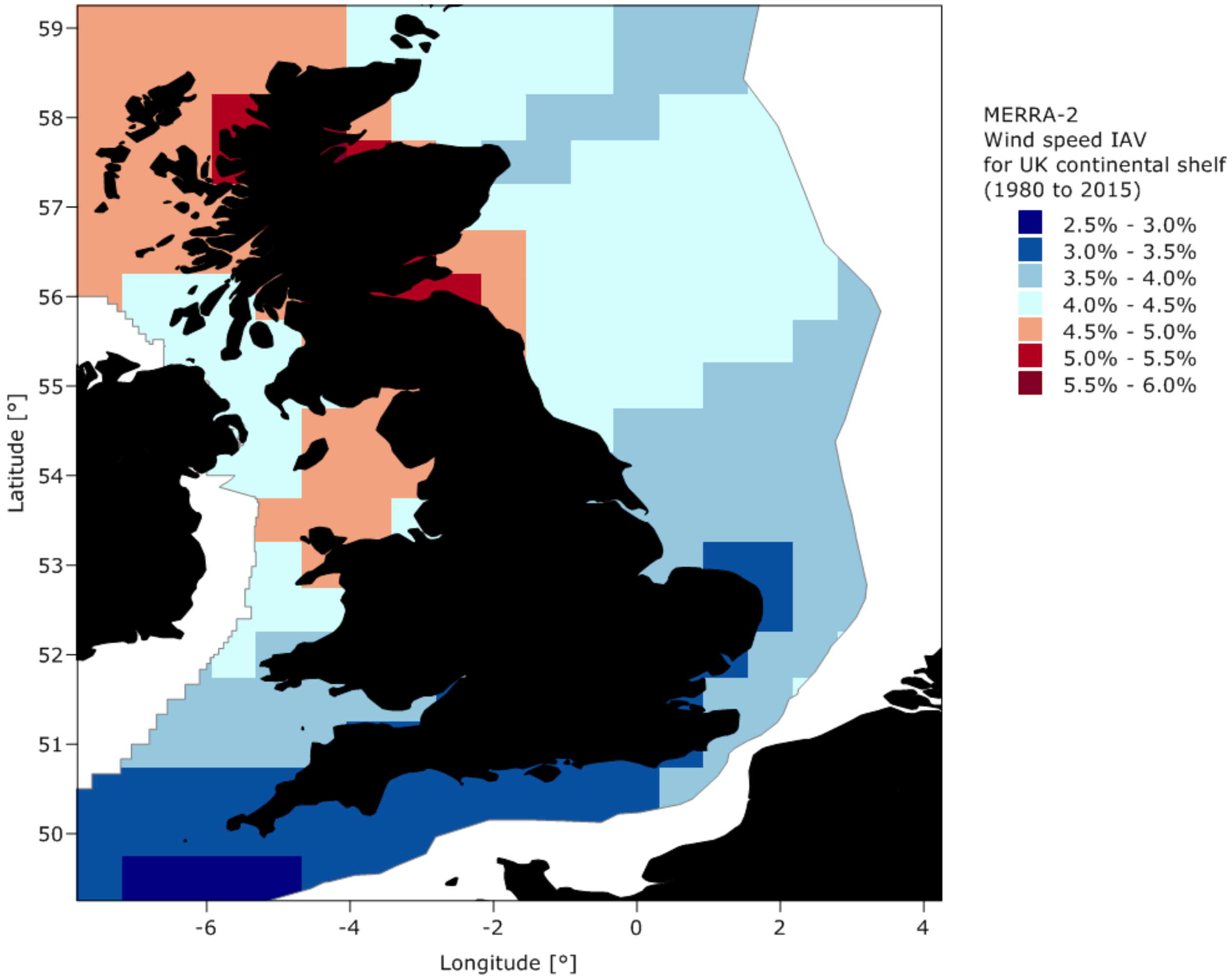
Notes: IAV has only been derived for projects with > 1 calendar year of data available.

4.3.4 IAV over a longer period

The MERRA-2 indices that have been used to derive wind speed IAV are based on a 20 year period from January 1996 to 2015, which is considered to be the consistent period of the MERRA-2 dataset in the UK offshore region. As discussed in Section 3.5, long datasets are required to account for long-term variability; 30 years is often considered to be the minimum number of years to derive statistically robust definitions of IAV.

DNV GL has therefore investigated the impact of including more historical MERRA-2 data in the definition of IAV. DNV GL has sourced additional MERRA-2 data from January 1980. Figure 4-12 presents the spatial pattern of IAV derived from MERRA-2 by grid cell across the UK offshore environment over the period 1980 to 2015, totalling 36 years. It is seen that IAV ranges from 3.0% to 5.5% by grid cell based on this longer period. These values are based on calendar years.

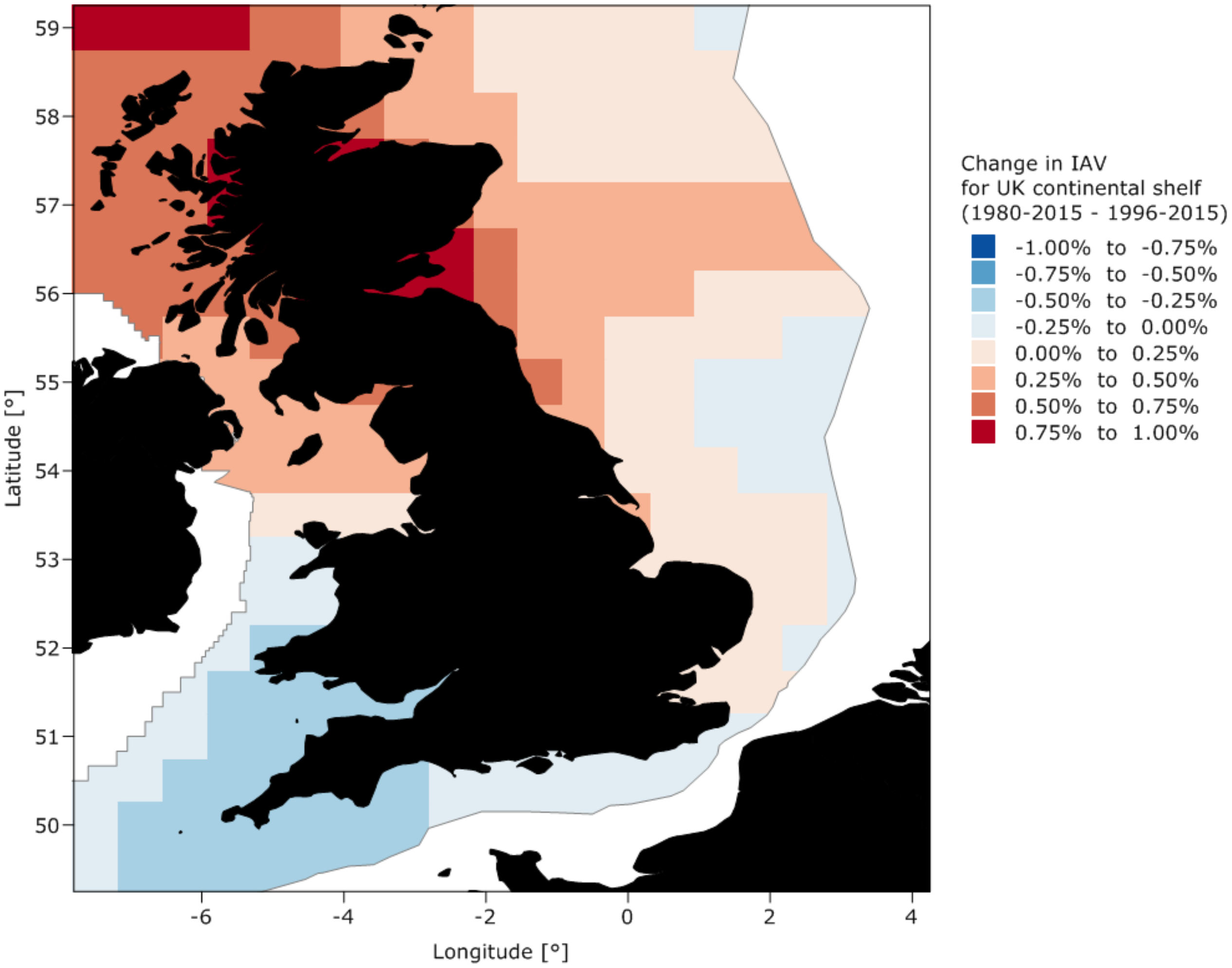
Figure 4-12 Spatial pattern of IAV by MERRA-2 grid cell (1980 to 2015)



To enable comparison, DNV GL has also plotted the change in IAV derived for the 1980 to 2015 period compared to the 1996 to 2015 period in Figure 4-13. It is seen that there are regional differences in the changes. For the longer period, IAV increases for much of the area considered in this study. The largest increase of 1.0% is seen in Zone 4 East Scotland. In contrast, the MERRA-2 dataset indicates a small reduction in IAV in Zone 2b South Coast over the longer period. Overall, these results indicate that the definition of IAV can be sensitive to the length of the period used to define it.

It is noted that DNV GL has not assessed the consistency of the MERRA-2 dataset over the period 1980 to 2015. Undetected consistency changes in the dataset could have an impact on the predicted IAV over this period and there is therefore elevated uncertainty in this check. Despite the potential introduction of inconsistencies, DNV GL considers there is benefit in utilising as long a dataset as possible to derive IAV.

