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WIND RESOURCE MAPPING IN THE MALDIVES

12 MONTH SITE RESOURCE REPORT

October 2018



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The content of this document is the sole responsibility of the consultant authors. Any improved or validated wind resource data will be incorporated into the [Global Wind Atlas](#).

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WIND RESOURCE ASSESSMENT AND MAPPING IN THE MALDIVES

12-month Site Resource Report

The World Bank

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Wind resource assessment at two Lidar locations in the Maldives, and energy estimates for preliminary wind farms at both locations.

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EXECUTIVE SUMMARY

The World Bank (the “Customer”) retained Garrad Hassan America, Inc. (DNV GL) to complete a 12-month Site Resource Report, which consists of an independent analysis of the wind regime and energy production at two locations in the Maldives, as part of the Wind Resource Assessment and Mapping in the Maldives project. The key results of the work are reported here.

The project is primarily funded by the Energy Sector Management Assistance Program (ESMAP). The original objective of the project was to provide a validated mesoscale wind atlas for the Maldives, including associated datasets. The project aimed to provide policy makers in the Maldives and other stakeholders with accurate and valuable knowledge of the national wind resource, including complementary tools, which can be of direct practical use, both for formulating energy policy and implementing wind projects.

As part of Phase 2 of the project, meteorological data is to be collected at two sites over a 2-year period. The 12-month Site Resource Report provides interim wind resource statistics at the two measurement locations and energy production estimates for wind turbines installed in the vicinity of the measurement locations.

A single Lidar unit was installed and commissioned at each of the two sites in April 2017. Based on a single year of data collection, DNV GL has evaluated the wind resource at each location, the long-term wind regime, and the estimated energy production based on two turbine options:

- The Vergnet GEV MP C 275 kW wind turbine, with a rotor diameter of 32 m and a hub height of 50 m.
- A generic 3 MW wind turbine, with a rotor diameter of 100 m and a hub height of 100 m.

A brief summary of the key results is presented in the table below.

Results	Hoarafushi		Thulusdhoo	
Turbine type	GEV MP C	Generic	GEV MP C	Generic
Turbine rated power [kW]	275	3000	275	3000
Hub height [m]	50	100	50	100
Average air density at hub elevation [kg/m ³]	1.15	1.14	1.15	1.14
On-site measurement period [years]	1.0		1.0	
Long-term reference period [years]	15.3		15.3	
Long-term hub height wind speed at Lidar [m/s]	4.9	5.2	5.5	5.7
Average turbine wind speed [m/s]	5.0	5.2	5.6	5.8
20-year P50 Net Energy [GWh/annum]	0.271	3.77	0.346	4.56
20-year P50 Net Capacity Factor [%]	11.2%	14.3%	14.3%	17.4%



Other key conclusions and recommendations from the analysis are as follows:

- The primary outcome of this study is the establishment of state-of-the-art remote sensing wind measurement systems at two locations in the Maldives. The measurements collected from the Lidar units at both sites are considered good both in terms of data quality and data coverage.
- The long-term wind regime at both sites has been estimated using a combination of MERRA-2 and ERA-Interim reanalysis data. There is increased uncertainty in these estimates due to the lack of ground-based reference data, and the relatively short period of data. This has led to the long-term wind regime uncertainty being a major contributor to the overall uncertainty in the energy prediction.
- The wind regime across both sites has been predicted using WAsP wind flow modelling. The proposed turbine locations are situated approximately 1 km from the Lidar monitoring locations. As a result, the horizontal extrapolation (or wind flow modelling) uncertainty is a relatively minor contributor to the overall uncertainty in the energy prediction.
- The proposed wind turbine locations are preliminary and consider only general siting requirements. Detailed environmental, technical, or construction constraints have not been considered at this stage. The analysis presented here aims to provide a general understanding of how a generic wind turbine would be sited and how it would perform.
- There are a number of losses and uncertainties applied to the energy estimates presented above, for which DNV GL's standard assumptions have been made at this stage, or for which an analysis was not within DNV GL's scope of work. It is recommended that the Customer considers each of the loss categories carefully when using the results in this report for stakeholder engagement.



1 INTRODUCTION

The World Bank (the “Customer”) retained Garrad Hassan America, Inc. (DNV GL) to complete a 12-month Site Resource Report, which consists of an independent analysis of the wind regime and energy production at two locations in the Maldives, as part of the Wind Resource Assessment and Mapping in the Maldives project. The results of the work are reported here.

The project is primarily funded by the Energy Sector Management Assistance Program (ESMAP). The overall objective consists of providing a validated mesoscale wind atlas for the Maldives, including associated datasets. This aims to provide policy makers in the Maldives and other stakeholders with accurate and valuable knowledge of the national wind resource, including complementary tools, which can be of direct practical use, both for formulating energy policy and implementing wind projects.

As part of Phase 2 of the project, meteorological data is to be collected at two sites over a 24-month period. This report is issued following the completion of the first 12 months of site measurements. The purpose of this report is to document the measurement operations at the sites for quality assessment purposes, and to provide measured datasets which can be used to compare with the results of the mesoscale wind modelling.

This report presents a description of the project sites and indicative turbine technology considered. It then describes the available measurements and analysis of the wind data. This is followed by an evaluation of the expected project gross and net energy for a wind turbine in the vicinity of the measurement locations, as influenced by assumed losses and uncertainties. It then provides an overview of the extreme winds and turbulence expected at the sites. Finally, it presents DNV GL’s observations and recommendations.