Figure 4-13 Change in MERRA-2 IAV for 1980-2015 period compared to 1996-2015 period

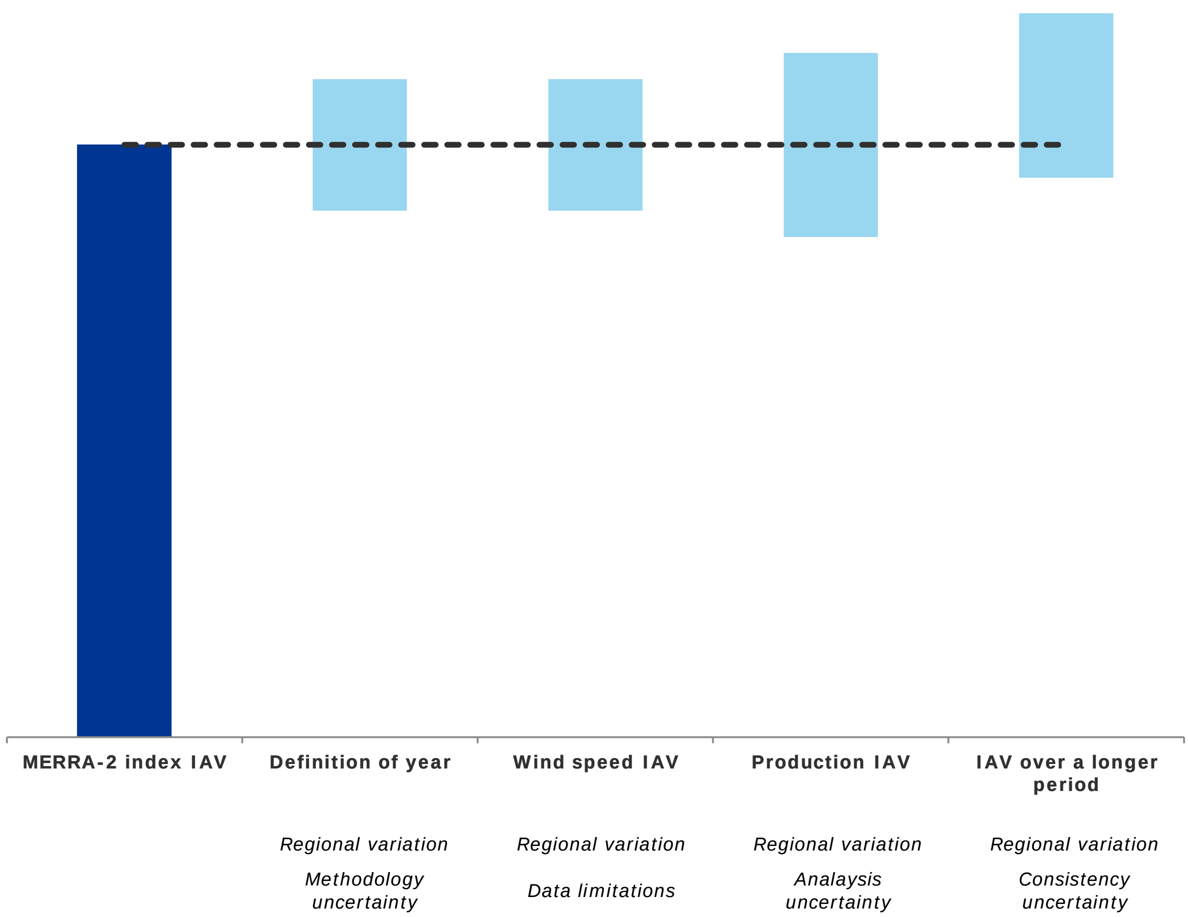


4.3.5 IAV discussion

In Phase 2 of this study, DNV GL has been able to gain confidence in the values of IAV derived from the MERRA-2 indices. However, this validation has been limited to certain geographical areas and relatively short periods of measurements: 2 years to 6 years at the offshore mast/Lidar locations; 2 years to 8 years in the production data and up to 20 years at the meteorological stations/measurement based indices. This study has also identified a potential sensitivity of IAV to height, and it is noted that the measurements used in the validation cover a range of heights which could have an impact on the validation. Furthermore, the consideration of longer periods has been shown to have an impact on the defined IAV. It is therefore considered that there remains uncertainty in the representativeness of the IAV values derived for each assessment zone.

In light of the results presented above, DNV GL considers that it would be appropriate to adjust the IAV predicted by the 20 year indices to account for a longer historical period and to account for the sources of uncertainty in the prediction. DNV GL considers that additional work would be required in order to define the value of this adjustment. Figure 4-14 provides a schematic demonstration of the various factors discussed in the previous sections and their potential impact on the definition of IAV for a generic region. The plot captures the uncertainty in the validations, regional variations and implied adjustments and is illustrative rather than quantitative. Given the ranges shown for each factor, it is not possible to determine the overall IAV that will result from any further investigations, as any given factor may imply either an upwards or downwards adjustment. Furthermore, the final IAV definition will need to include provisions for the uncertainties in any investigations.

Figure 4-14 Schematic demonstration of IAV range



The results presented in this report suggest that there is strong evidence to move away from the industry standard value of 6.0% to lower IAV values for the UK offshore regions that have been considered in this study. Based on the results of this study, an IAV range of 4% to 5.5% is considered more appropriate. This range has been considered for the purpose of the uncertainty and LCoE assessment presented in Section 5, in comparison to a base case IAV of 6%. .

It is emphasised that these values have been taken forward for this study alone based on the results presented above; this does not represent a formal change in DNV GL stance.

4.4 Phase 2 summary

Following the validation exercise, the following conclusions are drawn.

Workstream A (wind speed index for the UK offshore environment):

- It is possible to obtain robust correlations between the regional MERRA-2 wind speed indices and site measurements. However, it is noted that higher quality correlations can generally be obtained using the nearest MERRA-2 grid cell.
- The regional MERRA-2 wind speed indices are considered to exhibit temporal consistency over the period January 1996 to December 2015, with similar long-term trends as measurement based indices.
- Across the offshore mast/Lidar locations, the regional MERRA-2 wind speed indices yield similar long-term wind speed predictions when compared to the nearest MERRA-2 grid cell and regional measurement based wind speed indices. However, it is noted that level of agreement varies by location. As part of any formal wind resource and energy production assessment, DNV GL generally recommends that multiple sources of long-term reference data are considered to gain confidence in the final wind speed adjustment.

Workstream B (Inter-Annual Variability specific to the UK offshore environment):

- There is good agreement between the IAV derived from the regional MERRA-2 wind speed indices and measured IAV:
    - Comparisons between wind speed measurements indicate good agreement overall, with a tendency for the IAV derived from the indices to be lower in Zone 1 Irish Sea and higher in Zone 2a English Channel and Zone 3 North Sea. It has not been possible to validate IAV predictions in Zone 2b South Coast and Zone 4 East Scotland. It is noted that some of the comparisons are based on a small number of data points, and are therefore subject to elevated uncertainty.
    - It is considered that the height of the measurements may also have an impact on the comparison between the index IAV and measurement IAV. This may account for some of the differences observed in the comparisons, although it has not been possible to identify a clear relationship.
    - Comparisons between production data also indicate good agreement overall, with a tendency for the wind speed indices to predict higher IAV. However, it is noted that there is elevated uncertainty in these comparisons due to the conversion of the wind speed indices to be representative of production in conjunction with other high level assumptions and adjustments made.
- In order to robustly define IAV, it is desirable to have long datasets (30 years). The IAV derived from the regional MERRA-2 indices is based on 20 years; there is evidence to suggest that the IAV derived from the regional MERRA-2 indices is sensitive to the period used based on comparisons with MERRA-2 data over the period 1980 to 2015. However, it is noted that consideration of longer periods may introduce consistency changes, which may have an impact on the derived IAV. Despite the potential introduction of inconsistencies, DNV GL considers there is benefit in utilising as long a dataset as possible to derive IAV.
- DNV GL considers that it would be appropriate to adjust the IAV predicted by the 20 year indices to account for a longer historical period and to cover the uncertainty in this validation.

- The results indicate that there is strong evidence to move away from the industry standard IAV of 6% to lower IAV values for the UK offshore regions that have been considered in this study. Based on the results of this study, an IAV range of 4% to 5.5% is considered more appropriate. This range has been considered for the purpose of the uncertainty and LCoE assessment in comparison to a base case IAV of 6% as described in Section 5.

5 PHASE 3 – RISKS AND OPPORTUNITIES

5.1 Uncertainty scenarios

As discussed in Section 2.1, DNV GL has identified four key areas of uncertainty within a formal energy production assessment that can be reduced or better quantified using the derived wind speed indices and IAV assessment in this study:

- Correlation uncertainty;
- Representativeness of long-term period;
- Consistency of reference source;
- Future period under consideration.

Lower project uncertainties lead to better financing conditions and hence a reduction LCoE.

In order to assess the opportunities that each workstream can offer in terms of EPA uncertainty reduction, DNV GL has defined a number of scenarios that consider different sources of long-term reference data and a range of IAV assumptions. A base case scenario, considering the use of a nearby meteorological station and an IAV of 6.0%, has been set to represent the current industry standard. The relevance of this scenario is discussed further in Section 5.4.3. Scenarios 1 and 2 represent the use of MERRA-2 data, either as regional wind speed indices or the selected nearest grid cell, over a range of IAV assumptions from 4.0% to 5.5%. The selection of these scenarios is driven by the results found in Phase 2 of this study, which showed that it is possible to obtain higher quality correlations with the nearest MERRA-2 grid cell.

Table 5-1 Uncertainty scenarios

Scenario	Long-term reference	IAV case
Scenario 0 – Base case	*Nearby meteorological station*	*A. 6.0%*
Scenario 1	MERRA-2 regional wind speed index	B. 5.5% C. 5.0% D. 4.5% E. 4.0%
Scenario 2	Nearest MERRA-2 grid cell	B. 5.5% C. 5.0% D. 4.5% E. 4.0%

In Section 5.2, DNV GL estimates the overall uncertainties under each scenario for a "typical project". A typical project has been defined as having:

- Single, on-site, hub height mast that is compliant with best-practice recommendations for instrument mounting;
- Two years of on-site measurements;
- Wind speed to energy sensitivity ratio of 1.3. Based on DNV GL experience, this is considered representative given current wind turbine technology and anticipated wind resource of UK offshore projects;

- 500 MW project;
- Uncertainties for typical loss factors;
- Future period of 10 years. Whilst loan terms tend to be longer, 10 years represents an industry standard for pre-construction energy assessments.

In Section 5.3, DNV GL estimates the impact of the uncertainty reduction under each scenario on the Levelised Cost of Energy (LCoE).

5.2 Uncertainty assessment

5.2.1 Methodology

The uncertainty associated with the projected energy production of a wind farm is commonly characterised by the P90/P50 ratio. The P50 corresponds to the central – or median – estimate of the predicted long-term energy production of the project. This represents a 50% chance that the actual energy yield will be greater than this value and 50% chance that the actual energy yield will be less than this value over the projected period. To a first approximation, the P50 value is insensitive to the magnitude of the project uncertainties.

The P90, conversely, captures the uncertainty in the prediction. The P90 represents a 90% chance that the average actual energy yield of the project will exceed this value over the projected period. The P90 value is commonly used within the lending community to quantify the uncertainty associated with the projected wind farm energy production, and inform commercial decisions accordingly. The P90/P50 ratio therefore quantifies the level of uncertainty in an energy prediction.

As described in Section 5.2.5, project uncertainty is dependent on the projection period i.e. due to inter-annual variability (in both wind speed and other quantities such as system availability) a 1-year projection is more uncertain than a 10-year projection. The 10-year P90 and the 10-year P90/P50 ratios are common metrics within the industry.

DNV GL has undertaken an indicative uncertainty analysis to derive the 10-year P90/P50 ratio of a typical UK offshore project.

For offshore wind farms currently in development, DNV GL would typically expect to see a 10-year P90/P50 ratio of the order of 88% to 92%, where the higher value represents projects with less uncertainty in the energy prediction.

It should be noted that in addition to the indicative assessment of uncertainty, a review of technical risks of a project are also important considerations. These issues are not included in this scope of work and therefore are not considered in this report.

As part of a detailed uncertainty analysis of a formal wind resource and energy production assessment report, a number of uncertainty categories are considered and defined as either a wind speed uncertainty or an energy uncertainty. A breakdown of the uncertainties typically considered as part of a detailed uncertainty analysis is given in Appendix B.

Wind speed uncertainties are converted to energy uncertainties using the wind speed to energy sensitivity calculated for the project and the resulting energy uncertainties are combined to give the total uncertainty in the energy prediction of the wind farm. Various methodologies are available for combining uncertainties; for the purpose of this indicative uncertainty analysis, the energy uncertainties considered have been summed as independent Gaussian errors (on a root-sum-square basis) to give the total indicative uncertainty in the projected energy output for a typical UK offshore project.

The resulting combined uncertainties are considered to represent the standard deviation of what is assumed to be a Gaussian process; the P90 is calculated from this assumed distribution. This process has been undertaken for each scenario under investigation and the resulting indicative P90/P50 ratios have been calculated and compared to the Base Case to calculate relative differences or 'Delta P90/P50' values, as presented in Table 5-2 and Table 5-3 to allow for a comparative analysis between scenarios.

Further discussion of the four key uncertainties identified as relevant to this study in Section 5.1 is presented in the following sections, along with details of how they have been defined. It is noted that for the remaining uncertainty categories listed in Appendix B, DNV GL has made appropriate, experience-based assumptions that sum to give an overall project uncertainty that is consistent with DNV GL expectations. To enable comparison, these uncertainties have been kept constant across all scenarios under investigation.

5.2.2 Correlation uncertainty

The uncertainty in the relationships used to describe the wind conditions between the site measurements and the reference data is typically based on the quality of the correlations and the amount of data synthesised.

The quality of the correlations can be assessed empirically using the amount of scatter in the correlation. DNV GL uses a boot strapping approach to define the amount of scatter by randomly selecting half the data points from the correlation and predicting the remaining data points. This process is repeated many times and the resulting errors in each prediction are used to estimate the correlation uncertainty. The resulting uncertainty is factored by the proportion of data that it is used to synthesise.

Under each scenario, DNV GL has assessed the average correlation uncertainty for each reference source. To do this, DNV GL has assessed the uncertainties in the correlations between the reference sources to each of the offshore mast/Lidar datasets. Since the uncertainty in the correlation is driven by the amount of scatter and the number of points, DNV GL has defined an empirical relationship between the period of data in the correlation and calculated uncertainty. This relationship has been used to estimate the average correlation uncertainty for each scenario for a 2 year correlation. Whilst it is acknowledged that there are different methodologies for undertaking this assessment, DNV GL considers that the results are in line with expectations.

The final correlation uncertainty for each scenario is presented in Table 5-2.

5.2.3 Representativeness of period of data

Since wind variability is assumed to be normally distributed, 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:

$$Historical\ period\ uncertainty = \frac{IAV}{\sqrt{N}} \quad (2)$$

The result is that the uncertainty in the prediction of the long-term mean wind speed reduces as more data are used to define the estimate. This method assumes that each annual mean wind speed is statistically independent. For the purpose of this comparison, DNV GL has assumed that the historical period obtained using a nearby meteorological station under the base case scenario is 10 years. For Scenarios 1 and 2, DNV GL has assumed that the historical period is 20 years.

The assumed historical period uncertainty for each scenario is presented in Table 5-2.

5.2.4 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.

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. A typical range is given below:

- Wind speed prediction supported by multiple, independent sources of reference data ≈1.0%.
- Single source of reference data, not possible to obtain verification of long-term wind speed prediction ≈3.0%.

As stated in Section 4.2.2, DNV GL has been able to gain confidence in the temporal consistency of the MERRA-2 dataset and regional MERRA-2 wind speed indices. As a result, DNV GL assumes a consistency uncertainty of 1% for Scenarios 1 and 2. For the base case scenario, DNV GL has also assumed a consistency uncertainty of 1%. This is due to the fact that it is generally possible to gain confidence in wind speed predictions from meteorological stations in the UK due to the coverage of the station network.

These values are factored by the proportion of historical data that has been synthesised and the final uncertainties are presented in Table 5-2.

5.2.5 Future period under consideration

The IAV accounts for the uncertainty on the one-year wind speed prediction. On longer time scales, there is some related uncertainty associated with whether or not the true long-term 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. As for the historical period uncertainty, the future period uncertainty is estimated by dividing the inter-annual variability by the square root of the number of years under consideration for the future period:

$$Future\ period\ uncertainty = \frac{IAV}{\sqrt{N}} \quad (3)$$

For the purpose of this comparison, DNV GL has assumed that the future period under consideration is 10 years, which is a typical assumption for UK offshore wind projects.

5.2.6 Impact of Workstream A

The four key areas of uncertainty have been assessed for each scenario for the “typical project” and are presented in Table 5-2 below for IAV case A (6.0%). Where uncertainties are weighted by data proportions, the resulting uncertainties are given in *italics*.

These uncertainties have been combined with the remaining fixed uncertainties for the “typical project” and used to define P90/P50 ratios assuming a normal distribution. It is seen that there is an improvement in the P90/P50 ratio for both Scenarios 1 and 2 compared to the base case. This results from the reduced correlation and historical period uncertainties. It is further noted that the biggest improvement is seen for Scenario 2. As seen in Section 4.2.1, it is generally possible to obtain higher quality correlations with the nearest MERRA-2 grid cell.

Table 5-2 Key uncertainties and delta P90/P50 ratios for IAV case A (6.0%)

Uncertainty (wind speed)	Scenario 0 Base Case	Scenario 1 MERRA-2 regional wind index	Scenario 2 Nearest MERRA-2 grid cell
Correlation uncertainty *(weighted)*	2.2% *(1.8%)*	1.7% *(1.5%)*	1.4% *(1.3%)*
Reference period (years)	10	20	20
Historical period uncertainty	1.9%	1.3%	1.3%
Consistency uncertainty *(weighted)*	1.0% *(0.8%)*	1.0% *(0.9%)*	1.0% *(0.9%)*
Future period (10 years)	1.9%	1.9%	1.9%
Change in P90/P50 relative to base case	**-**	**+0.4%**	**+0.5%**

5.2.7 Impact of Workstream B

The four key areas of uncertainty presented in Table 5-2 have also been assessed for each IAV case by changing the historical period and future period uncertainties. The resulting impact on the P90/P50 ratios is shown in Table 5-3 for Scenario 1. Values are presented as the change in P90/P50 relative to IAV case A. It is noted that the changes were observed to be very similar for Scenarios 1 and 2.