2 PROJECT DESCRIPTION

Site measurements have been recorded across the Maldives during Phase 2 of the ESMAP program. Measurements of the wind regime have been made using Lidar remote sensing at two locations, Hoarafushi and Thulusdhoo, as shown in Figure 2-1. DNV GL has analysed a single turbine at hub heights of 50 m and 100 m located near each measurement location to assess the potential energy production at each site.

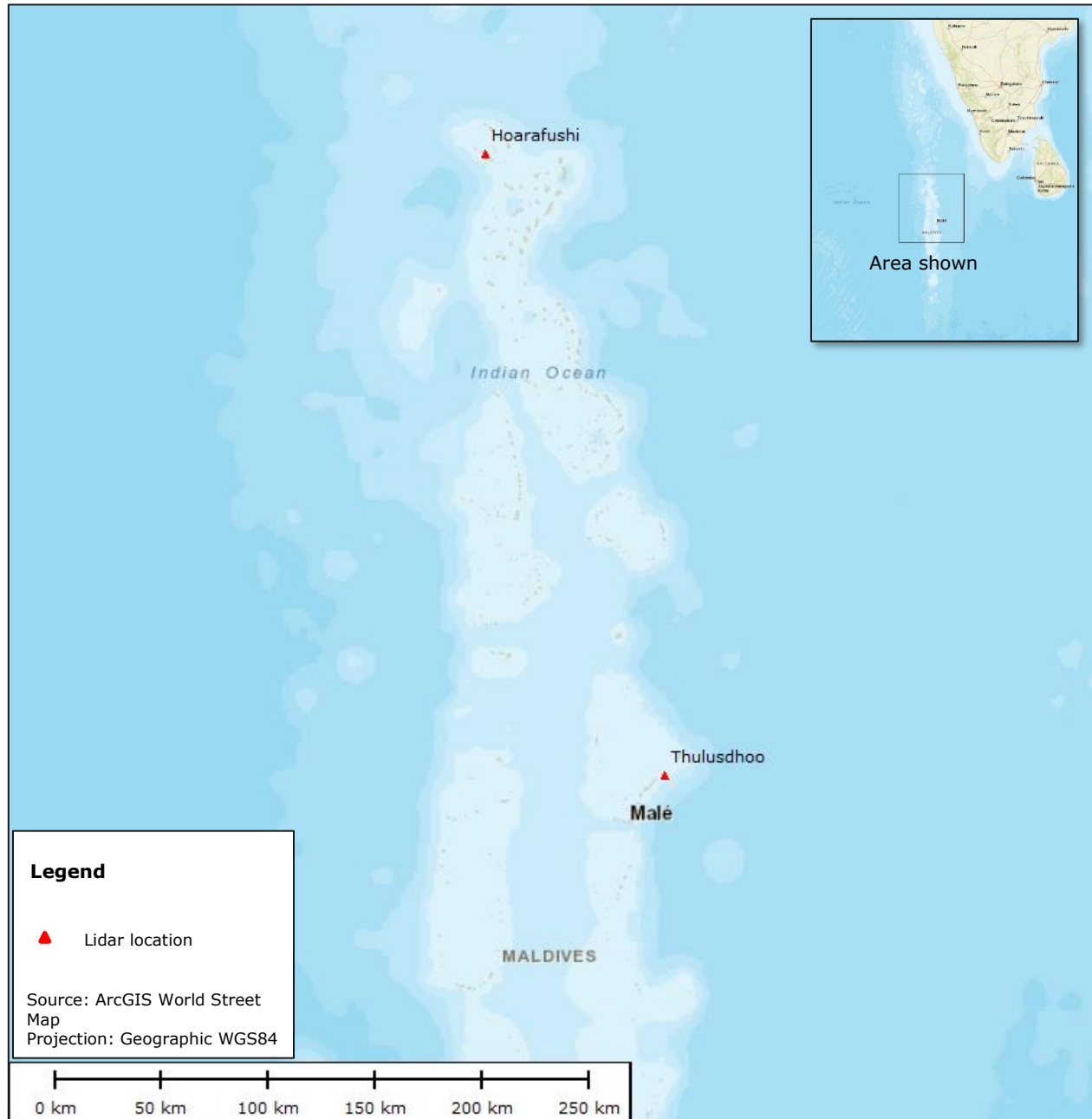


Figure 2-1 Measurement locations

2.1 Site description

DNV GL has installed the Lidar devices and assessed the site characteristics at both locations on Hoarafushi and Thulusdhoo. Table 2-1 below provides a brief summary of each site in terms of the terrain and ground cover. In both cases, the proposed turbine location is situated approximately 1.1 km from the Lidar measurement location.

Table 2-1 Site descriptions

Site location	Brief description
Hoarafushi	The Lidar is situated within a diesel electricity generation compound within 100 m of the eastern shoreline of the island. The surrounding terrain to the west is flat, but covered with trees and low-lying buildings. There are patches of trees and other vegetation, as well as some open clearings, toward the northern and western sides of the island.
Thulusdhoo	The Lidar is situated within a diesel electricity generation compound within 300 m of the shoreline of the island to the north, east and south. The surrounding terrain is flat, but covered with trees and low-lying buildings. There is an area of reclaimed land on the western end of the island which currently consists of sand and coral with minimal ground cover; however DNV GL understands that development plans are in place for this area.

The sites are documented in greater detail in the corresponding Lidar site installation reports [1] [2], which include panoramic photos of the Lidar locations.

A map of each site is presented in Appendix C showing the locations of the installed Lidar device and proposed wind turbine.

2.2 Turbine technology

Two indicative turbine options have been considered for this analysis: (i) the Vergnet GEV MP C [3], and (ii) a generic turbine model generated by DNV GL, based on a range of turbines with similar dimensions [4]. Table 2-2 summarises the turbine models under consideration for both sites. The power curves for both turbines are presented in Appendix D.

Table 2-2 Proposed turbine model parameters

Turbine	Rated power [kW]	Hub height [m]	Peak power coefficient [C_p]	Valid PC density [kg/m^3]
Vergnet GEV MP C	275	50	0.39	1.225
Generic 3 MW	3000	100	0.45	1.225

The Vergnet option was selected in order to investigate the application of a small-scale turbine at the sites. DNV GL understands that there are limited options in this turbine category, and the Vergnet turbine has been demonstrated in remote area applications. It also has the advantage of relative ease of installation and maintenance [3].

The Generic 3 MW turbine was used as the reference turbine in the Phase 1 Mesoscale Wind Modelling Report [4]. It is included here for consistency with the results and data provided as part of that analysis.



However it is noted that there are turbine on the market now that may be more suitable for the wind regime in the Maldives, than those considered here.

Given the preliminary nature of this assessment, DNV GL recommends that potential stakeholders conduct a thorough market review of available technologies when assessing a potential wind farm site in the Maldives. Turbine manufacturers should be approached at an early stage to gain acceptance of proposed turbine layouts and turbine suitability for each site.

2.3 Preliminary wind turbine locations

DNV GL has sited individual wind turbines near the Lidar location at each of the Hoarafushi and Thulusdhoo sites. The proposed wind turbine locations are preliminary and consider general siting requirements, but not detailed environmental, technical, or construction constraints. The purpose of the locations is to provide a general indication of where a wind turbine may be sited and how it would perform, while taking into consideration the uncertainties and recommendations throughout this report.

The proposed turbine siting is based on locations previously suggested by DNV GL for the installation of meteorological masts [6] [7]. DNV GL did not consider mechanical loading on wind turbines to ensure suitability with site conditions, sound levels at nearby inhabited areas, or interconnection feasibility. It is recommended that a detailed site specific review is carried out at both locations for any layout development and optimisation study.

The wind turbine layouts are presented in maps in Appendix C, and the coordinates are listed in Appendix D.

2.4 Neighbouring wind farms

To DNV GL's knowledge, there are currently no utility-scale operational wind farms in the vicinity of Hoarafushi and Thulusdhoo islands. Therefore, no external wake effects are considered in the analysis.

3 ON-SITE WIND MONITORING

3.1 Wind resource measurements

Wind resource measurements are currently being recorded at the two sites using ZephIR 300 Lidar units, with measurements included in this analysis taken from April 2017 to April 2018. The characteristics of these measurements are summarised in Table 3-1.

Table 3-1 Lidar measurement summary

Measurement location	Measurement Heights [m AGL]	Lidar manufacturer and model	Period considered	Auxiliary measurements
Hoarafushi	11, 20, 30, 39, 50, 60, 80, 100, 120, 150, 200	ZephIR 300	April 2017 – April 2018	Meteorological station
Thulusdhoo	11, 20, 30, 39, 50, 60, 80, 100, 120, 150, 200	ZephIR 300	April 2017 – April 2018	Meteorological station

The auxiliary meteorological station at each site utilises ultrasonic measurements to verify the wind direction measured by the Lidar, and records other atmospheric parameters including wind speed, temperature, air pressure, relative humidity and precipitation.

Both Lidar units have been subjected to independent testing and performance verification in accordance with the second edition of the reviewed IEC 61400-12-1 standard, Annex L [5]. Additional details about the configurations of each unit are available in the corresponding site installation reports [1] [2].

3.2 Data processing

Raw data from the Lidar unit at each site have been collected by DNV GL. The wind data have been subject to a quality checking procedure by DNV GL to identify and exclude erroneous records.

The ZephIR Lidar unit uses measurements from its scanning laser and auxiliary meteorological station to determine the wind direction. If the meteorological station is affected by shadowing effects or wind recirculation, there is the potential for a 180-degree ambiguity in the measured wind direction. Additional details on this issue are provided in the Lidar installation reports [6] [7]. Given the locations of the Lidars relative to surrounding trees and buildings, instances of the 180-degree direction ambiguity occur periodically in the measured data. DNV GL has reviewed all the wind direction data at both sites and corrected instances where a 180-degree offset has been identified.

The duration, wind statistics and data coverage for representative measurement heights at the Lidar units are summarised in Appendix A. Wind data coverage is generally very good, with lower coverage only observed at lower measurement heights, particularly at 11 m. Overall data coverage levels and other key parameters at representative measurement heights are shown in Table 3-2.

Table 3-2 Summary of site measurement data coverage

Site	Height [m]	Available period [years]	Valid period [years]	Measured wind speed [m/s]	Wind speed data coverage [%]
Hoarafushi	50	1.04	1.01	5.1	97
	100	1.04	1.00	5.3	96
Thulusdhoo	50	1.05	1.02	5.6	97
	100	1.05	1.02	5.9	97

4 WIND ANALYSIS

The analysis of the site wind regime involved several steps. A summary of the results for each step of the process are provided in the following sections.