Table 5-3 Impact of IAV cases

IAV case	Change in P90/P50 compared to IAV case A for Scenario 1
A. 6.0%	-
B. 5.5%	+0.1%
C. 5.0%	+0.3%
D. 4.5%	+0.4%
E. 4.0%	+0.5%

5.3 Impact on LCoE

5.3.1 LCoE

Although precise definitions vary, LCoE is typically defined as the lifetime cost of the project, per unit of energy generated.

For the purpose of this study, LCoE is defined as:

$$LCoE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ energy\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (4)$$

Where:
n = expected lifetime
E_t = energy produced in year t
C_t = costs in year t
r = discount rate

Generation costs include capital expenditure, operational expenses and decommissioning costs incurred by the generator over the lifetime of the project.

In this study, the costs and energy production are discounted to their net present value using a discount rate defined by the weighted average cost of capital (WACC):

$$WACC = \left(\frac{D}{V} \times C_D\right) + \left(\frac{E}{V} \times C_E\right) \quad (5)$$

Where:
D/V = proportion of debt in project
C_D = cost of debt
E/V = proportion of equity in project
C_E = cost of equity

WACC is therefore determined by the capital structure of the project and financing costs. For the purpose of this study, it is assumed that it is the value of WACC that changes with the level of uncertainty in pre-construction energy assessments. The rationale behind this is discussed further in Section 5.3.2.

5.3.2 How does the P90 affect LCoE?

This study considers the impact of changing uncertainties in pre-construction energy assessments on a non-recourse project finance structure. It is assumed that debt capital comes from one or more lenders, with the remaining equity provided by the project/equity investors.

In general, the magnitude of the P90 from a pre-construction energy assessment is used to define the magnitude of the debt offered by the lender(s). The size of the loan is dependent on both the P90 (which indicates project revenue) and the minimum debt service coverage ratio (DSCR) set by the lender, to ensure a certain relationship between the cash flow available and the required loan payment. In general, a larger P90 results in a larger debt. Therefore the value of the P90 has a direct impact on the relative proportion of debt to equity, commonly referred to as "gearing", for a project.

Furthermore, the cost of debt is typically cheaper than the cost of equity. This is due to the different levels of risk faced by lenders and equity investors. Additionally, interest payments on loans are not subject to tax. Therefore, a larger proportion of debt results in a higher project value.

The combination of the above points results in a reduced WACC for projects with higher P90. The change in WACC has therefore been assessed to determine the impact of changing project uncertainties on LCoE. The modelling approach used in this study is summarised in Section 5.3.3 below.

5.3.3 Modelling approach

LCoE model

TCE has developed a simple LCoE model as part of the Offshore Wind Cost Reduction Pathways Study /11/. This has been used as the basis for the LCoE calculation. The tool uses a value of WACC as the discount rate.

For the purpose of this study, TCE has supplied DNV GL with assumptions for a project reaching Financial Investment Decision (FID) in 2020 /12/. These are summarised in Table 5-4 below and are representative for site type "B" as defined in /11/.

Table 5-4 Project assumptions (FID 2020)

Project assumptions[1]	
Capacity	500 MW
Capacity factor	46.9%
Project lifetime	25 years
CAPEX	£2,510[2]
OPEX	£140[2,3]
Decommissioning costs	£334[2]

Notes: 1. Site type "B" (depth = 35 m, distance to O&M port = 40 km, average wind speed = 9.4 m/s)
2. In £000s/MW
3. Per year

The above assumptions combine to yield an LCoE target of £100/MWh for projects reaching FID in 2020. To enable comparison of changing uncertainty levels, this has been assumed to represent *Scenario 0 – Base case* as defined in Section 5.1. The value of WACC has then been adjusted to assess the impact of the reduced uncertainty scenarios.

Debt sizing model

DNV GL has used an in-house debt sizing model to determine the change in WACC, or "delta-WACC", for each uncertainty scenario. The level of debt has been determined based on assumptions for the energy price, loan term, minimum DSCR, and interest rate given in Table 5-5 below. These assumptions were made in agreement with TCE. The cost of equity has been assumed to be constant, at 10%, for each uncertainty scenario.

Table 5-5 Financial assumptions (FID 2020)

Financial assumptions	
Energy price	£105/MWh[1]
Loan term	12 years
Minimum DSCR	1.3
Loan interest rate	4%
Cost of equity	10%
P90	As per each uncertainty scenario

Notes: 1. See reference /13/

Equation (5) in Section 5.3.1 has been used to define WACC for each scenario, and subsequently delta-WACC has been calculated.

It is noted that the derivation of WACC is highly sensitive to the financial model and assumptions used. DNV GL has therefore used delta-WACC approach in this study in order to enable the results to be applied in the LCoE model /12/ and assessed against the £100/MWh base case.

5.3.4 Results

The change in LCoE has been assessed for each uncertainty scenario and is presented in Figure 5-1.

The largest change in LCoE results from Scenario 2 IAV case E (nearest MERRA-2 grid cell and IAV of 4.0%). For this scenario, the change in 10-year P90/P50 was approximately 0.9% compared to the base case, resulting in a 0.7% reduction in LCoE.

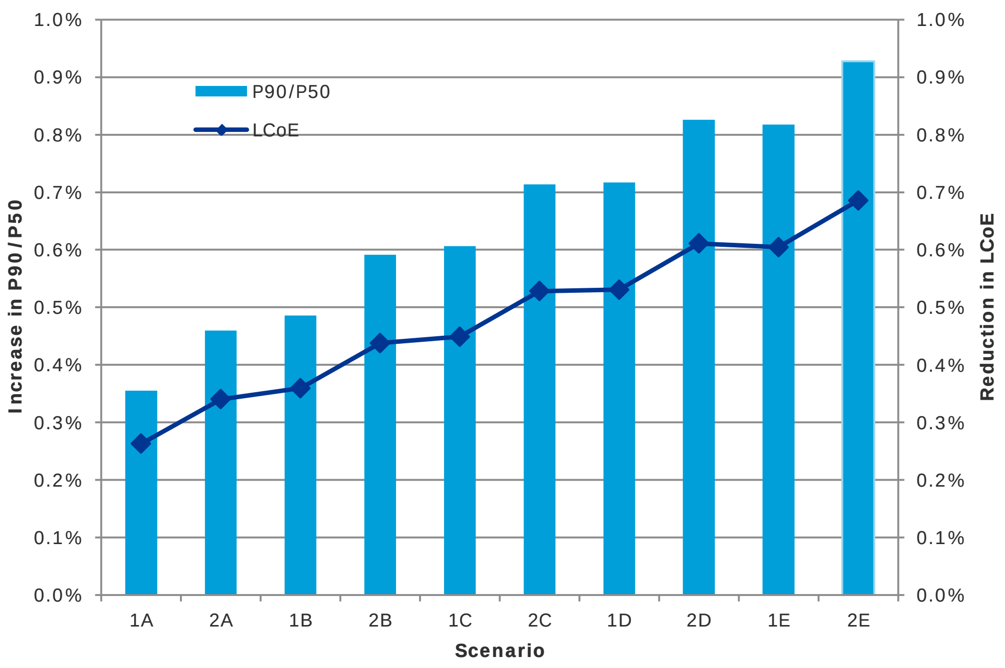
The smallest impact on LCoE is seen for Scenario 1 IAV case A (regional MERRA-2 index and an unchanged IAV of 6%). For this scenario, the change in P90/P50 was approximately 0.4%, resulting in a 0.3% reduction in LCoE.

Scenarios 1A and 1B in Figure 5-1 demonstrate the isolated impact of Workstream A on the LCoE estimate, with reductions close to 0.3% in each case.

The isolated impact of Workstream B can be assessed by comparing each IAV case in Figure 5-1 for the two scenarios. For example, the maximum impact is seen by comparing IAV case E to IAV case A, with an estimate LCoE reduction of approximately 0.3%.

It is noted that DNV GL has not undertaken detailed financial modelling for this study and there is significant uncertainty associated with the estimation of the reduction of LCoE for each of the scenarios and IAV cases. A number of high level assumptions have been made regarding the characteristics of a project and the inputs to the models used to calculate debt sizing, delta-WACC and LCoE. However, it is considered that the results presented here provide an illustration of the potential benefit of the products designed in this study.

Figure 5-1 Change in 10-year P90/P50 and LCoE compared to base case scenario



5.4 Technical and commercial risks

Throughout this study, and through discussions with the Technical Steering Committee (TSC), DNV GL has identified a number of key technical and commercial risks associated with the results presented in this report. These are summarised in Table 5-6 and the following sections, along with suggestions for appropriate mitigation measures.