4.1 Measurement height wind regime

4.1.1 Site period wind speeds

Data were recorded at the Lidar units up to a measurement height of 200 m and over a period ranging from April 2017 to April 2018. At both sites, overall data coverage at the measurement heights equivalent to the hub heights under consideration was between 96% and 97%. The annual average wind speeds measured by each device at both hub heights are shown in Table 4-1.

Table 4-1 Site period wind speeds

Measurement location	Height [m]	Measured annual average wind speed [m/s]
Hoarafushi	50	5.1
	100	5.4
Thulusdhoo	50	5.7
	100	6.0

Appendix A presents site data in greater detail including monthly average wind speeds and data coverage at selected measurement heights. A 12-month by 24-hour table of wind speeds at the representative 100 m height is also presented, outlining the seasonal and diurnal variation in wind speed at each site.

4.1.2 Extension of the site period to the reference period

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

4.1.2.1 Reference data considered

DNV GL has undertaken a review of the sources of reference data at each site in order to identify appropriate long-term reference stations for this analysis. While nearby ground-based stations have been identified, DNV GL has previously identified consistency issues with recorded data from these stations, specifically for wind resource assessment purposes. Given the lack of nearby long-term, consistent ground reference station data, this analysis has relied upon reanalysis and virtual datasets. At each site, DNV GL has correlated the measured wind data to MERRA-2, ERA-Interim and DNV GL's Virtual Met Data (VMD). More information about these reference stations are provided in Appendix B. Table 4-2 summarises the reference data considered.

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

Site location	Meteorological data source	Network	Start date	End date
Hoarafushi	MERRA-2	NASA	Jan 2003	Apr 2018
	ERA-Interim	ECMWF	Jan 2003	Apr 2018
	VMD ¹	DNV GL	Jan 2003	Apr 2018
Thulusdhoo	MERRA-2	NASA	Jan 2003	Apr 2018
	ERA-Interim	ECMWF	Jan 2003	Apr 2018
	VMD ¹	DNV GL	Jan 2003	Apr 2018

1. Initiated using MERRA-2 reanalysis

Figure 4-1 and Figure 4-2 below show the location of the reference source grid cells in relation to each of the Hoarafushi and Thulusdhoo sites respectively. For clarity, only the central grid cells for the MERRA-2 and ERA datasets are shown.