Table 5-6 Summary of technical and commercial risks

Potential risk	Mitigation measures
MERRA-2 related risks	
Future discontinuation of MERRA-2	Consider the use multiple sources of reference data to inform long-term mean wind speed or IAV assessment. It is noted that this risk is present for any dataset that is subject to discontinuation or changes in the future.
Industry acceptance of MERRA-2 consistent period (1996 to present)	Form stronger consensus through presentation of the results of this work and engagement with key industry working groups.
Industry acceptance of defined assessment zones for regional wind speed indices	Form consensus through presentation of the results of this work and engagement with key industry working groups. Strengthen regional validation through consideration of additional measurements.
Convenience of regional wind speed indices versus MERRA-2	Present regional wind speed indices as a tool for a convenient "first check" for long-term correlations under Workstream A. Highlight benefits of using regional wind speed indices to define IAV under Workstream B.
Limitations of validation	
Small number of validation points in some assessment zones	Include additional datasets in validation (e.g. additional "raw" measurements not considered in this study).
"Industry accepted" definition of a year for IAV	Further investigation and industry engagement to define methodology.
Impact of height on IAV	Further investigations using long-term measurements at a range of heights where available.
Impact of correlation offset on IAV	Further investigations to establish whether and how this observation is accounted for in the definition of IAV.
Industry assumption of annual mean wind speed independence	Further investigations to establish whether this is an appropriate assumption.
Limited geographical extent of study to UK offshore	Extend scope to include other offshore markets.
LCoE modelling	
High uncertainty in assumptions used for LCoE modelling	Commission a detailed study into financing arrangements for typical offshore projects.
Representativeness of base-case scenario under Workstream A	Reduction in LCoE resulting from Workstream A demonstrates the impact of the industry progression that is already taking place.
Industry acceptance	
Wider industry acceptance of results	Mitigation measures already considered in this study: • Regional validation approach; • Establishment of TSC to challenge work.

5.4.1 MERRA-2 related risks

The use of MERRA-2 as the basis of the regional wind speed indices and IAV assessment carries some risks, which are summarised below:

- The MERRA dataset was discontinued in February 2016 and replaced by MERRA-2. There is a possibility that MERRA-2 will also be discontinued and/or replaced by a new dataset at some point in the future. This would affect the ongoing implementation of this work and further studies may be required in future if new datasets become available. This could be mitigated to some extent by using multiple sources of data. However, it is noted that this risk is present for any dataset that may be subject to discontinuation or changes in the future. This risk could also be mitigated by further industry engagement with the developers of these datasets, such as NASA, in order to understand and prepare for future changes.

- The use of the MERRA-2 dataset in this study assumes that it is consistent over the period 1996 to present in the UK offshore environment. This is a result of studies conducted by DNV GL into the consistency of the MERRA dataset /2/ and additional checks on MERRA-2 conducted in this study. However, it is noted that this does not necessarily represent a standard assumption for the UK offshore industry. There is therefore a risk associated with the industry acceptance of the products designed here. This could be mitigated to some extent by forming a stronger consensus through the results of this work and key industry working groups.
- In this study, assessment zones have been defined by DNV GL and MERRA-2 grid cells have been selected accordingly in the derivation of the wind speed indices. There is a risk that the selection of these is disputed by the industry, particularly where projects are located at the edge of the assessment zones. This has been mitigated to some extent during the study through the regional validation and presentation of results to the TSC. This could be mitigated further through the inclusion of additional regional validation data and presentation of the results to the wider industry.
- Under Workstream A, lower uncertainty can be obtained in correlations between site measurements and the nearest MERRA-2 grid cell than with the regional MERRA-2 indices derived in this study. Whilst MERRA-2 data are publically available, large datasets need to be downloaded, processed and stored. DNV GL therefore considers that there is a benefit in deriving regional wind indices that are easily accessible and well validated. However, in discussions with the TSC, the convenience of a finite number of MERRA-2 based indices was not considered to be a significant selling point. As a result, there is a risk that the wind speed indices may not be widely accepted or used by the industry as source of long-term reference data. A potential mitigation measure is to pitch the regional indices as a convenient first check before downloading MERRA-2 data for the specific site. Under Workstream B, DNV GL considers it preferable to define IAV over an area rather than at a point location.

5.4.2 Limitations of validation

In Phase 2 of this study, DNV GL has conducted a number of validation exercises for the regional wind speed indices and assessment of IAV. These have highlighted a number of risks and areas requiring potential further work, as summarised below:

- The impact of the use of the regional wind speed indices and/or MERRA-2 on LCoE has been estimated based on a selection of sites in the UK offshore environment. However, on a site-by-site basis, the benefit seen in Figure 5-1 may be higher or lower.
- There is a small number of validation points in Zone 2b South Coast and Zone 4 East Scotland, and it has not been possible to validate IAV in these regions. Furthermore, the validation points in Zone 3 are largely concentrated in the coastal regions, whilst future developments in this zone are situated further offshore. Therefore, the representativeness of the results in this zone may be limited. This could be mitigated by the inclusion of additional datasets in the validation. In this study, DNV GL has focussed on data that were pre-processed and cleaned. Additional work could be undertaken to include the additional raw datasets to which TCE has access.
- The review of IAV derived from the regional MERRA-2 indices indicates that IAV is sensitive to the definition of a year (e.g. calendar year, July to June etc…). DNV GL considers that further

work and engagement may be required in order to find industry acceptance regarding the method for defining IAV. For example, this may be the use of an average IAV across the years, or the use of the highest IAV to cover the maximum risk. Furthermore, consideration should be given to how this definition aligns with the application of the P90 in a financial model, for example, if the model assumes calendar years then the IAV definition should be aligned with that assumption.

- As highlighted in Section 4.3.2, IAV may be sensitive to the height of interest. The MERRA-2 dataset used in this study represents the 50 m height level. Whilst this is closer to hub height than historical definitions of IAV based on 10 m meteorological stations, there remains a risk that this definition is not fully representative of IAV at a typical offshore hub height. DNV GL considers that there is the potential for further study into this, if long-term measurements at a range of heights were available.

- In Section 4.3.2, it is seen that the offset from a linear regression fit to monthly correlations between the wind speed indices and site measurements has a tendency to be positive. This indicates that the datasets exhibit different variability. DNV GL considers that further investigation would be beneficial to establish whether and how this observation can be accounted for in the definition of IAV. It is also noted that it has not been possible to isolate the impact of the variation of IAV with height from this investigation.

- The use of IAV to define the historical and future period uncertainties described in Sections 5.2.3 and 5.2.5 assumes independence of annual mean wind speeds, which is an industry standard assumption. The risk associated with the validity of this assumption has not been addressed in this study; DNV GL considers that there is a potential for further work into this.

- The validation conducted in this study is limited to the measurements available and the extents of the UK offshore zones considered. Whilst the methodology used could be translated to other offshore wind markets, the results presented in this study are specific to the UK offshore environment.

5.4.3 LCoE modelling

In Phase 3 of this study, DNV GL has assessed the benefit of workstreams A and B on LCoE relative to a base case scenario. A number of risks have been highlighted during this process:

- DNV GL has not undertaken detailed financial modelling for this study and there is significant uncertainty associated with the estimation of the reduction of LCoE for each of the scenarios and IAV cases. A number of high level assumptions have been made regarding the characteristics of a project and the inputs to the models used to calculate debt sizing, delta-WACC and LCoE. This could be mitigated by commissioning a detailed study into financing arrangements for typical offshore projects.

- The changes in LCoE presented in Section 5.3 are relative to a base case that assumes the use of a nearby meteorological station as a source of long-term reference data. DNV GL considers that this may not be representative of current industry practice, as there already appears to have been a shift towards the use of reanalysis and mesoscale model data for long-term wind speed investigations. As a result, there is a risk that the reduction in LCoE is smaller than estimated in Section 5.3. To assess this, DNV GL has isolated the impact of Workstream B and finds that the change in the assumed IAV from 6% to 4%, when assuming the same source of long-term reference, reduces the LCoE by approximately 0.3%. However, it is considered that reduction in LCoE resulting from Workstream A demonstrates the impact of the industry progression that is already taking place.

- This study has also highlighted a potential disconnect between the period used for the P90 definition, typically 10 years, and the period of the loan term, typically 12 to 15 years. It is considered there is scope for further review into how P90 estimates are utilised by lenders and if and how industry practice should change accordingly.

5.4.4 Industry acceptance

The industry acceptance of the results of this study is paramount in order for the products to be implemented; there is a risk that industry consensus cannot be built and therefore the work cannot be utilised. Several risks associated with industry acceptance have been highlighted in the preceding sections. Through this study, DNV GL and TCE have already taken a number of measures to help mitigate these risks:

- Establishment of the Technical Steering Committee (TSC) to challenge the work from a technical perspective, ensuring it is in line with industry expectations and to build industry consensus on if and how the work should be implemented and utilised.
- Regional validation has been conducted using a small number of assessment zones and offshore specific datasets.

There are a number of potential options for engaging the offshore wind industry further, which are discussed in Section 6.

5.5 Phase 3 summary

Following a review of the risks and opportunities posed by the different workstreams, the following conclusions are drawn.

Workstream A (wind speed index for the UK offshore environment):

- The regional MERRA-2 wind speed indices have the potential to reduce uncertainties in pre-construction energy assessments compared to the use of a nearby meteorological station as a source of long-term reference data. The potential impact of this on LCoE is estimated to be an indicative reduction of approximately 0.3% compared to the base case scenario. However, it has been demonstrated that uncertainties can be reduced further by using the nearest MERRA-2 grid cell as the long-term reference source. It is noted that DNV GL has not conducted detailed financial modelling as part of this study.
- The “convenience” of having a small number of validated regional MERRA-2 indices is not considered to be a key selling point by the Technical Steering Committee (TSC) under Workstream A. However, the regional indices could be utilised as a product for conducting high level windiness checks as part of initial feasibility studies. Furthermore, DNV GL considers that the regional indices may be an appropriate tool for defining regional IAV under Workstream B.
- There are a number of risks associated with the use of MERRA-2 data in the regional wind speed indices, including the potential discontinuation of the data in the future. Furthermore, the industry acceptance of the consistent period of January 1996 to present poses a risk for the implementation of this work, which could be mitigated by further industry engagement.
- It is considered that the selection of the base case scenario, assuming the use of a nearby meteorological station, may not be representative of current industry practice. There already

appears to have been a shift towards the use of reanalysis and mesoscale model data. However, the reduction in LCoE resulting from Workstream A is considered to demonstrate the impact of the industry progression that is already taking place.

Workstream B (Inter-Annual Variability specific to the UK offshore environment):

- The reduction in the assumed IAV from the current industry standard assumption of 6% to 4% has the potential to reduce LCoE by up to an estimated 0.3%. When combined with the impact of using the nearest MERRA-2 grid cell as a long-term reference source in Workstream A, the overall reduction in LCoE is estimated to be up to 0.7%. It is noted that DNV GL has not conducted detailed financial modelling as part of this study.
- There are a number of risks associated with the implementation of a reduced IAV, which result from limitations in the validation conducted here. These include limitations in the number of validation points, particularly in Zone 2b South Coast and Zone 4 East Scotland, which could be mitigated through the inclusion of more datasets in the study. Furthermore, the study has highlighted various technical aspects relating to the definition of IAV that could be investigated further across the wider global wind energy industry. For example the definition of a year, the impact of height on the assumed value and the method used to adjust IAV to represent longer periods.

6 CONCLUSIONS

In this study, DNV GL has identified, assessed and tested options for deriving two potential industry "products":

- A robust definitive wind speed index for UK offshore wind (Workstream A); and,
- A new characterisation of Inter-Annual Variability (IAV) in wind speed that is specific to the UK offshore wind climate (Workstream B).

The aim of the study is to assess the feasibility of a reduction in Levelised Cost of Energy (LCoE) for future offshore wind projects by improving financing conditions through the provision of an improved characterisation of the long-term UK wind resource.

The key conclusions from this study are summarised as follows:

Workstream A: wind speed index for the UK offshore environment

1. It is possible to obtain robust correlations between the regional MERRA-2 wind speed indices and site measurements. However, it is noted that higher quality correlations can generally be obtained using the nearest MERRA-2 grid cell.
2. The regional MERRA-2 wind speed indices are considered to exhibit temporal consistency over the period January 1996 to December 2015, with similar long-term trends as measurement based indices.
3. Across the offshore mast/Lidar locations, the regional MERRA-2 wind speed indices yield similar long-term wind speed predictions when compared to the nearest MERRA-2 grid cell and regional measurement based wind speed indices. However, it is noted that level of agreement varies by location. As part of any formal wind resource and energy production assessment, DNV GL generally recommends that multiple sources of long-term reference data are considered in the derivation of the long-term wind speed to gain confidence in the final wind speed adjustment.
4. The regional MERRA-2 wind speed indices have the potential to reduce uncertainties in pre-construction energy assessments compared to the use of a nearby meteorological station as a source of long-term reference data. The potential impact of this on LCoE is estimated to be an indicative reduction of approximately 0.3% compared to the base case scenario. However, it has been demonstrated that uncertainties can be reduced further by using the nearest MERRA-2 grid cell as the long-term reference source. It is noted that DNV GL has not conducted detailed financial modelling as part of this study.
5. The "convenience" of having a small number of validated regional MERRA-2 indices is not considered to be a key selling point by the Technical Steering Committee (TSC). However, the regional indices could be utilised as a product for conducting high level windiness checks as part of initial feasibility studies. Furthermore, DNV GL considers that the regional indices may be an appropriate tool for defining regional IAV under Workstream B as discussed below.
6. There are a number of risks associated with the use of MERRA-2 data in the regional wind speed indices, including the potential discontinuation of the data in the future. Furthermore the industry acceptance of the consistent period of January 1996 to present poses a risk for the implementation of this work, which could be mitigated by further industry engagement.
7. It is considered that the selection of the base case scenario, assuming the use of a nearby meteorological station, may not be representative of current industry practice. There already

appears to have been a shift towards the use of reanalysis and mesoscale model data. However, the reduction in LCoE resulting from Workstream A is considered to demonstrate the impact of the industry progression that is already taking place.

The results of this work demonstrate that there is not a strong argument for deriving regional wind speed indices for use as a long-term reference source in the UK offshore environment. This is due to the availability of reanalysis datasets, which provide full spatial coverage, high quality correlations, long-term consistent data in the region and lower overall uncertainties, as demonstrated for the MERRA-2 dataset in this study. Furthermore, it is acknowledged that whilst the use of MERRA-2 has been shown to have a positive impact on LCoE compared to the use of a nearby meteorological station, this is considered representative of the progression that the industry has already made in recent years.

Workstream B: Inter-Annual Variability specific to the UK offshore environment

1. There is good agreement between the IAV derived from the regional MERRA-2 wind speed indices and measured IAV:

    a. Comparisons between wind speed measurements indicate good agreement overall, with a tendency for the IAV derived from the indices to be lower in Zone 1 Irish Sea and higher in Zone 2a English Channel and Zone 3 North Sea. It has not been possible to validate IAV predictions in Zone 2b South Coast and Zone 4 East Scotland. It is noted that some of the comparisons are based on a small number of data points, and are therefore subject to elevated uncertainty.

    b. It is considered that the height of the measurements may also have an impact on the comparison between the index IAV and measurement IAV. This may account for some of the differences observed in the comparisons, although it has not been possible to identify a clear relationship.

    c. Comparisons between production data also indicate good agreement overall, with a tendency for the wind speed indices to predict higher IAV. However, it is noted that there is elevated uncertainty in these comparisons due to the conversion of the wind speed indices to be representative of production in conjunction with other high level assumptions and adjustments made.

2. In order to robustly define IAV, it is desirable to have long datasets (30 years). The IAV derived from the regional MERRA-2 indices is based on 20 years; there is evidence to suggest that the IAV derived from the regional MERRA-2 indices is sensitive to the period used based on comparisons with MERRA-2 data over the period 1980 to 2015.

3. DNV GL considers that it would be appropriate to adjust the IAV predicted by the 20 year indices to account for a longer historical period and to cover the uncertainty in this validation.

4. The results indicate that there is strong evidence to move away from the industry standard IAV of 6% to lower IAV values for the UK offshore regions that have been considered in this study. Based on the results of this study, an IAV range of 4% to 5.5% is considered more appropriate. This range has been considered for the purpose of the uncertainty and LCoE assessment in comparison to a base case IAV of 6%.

5. The reduction in the assumed IAV from the current industry standard assumption of 6% to 4% has the potential to reduce LCoE by up to an estimated 0.3%. When combined with the impact of using the nearest MERRA-2 grid cell as a long-term reference source in Workstream A, the

overall reduction in LCoE is estimated to be up to 0.7%. It is noted that DNV GL has not conducted detailed financial modelling as part of this study.

6. There are a number of risks associated with the implementation of a reduced IAV, which result from limitations in the validation conducted here. These include limitations in the number of validation points, particularly in Zone 2b South Coast and Zone 4 East Scotland, which could be mitigated through the inclusion of more datasets in the study. Furthermore, the study has highlighted various technical aspects relating to the definition of IAV that could be investigated further across the wider global wind energy industry. For example the definition of a year, the impact of height on the assumed value and the method used to adjust IAV to represent longer periods.

The results of this work demonstrate that there is strong evidence for moving away from the current industry standard assumption of 6% IAV in the UK offshore environment. A range of 4% to 5.5% is considered more appropriate. This study has shown that a reduction in the assumed IAV can have a positive impact on the LCoE of offshore wind.

Whilst this work has also identified areas of potential further study, these are considered applicable to the wider, global wind industry and not specific to the UK offshore environment. DNV GL therefore considers the work reported here to be sufficient to form the basis of discussions within the wind industry to change current industry practice and move away from the current industry assumption of 6% for IAV for the UK offshore environment.

7 CONSIDERATIONS

DNV GL has identified a number of areas of potential further work that could be conducted in the future to refine the assessment of IAV, both in the UK offshore environment and across the global wind energy industry as a whole.

In this study, the validation of IAV has been conducted using offshore measurements provided by The Crown Estate and other publically available sources of data across the UK offshore environment. Furthermore, this study has focussed on the impact of changing IAV assumptions on pre-construction energy assessments only. It is considered that the study could be extended to include further measurements in the UK offshore environment, if available, and to assess the impact of IAV on operational energy assessments.

The results of the study have also highlighted a number of technical considerations that would serve to refine the definition and assessment of IAV across the wider, global wind energy industry. These include the definition of a “year”, the impact of height on IAV, and the method used to adjust IAV to represent longer periods.

Table 7-1 provides a summary of the key areas for potential further work identified by DNV GL.

It is noted that, whilst more work could be done in the future, the results presented in this report are considered to provide sufficient evidence to form the basis of discussions within the wind industry to revise current industry standard assumptions of IAV for the UK offshore environment.