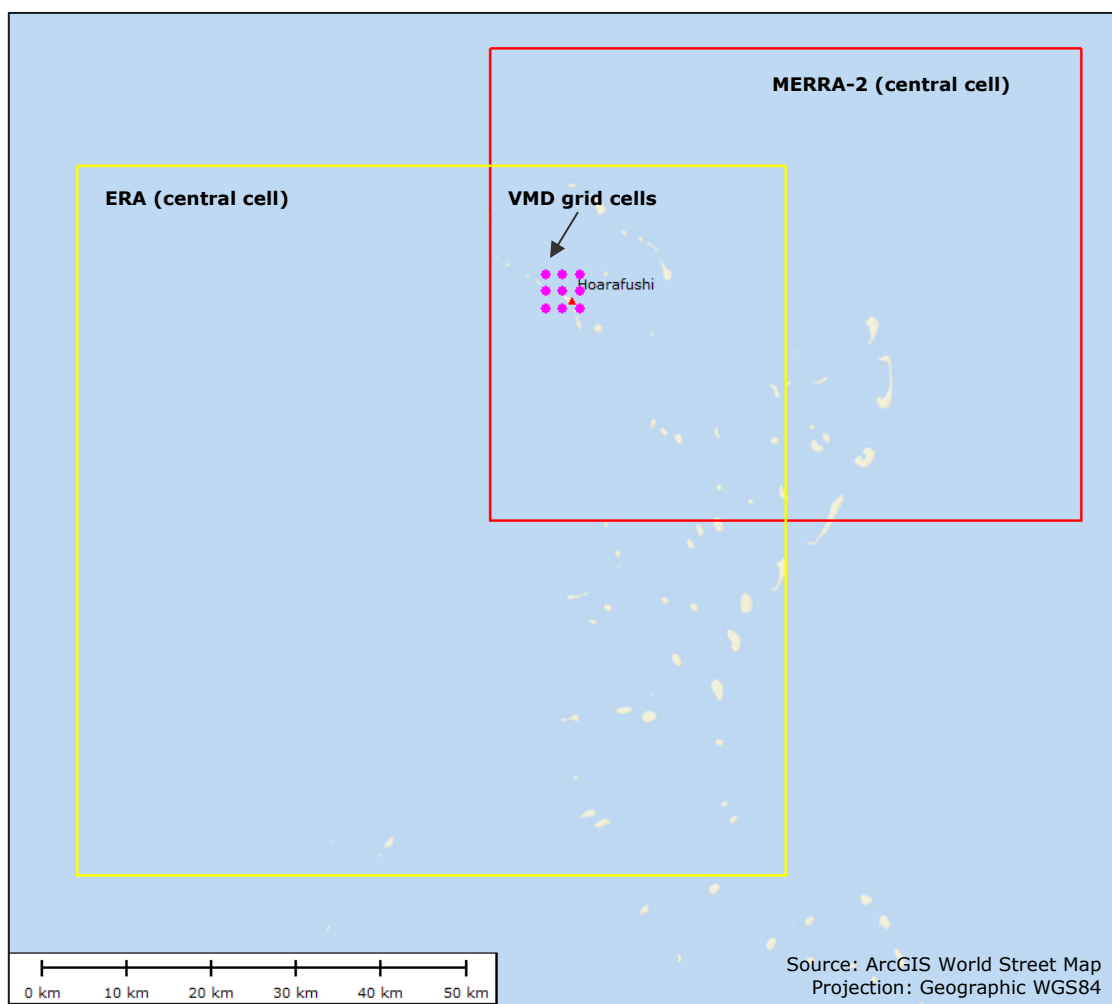


Figure 4-1 Location of Hoarafushi site and reference data sources considered

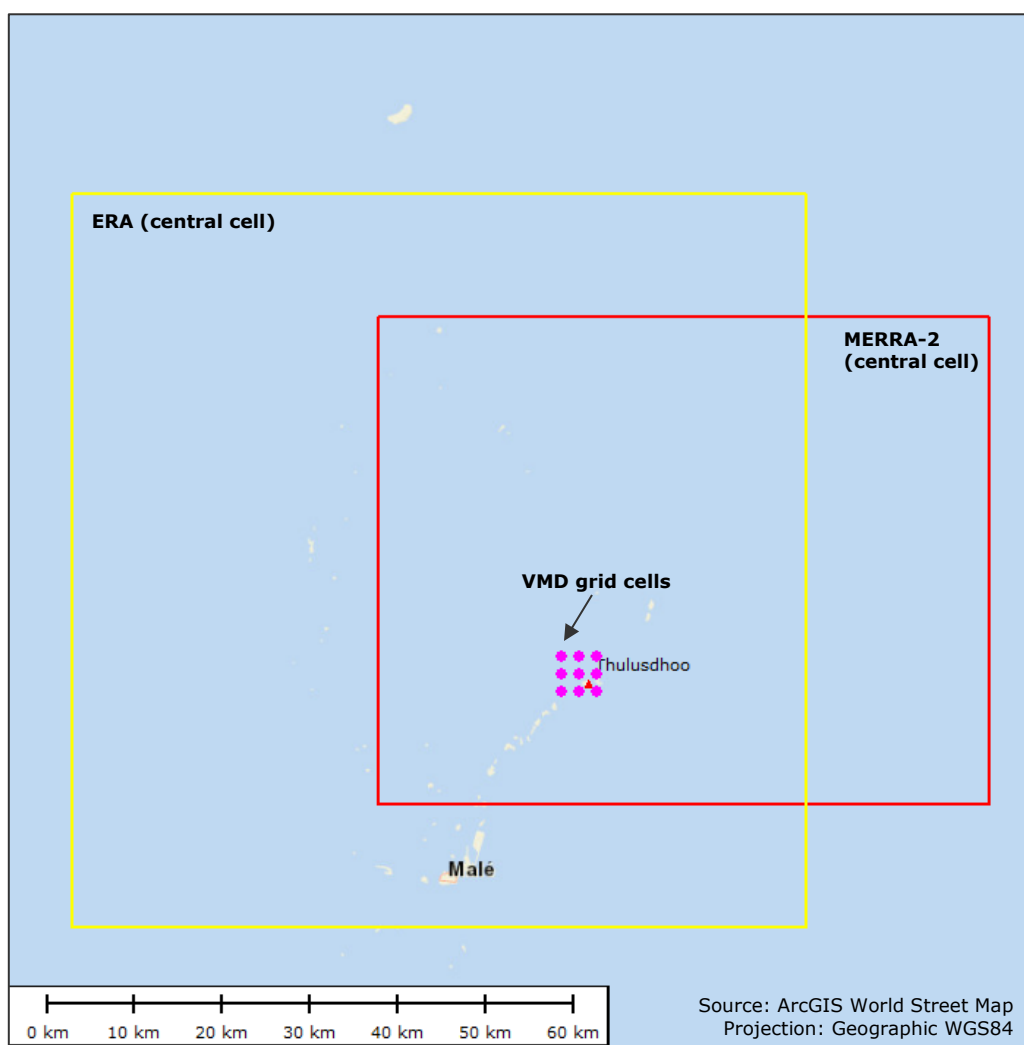


Figure 4-2 Location of Thulusdhoo site and reference data sources considered

To determine whether use of reference data will reduce uncertainty, correlations of monthly mean wind speeds were carried out between each reference station and the site. Correlations were also carried out using a wind index based on both MERRA-2 and ERA data. These correlations were conducted at both the 50 m and 100 m Lidar measurement heights. The results of this analysis are summarised in Table 4-3.

Table 4-3 Reference data sets considered for correlation to site data

Site	Site measurement height [m]	Highest coefficient of determination, R^2 (monthly correlation)		
		MERRA-2	ERA	VMD
Hoarafushi	50	0.97	0.97	0.95
	100	0.97	0.97	0.95
Thulusdhoo	50	0.90	0.71	0.83
	100	0.94	0.78	0.88

In addition to the reference sources listed above, a series of monthly wind indices was created at each site using both MERRA-2 and ERA data and correlated to the site measurements.

During the analysis, DNV GL evaluated each long-term reference source for each site based on:

- the strength of the correlation between the reference source data and the site measurement data
- the relative adjustment in wind speed between the long term reference and site measurements
- the consistency of the reference source data.

Using the above criteria, the wind indices created using the MERRA-2 and ERA datasets were selected to derive the long-term wind speed estimate at both sites. DNV GL's resulting choice of reference data sources and the corresponding long term adjustment for each site are shown in Table 4-4.

Table 4-4 Applied long-term wind speed adjustments

Site	Reference data sources included in long-term adjustment	Hub height [m]	Coefficient of determination, R^2	Long term adjustment [%]	Long-term adjusted mean wind speed [m/s]
Hoarafushi	MERRA-2 / ERA index	50	0.97	96.1%	4.9
	MERRA-2 / ERA index	100	0.97	95.8%	5.2
Thulusdhoo	MERRA-2 / ERA index	50	0.82	96.8%	5.5
	MERRA-2 / ERA index	100	0.88	96.6%	5.7

It is noted that there is a lack of viable ground-station reference data to evaluate the consistency of the reanalysis and virtual datasets considered in this assessment. For this reason, there is increased uncertainty in the long-term wind regime at each site. This elevated uncertainty is considered in Section 6.

4.2 Hub-height wind regime

4.2.1 Wind shear analysis

The hub heights of the preliminary turbines considered in this assessment correspond to the 50 m and 100 m measurement heights at the Lidar units at both sites. Therefore, no vertical extrapolation is necessary to derive the long-term wind speed estimates at both hub heights. However, DNV GL has examined the wind shear profile at both sites in order to characterise the local wind regimes.

Shear analysis was carried out using Lidar data at a range of measurement heights using the power law on a time series basis. The results have been considered in light of the variation in the monthly wind roses at each site.

Figure 4-3 presents the diurnal variation in shear exponent (α) based on measurements at heights below 100 m at Hoarafushi. The diurnal shear patterns are grouped by month. The wind roses based on Lidar measurements for the months of January and June are also shown.

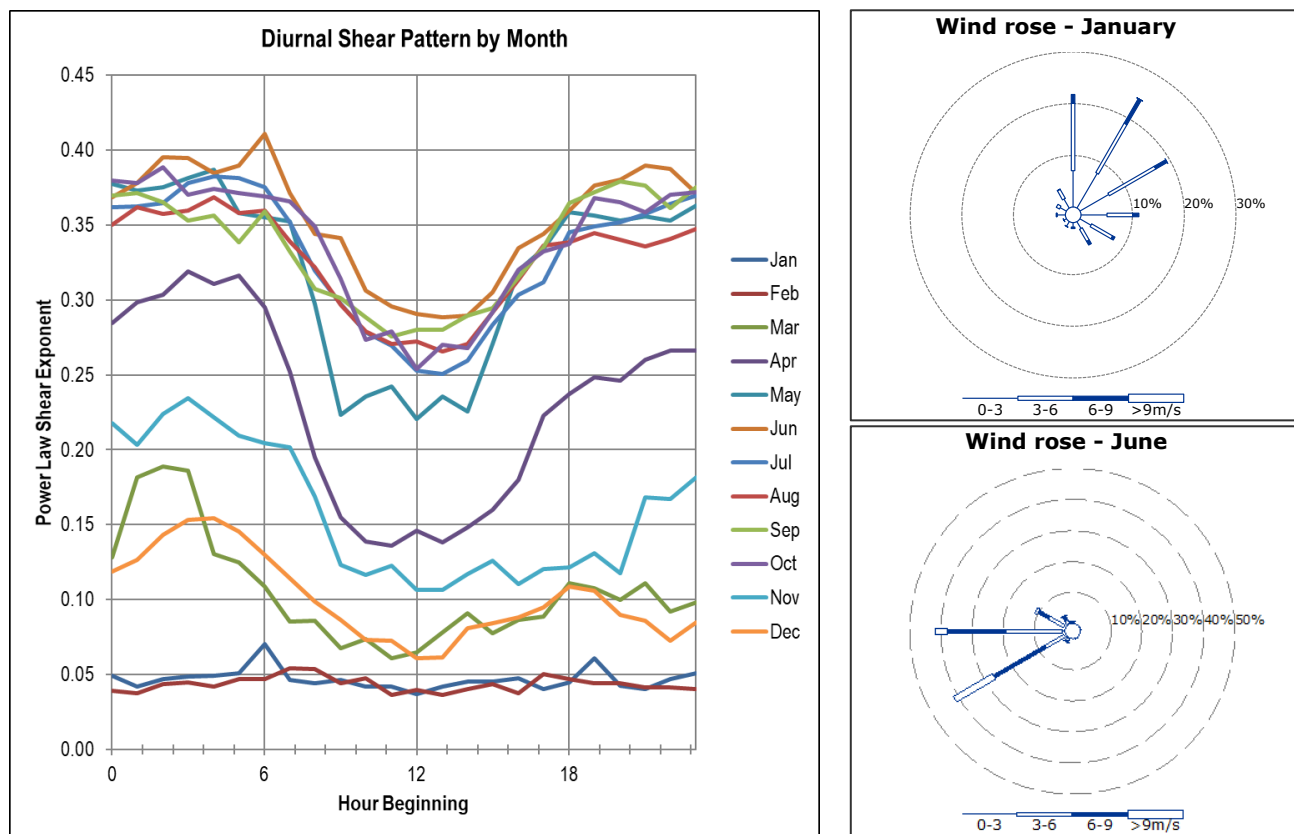


Figure 4-3 Diurnal shear patterns by month and representative monthly wind roses - Hoarafushi

At the Hoarafushi Lidar site, the observed wind patterns indicate that during the period from approximately December to March (northeast monsoon season), the wind is mainly from the 0 – 90° sector, which is from the direction almost directly adjacent to the sea (refer to the site map in Appendix C). As a result, during this period shear exponent α values are generally low with little variation throughout the day. During the period from approximately April to November (southwest monsoon season), the wind is mainly from westerly sectors, meaning the wind flows over the land mass of the island before reaching the Lidar. Therefore the wind is influenced by flow over the land mass and surface roughness. During this period, α values are relatively higher with greater diurnal variation, as can be seen in Figure 4-3.