Table 7-1 Potential further work

Further work	Summary
Additional validation of IAV	*Increase the number and period of measured datasets used in the validation of IAV, particularly in Zone 2b South Coast, Zone 4 East Scotland and the far-shore areas of Zone 3.* Consideration of additional raw datasets, confidential datasets, or periods of data that have become available since this study was initiated. It is acknowledged that it may not be possible to obtain further data in these zones. The geographical scope of the study could be extended to other offshore areas where data are available (e.g. in German, Danish and Dutch waters) to further assess the representativeness of IAV derived from regional MERRA-2 indices close to the UK offshore environment.
Extension of scope to cover operational assessments	*Repeat the LCoE study to estimate the impact of the reduced uncertainties on operational offshore wind farm assessments.* Consideration of uncertainties in operational assessments and the impact that changing wind speed IAV can have on refinancing/repowering. Furthermore, extend the scope to consider other sources of inter-annual variability in production, such as energy loss factors.
Review of definition of IAV	*Undertake further investigations to define a "standard" approach for calculating IAV.* Technical considerations include: • The definition of a "year"; • Adjustments to IAV to be representative of a longer period (30+ years); • Potential adjustments to IAV using the offset from a linear regression fit to a correlation with measurements. • Adjustments to account for the uncertainty in IAV definition.
Review of impact of height on IAV	*Undertake further investigations into the representativeness of the regional index IAV of IAV at typical offshore hub heights.* Assessment of IAV derived from measurements at different heights, where available.
Review of industry assumption of annual mean wind speed independence	*Undertake a review of the method used to adjust IAV to longer periods.* The use of IAV to define the historical and future period uncertainties assumes independence of annual mean wind speeds. This assumption has not been tested as part of this study; extend the scope to assess any autocorrelation in the datasets and whether this assumption is valid.

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APPENDIX A
Regional wind speed indices

Table A-1 MERRA-2 index for Zone 1 Irish Sea

Month	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	1.36	0.81	1.17	1.29	1.19	1.02	1.28	1.29	1.24	1.54	0.99	1.56	1.38	1.15	1.01	0.93	1.31	1.15	1.25	1.46
Feb	1.11	1.59	1.31	1.29	1.45	0.95	1.53	1.10	1.07	1.12	1.01	0.99	1.19	0.90	0.74	1.14	1.04	1.01	1.49	1.05
Mar	0.98	1.10	1.02	1.07	1.02	0.96	1.08	0.92	1.08	1.01	1.11	1.17	1.30	1.09	0.88	0.70	0.82	1.03	1.07	1.16
Apr	0.91	0.81	0.95	0.97	0.84	0.92	0.93	0.91	0.94	1.04	0.95	0.80	0.93	0.84	0.75	0.86	0.92	1.08	0.86	0.79
May	0.88	0.78	0.80	0.94	0.81	0.73	1.04	1.04	0.63	0.96	0.92	0.87	0.84	1.09	0.68	1.23	0.75	1.01	0.82	1.06
Jun	0.81	0.92	0.95	0.75	0.83	0.84	1.01	0.83	0.92	0.78	0.70	0.77	0.87	0.73	0.64	0.80	0.87	0.77	0.65	0.85
Jul	0.78	0.70	0.96	0.82	0.67	0.80	0.73	0.88	0.78	0.75	0.71	0.87	0.94	0.92	0.93	0.66	0.76	0.61	0.68	0.92
Aug	0.76	0.77	0.94	0.80	0.69	0.71	0.67	0.68	0.81	0.84	0.89	0.87	0.91	1.05	0.85	0.76	0.84	0.84	1.01	0.84
Sep	0.90	0.98	0.93	0.90	0.89	1.02	0.64	0.72	1.17	0.99	0.95	0.96	0.88	0.92	1.00	1.16	1.07	0.92	0.60	0.79
Oct	1.27	0.93	1.32	1.14	1.21	1.24	1.04	1.05	1.08	1.06	1.07	0.78	1.27	0.96	1.04	1.22	0.91	1.20	1.20	0.81
Nov	1.22	1.04	1.15	1.19	1.27	1.07	1.11	1.15	1.04	1.08	1.33	1.12	1.18	1.36	1.13	1.22	1.06	1.04	1.00	1.35
Dec	1.06	1.24	1.24	1.43	1.24	1.09	1.11	1.08	1.18	1.02	1.29	1.26	1.00	1.03	0.80	1.49	1.20	1.49	1.30	1.55
Annual	1.00	0.97	1.06	1.05	1.01	0.94	1.01	0.97	0.99	1.02	0.99	1.00	1.06	1.01	0.87	1.01	0.96	1.01	0.99	1.05

Table A-2 MERRA-2 index for Zone 2a English Channel

Month	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	1.15	0.86	1.37	1.31	1.19	1.09	1.23	1.27	1.30	1.44	1.01	1.53	1.48	1.07	0.95	1.08	1.22	1.04	1.34	1.32
Feb	1.18	1.47	1.12	1.21	1.29	1.01	1.56	1.01	1.20	1.13	1.07	1.04	1.05	0.91	1.04	1.16	1.04	1.06	1.51	1.04
Mar	0.93	0.94	1.12	0.87	1.06	1.01	1.01	0.88	1.02	1.00	1.13	1.12	1.32	0.98	1.00	0.82	0.76	1.06	0.93	1.11
Apr	0.81	0.85	0.95	0.92	0.91	1.05	1.00	0.98	0.82	0.85	0.91	0.83	0.93	0.76	0.81	0.85	0.96	1.00	0.83	0.81
May	1.02	0.84	0.84	0.93	0.90	0.91	1.01	0.90	0.67	0.96	0.99	0.94	0.95	0.97	0.77	0.94	0.88	0.95	0.81	0.96
Jun	0.75	0.93	0.97	0.78	0.83	0.83	0.84	0.75	0.86	0.79	0.69	0.83	0.78	0.68	0.73	0.90	1.02	0.92	0.63	0.88
Jul	0.77	0.72	0.91	0.85	0.74	0.78	0.84	0.81	0.74	0.78	0.74	0.97	0.86	0.93	0.71	0.84	0.80	0.68	0.80	0.91
Aug	0.86	0.74	0.85	0.75	0.67	0.80	0.62	0.69	0.90	0.79	0.88	0.86	1.02	0.83	0.96	0.82	0.83	0.76	0.94	0.86
Sep	1.00	0.85	0.99	0.93	0.95	1.06	0.82	0.69	1.12	0.81	0.89	0.98	0.94	0.95	0.92	1.03	0.97	0.87	0.64	0.92
Oct	1.08	1.02	1.41	1.14	1.25	1.21	1.12	1.12	1.18	1.03	1.13	0.77	1.08	0.98	1.12	1.12	1.02	1.21	1.11	0.88
Nov	1.25	1.08	1.03	1.22	1.32	1.06	1.03	1.08	0.97	1.16	1.31	1.18	1.19	1.38	1.06	1.03	1.11	1.08	0.99	1.42
Dec	1.06	1.28	1.22	1.44	1.32	1.12	1.11	1.12	0.98	1.12	1.26	1.20	1.01	1.15	0.99	1.48	1.27	1.35	1.33	1.51
Annual	0.99	0.96	1.07	1.03	1.04	0.99	1.01	0.94	0.98	0.99	1.00	1.02	1.05	0.97	0.92	1.01	0.99	1.00	0.99	1.05

Table A-3 MERRA-2 index for Zone 2b South Coast

Month	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	1.20	0.96	1.43	1.35	1.07	1.20	1.26	1.35	1.33	1.39	1.07	1.48	1.42	1.11	0.96	1.11	1.22	1.05	1.33	1.32
Feb	1.24	1.45	0.84	1.13	1.23	1.05	1.62	1.04	1.11	1.09	1.10	1.16	1.07	0.86	1.11	1.12	0.91	1.10	1.55	1.07
Mar	0.92	0.86	1.05	0.88	0.98	1.06	1.00	0.99	1.00	0.93	1.24	1.08	1.32	0.95	1.07	0.90	0.77	1.04	0.91	1.07
Apr	0.76	0.79	1.00	1.01	1.02	1.02	1.01	0.97	0.82	0.82	0.91	0.75	0.95	0.71	0.86	0.78	1.03	1.05	0.79	0.86
May	1.09	0.93	0.83	0.90	0.92	0.91	0.99	0.90	0.65	0.95	0.99	1.04	0.84	0.96	0.75	1.01	0.84	0.92	0.86	1.01
Jun	0.68	0.94	1.04	0.80	0.79	0.75	0.85	0.75	0.85	0.79	0.64	0.83	0.79	0.70	0.70	0.99	1.04	0.99	0.62	0.92
Jul	0.85	0.68	0.94	0.81	0.74	0.76	0.81	0.78	0.81	0.81	0.79	1.01	0.94	0.98	0.76	0.74	0.86	0.74	0.75	0.95
Aug	0.79	0.71	0.76	0.76	0.79	0.84	0.61	0.73	0.88	0.72	0.91	0.85	1.02	0.80	0.95	0.81	0.87	0.77	0.92	0.79
Sep	0.95	0.80	1.03	0.93	0.96	1.00	0.85	0.64	1.08	0.78	0.89	0.84	0.99	0.92	0.94	1.05	0.89	0.83	0.69	0.93
Oct	1.09	1.03	1.35	1.10	1.23	1.15	1.07	1.11	1.24	1.03	1.15	0.75	1.06	0.91	1.09	1.09	1.09	1.18	1.07	0.93
Nov	1.24	1.10	1.07	1.21	1.31	1.01	1.14	1.09	0.90	1.08	1.23	0.99	1.17	1.59	1.08	1.04	1.08	1.10	1.04	1.40
Dec	1.09	1.23	1.20	1.46	1.32	1.13	1.19	1.15	0.96	1.06	1.31	1.29	1.02	1.17	1.00	1.42	1.35	1.30	1.27	1.54
Annual	0.99	0.95	1.05	1.03	1.03	0.99	1.03	0.96	0.97	0.95	1.02	1.01	1.05	0.97	0.94	1.00	1.00	1.00	0.98	1.07