Figure 4-4 below presents the diurnal shear patterns by month and representative wind roses for the Thulusdhoo site, based on measurements below 100 m.

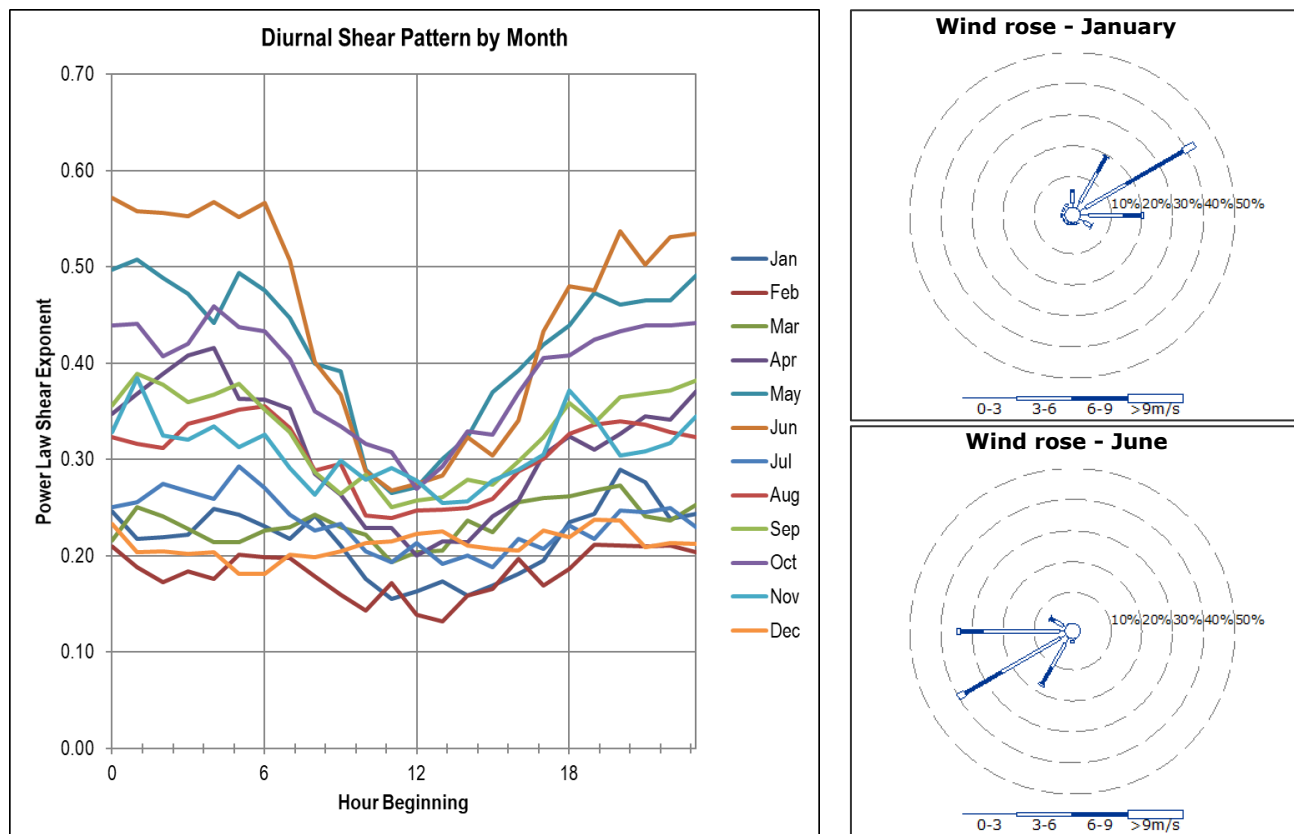


Figure 4-4 Diurnal shear patterns by month and representative monthly wind roses - Thulusdhoo

The Thulusdhoo Lidar site is surrounded by land (as shown in the site map in Appendix C), however, there is a greater proportion of land mass to the west. During the period from approximately December to March, the wind is mainly from the 0 – 90° sector. The wind flow is therefore less influenced by flow over the land mass, and the diurnal shear profile for this period does not show significant variation. From approximately April to November, the wind is mainly from the westerly sectors, and crosses a greater amount of land mass. There is greater diurnal variation in shear due to flow over this land mass and surface roughness. However, the shear variation is less pronounced compared to the data from Hoarafushi.

It noted that the shear values presented are generally high. This is a result of the shear calculation including measurements from heights near the ground where the impact of land effects and surface roughness, including surrounding trees and buildings on the measurements is high.

The results of the shear analysis at both sites also indicate that above a height of 100 m, α values are estimated to be less than 0.1, with monthly variation not significant. This indicates that the wind profile at upper hub heights is not significantly influenced by land effects, and the effects of wind flow over the ocean can be considered more dominant.

The results of the above analysis suggest that:

- The 50 m hub height turbine option would be more likely to experience seasonal variations in shear, depending on siting, with greater seasonal variation expected if located at a coastal site.

- The 100 m hub height turbine option would be less likely to experience seasonal shear variation.

4.2.2 Hub-height wind speed and direction distributions

The hub-height wind speed and direction distributions were generated based on data recorded at the 50 m and 100 m measurement heights. Key project specific aspects of the analysis were:

- The distribution from each site Lidar was used as the basis of the analysis.
- The frequency distributions from site measurements were scaled to the representative long term hub height mean wind speeds.