Table A-4 MERRA-2 index for Zone 3 North Sea

Month	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	1.34	0.79	1.23	1.27	1.30	0.97	1.22	1.29	1.24	1.57	1.00	1.52	1.43	1.14	1.08	1.04	1.29	1.10	1.26	1.40
Feb	1.17	1.47	1.30	1.32	1.38	1.04	1.45	1.02	1.17	1.19	1.04	1.03	1.14	0.94	0.87	1.16	1.10	1.03	1.45	1.09
Mar	1.03	1.03	1.09	0.95	1.11	0.97	1.04	0.83	1.02	1.07	1.12	1.14	1.34	1.03	0.94	0.78	0.80	1.11	1.07	1.13
Apr	0.82	0.92	0.96	0.90	0.90	0.99	0.90	0.95	0.91	0.93	0.95	0.83	0.93	0.80	0.81	0.87	0.88	0.97	0.90	0.81
May	0.94	0.80	0.82	0.90	0.85	0.72	1.00	0.92	0.74	0.95	0.97	0.85	0.85	0.99	0.69	1.02	0.83	0.96	0.82	0.97
Jun	0.81	0.90	0.90	0.77	0.89	0.87	0.95	0.81	0.86	0.77	0.72	0.75	0.84	0.71	0.67	0.80	0.92	0.76	0.65	0.84
Jul	0.74	0.72	0.92	0.78	0.69	0.79	0.71	0.84	0.76	0.80	0.65	0.88	0.86	0.90	0.83	0.85	0.79	0.63	0.73	0.86
Aug	0.84	0.70	0.90	0.76	0.68	0.77	0.71	0.76	0.88	0.87	0.85	0.87	0.88	0.93	0.88	0.83	0.81	0.80	0.96	0.87
Sep	0.97	0.85	0.95	0.86	0.94	1.12	0.76	0.76	1.13	0.94	0.90	1.05	0.85	0.94	1.03	1.08	1.05	0.91	0.65	0.84
Oct	1.14	0.98	1.41	1.17	1.16	1.22	1.14	1.05	1.14	1.06	1.06	0.76	1.18	1.01	1.10	1.17	0.98	1.27	1.14	0.87
Nov	1.24	1.10	1.05	1.25	1.20	1.10	0.99	1.11	1.05	1.18	1.38	1.24	1.24	1.23	1.13	1.14	1.11	1.07	0.99	1.33
Dec	1.05	1.22	1.23	1.44	1.23	1.08	1.11	1.10	1.11	1.13	1.21	1.13	1.02	1.02	0.92	1.48	1.23	1.46	1.28	1.47
Annual	1.01	0.95	1.06	1.03	1.02	0.97	1.00	0.95	1.00	1.04	0.99	1.01	1.05	0.97	0.91	1.02	0.98	1.01	0.99	1.04

Table A-5 MERRA-2 index for Zone 4 East Scotland

Month	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	1.39	0.80	1.14	1.22	1.37	0.93	1.21	1.34	1.10	1.57	1.04	1.48	1.34	1.23	1.19	1.01	1.29	1.17	1.29	1.53
Feb	1.20	1.53	1.38	1.40	1.41	1.18	1.29	1.10	1.14	1.17	1.05	1.08	1.22	0.97	0.85	1.20	1.19	0.99	1.34	1.21
Mar	1.11	1.17	1.08	1.11	1.07	0.95	1.09	0.88	1.01	1.10	1.12	1.18	1.27	1.13	0.97	0.94	0.97	0.99	1.16	1.14
Apr	0.95	0.93	1.07	0.94	0.87	0.95	0.86	0.81	0.95	1.08	1.04	0.84	0.88	0.87	0.87	0.84	0.89	0.97	0.95	0.81
May	0.89	0.83	0.80	0.84	0.69	0.64	0.89	0.89	0.77	0.89	0.89	0.85	0.75	0.96	0.67	1.07	0.72	0.95	0.73	0.98
Jun	0.92	0.91	0.81	0.83	0.85	0.86	0.97	0.86	0.89	0.75	0.73	0.75	0.87	0.68	0.70	0.71	0.82	0.65	0.63	0.82
Jul	0.74	0.66	0.91	0.71	0.63	0.73	0.64	0.82	0.77	0.75	0.73	0.76	0.87	0.82	0.88	0.75	0.75	0.68	0.67	0.82
Aug	0.78	0.69	0.93	0.79	0.65	0.73	0.69	0.82	0.92	0.87	0.83	0.86	0.84	0.94	0.68	0.81	0.77	0.79	0.91	0.89
Sep	0.89	0.93	0.92	0.90	0.94	0.99	0.70	0.79	1.09	1.05	0.85	1.02	0.85	0.95	1.05	1.05	1.12	0.93	0.72	0.85
Oct	1.24	0.96	1.29	1.14	1.13	1.22	1.09	1.03	1.06	1.11	0.97	0.90	1.34	1.08	1.10	1.26	0.87	1.13	1.14	0.86
Nov	1.12	1.17	1.11	1.23	1.07	1.17	1.20	1.12	1.11	1.20	1.41	1.17	1.17	1.16	1.15	1.21	1.07	1.20	1.04	1.22
Dec	0.98	1.14	1.28	1.38	1.20	1.07	1.01	1.13	1.25	1.13	1.25	1.14	1.15	0.89	0.93	1.46	1.22	1.53	1.28	1.42
Annual	1.02	0.97	1.06	1.04	0.99	0.95	0.97	0.97	1.01	1.06	0.99	1.00	1.04	0.97	0.92	1.02	0.97	1.00	0.99	1.05

APPENDIX B
Typical uncertainty categories

Source of uncertainty / variability	Type of uncertainty
Measurement accuracy	Wind speed
Long-term measurement height wind regime	Wind speed
Vertical extrapolation	Wind speed
Spatial extrapolation	Wind speed
Loss factors (10 year)	Energy
Inter-annual variability	Wind speed and energy
Overall energy uncertainty	Energy

Overview of DNV GL formal uncertainty analysis (for reference)

The uncertainty in the net energy estimates 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.

E-9.1 Wind speed uncertainty

There is uncertainty in the measurement device wind speed estimates due to a variety of factors described below. Uncertainties are estimated as a percentage of the 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-9.1.1 Measurement accuracy

There is an uncertainty associated with the accuracy of the wind speed measurements. This estimate typically includes instrument accuracy, Measurement interference, and consistency of measurement, as described below.

Instrument accuracy

This uncertainty is to account for the calibration accuracy of the instrument and to include an allowance for second order effects such as over-speeding, degradation, air density variations, and additional turbulence effects. An uncertainty of 2.0% on wind speed is typical for anemometers calibrated in a Measnet facility. An uncertainty of 2.5% 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 0.3%.

Measurement interference

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

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 DNV GL's review of the data, information from any site visit, any supplied documentation, and the data recovery percentages.

E-9.1.2 Long-term measurement height wind regime

On-site data synthesis

DNV GL estimates, based on statistical methods, the uncertainty associated with the relationships used to synthesise wind data. The magnitude of this uncertainty is based on the quality of the correlations and the amount of data synthesized.

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.

Correlation to reference station

DNV GL estimates the uncertainty on the relationships used to describe the wind conditions between the site measurements and reference data based on the quality of the correlations and the amount of data synthesised.

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.

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.

Wind frequency distribution - past

The wind frequency distribution varies from year to year such that for a given annual 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, 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 GL estimates this uncertainty as 2% divided by the square root of the number of years of on-site data.

E-9.1.3 Vertical extrapolation

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

E-9.1.4 Spatial extrapolation

This uncertainty represents the uncertainty in the ability to extrapolate from the measurement locations to the wind turbine locations. DNV GL 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, the reliability of the model inputs, variations in ground cover and the complexity of the terrain and wind flow at the site.

E-9.2 Loss factor uncertainty

E-9.2.1 Wakes

The wakes uncertainty is 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% of the overall wake effect.

E-9.2.2 Availability

The project availability is modelled as a Weibull distribution with a standard deviation of 3% for each analysed wind farm year, and is assumed to be independent from year-to-year.

E-9.2.3 Electrical

To acknowledge the uncertainty on this estimate a normal distribution is assumed with a standard deviation of 0.3% to 0.6% depending on the level of review undertaken.

E-9.2.4 Turbine performance

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

E-9.2.5 Environmental

The uncertainty on the overall environmental loss estimate is typically modelled as a normal distribution and is dependent on the level and complexity of the project environmental losses.

E-9.2.6 Curtailment

The uncertainty on the overall curtailment loss estimate is typically modelled as a normal distribution and is dependent on the level and complexity of the project curtailment.

E9.3 Inter-annual variability

E-9.3.1 Wind frequency distribution - future

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

E-9.3.2 Inter-annual variability of the wind

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 the one-year wind speed and is an input in the uncertainty model. DNV GL typically uses data from long-term reference stations as well as knowledge of the region when estimating this value, which typically ranges between 4% and 6%.

On longer time scales, there is some related uncertainty associated with whether or not the true long-term 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 20-year uncertainty can be estimated by dividing the inter-annual variability by the square root of 20.

Year-to-year variations in wind speed result from a variety of phenomena, potentially including climate change. DNV GL 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 isn't agreement among models regarding the direction of any changes.

E-9.3.3 Environmental losses variability

This category represents the year-to-year variability in energy losses due to changes in the amount and severity of icing observed or changes in the temperature leading to variable amounts of temperature shutdown. This value is highly dependent on the site specific conditions and the magnitude of the losses.

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.