A long term wind rose and wind speed histogram at the representative hub height of 100 m is shown in Figure 4-5 for each site.

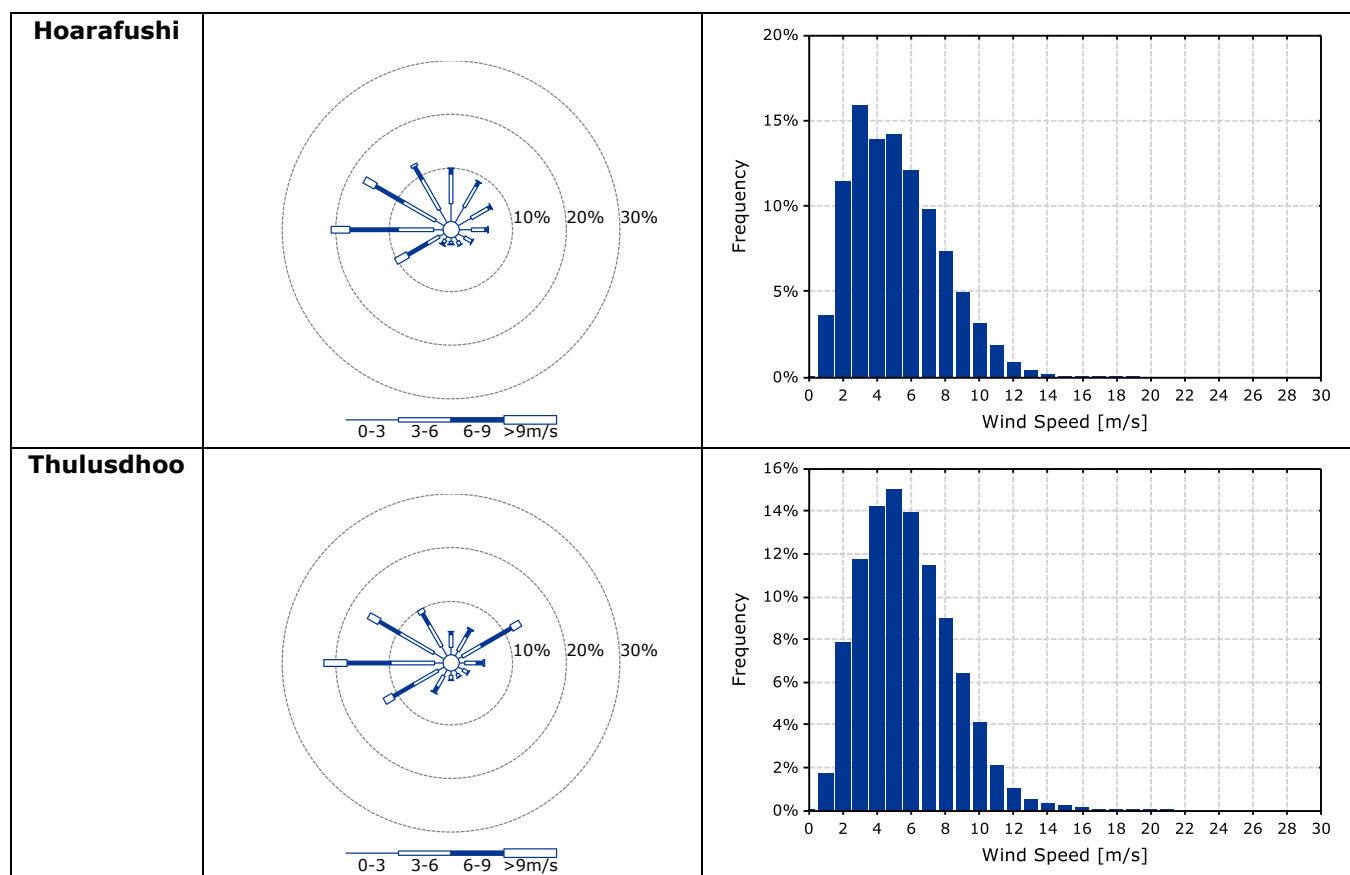


Figure 4-5 Long-term 100 m hub height frequency distribution and wind roses

4.3 Wind regime across the site

The variation in wind speed over each site was predicted using the industry standard commercial WASP wind flow modelling software. For each site, data from the Lidar location has been used to initiate the wind flow modelling used to predict the long-term wind regime at the turbine location. The horizontal extrapolation distance from Lidar to turbine is approximately 1.1 km at both sites. Based on this approach, the predicted long-term mean wind speeds at each turbine at the proposed hub heights are presented in Table 4-5.

Table 4-5 Average long-term hub height wind speed estimates at the turbine locations

Site	Hub height [m]	Average turbine wind speed [m/s]
Hoarafushi	50	5.0
	100	5.2
Thulusdhoo	50	5.6
	100	5.8



5 ENERGY ANALYSIS

5.1 Gross and net energy estimates

The gross energy production at the individual turbine locations has been calculated using the DNV GL WindFarmer software and the results of the wind analysis.

The energy production results for the preliminary layouts at Hoarafushi and Thulusdhoo are shown in Table 5-1 and Table 5-2 respectively. The projected net energy production was calculated by applying a number of energy loss factors to the gross energy production. The predictions represent the estimate of the annual production expected over a 20-year operational lifetime.

Table 5-1 Energy production summary: Hoarafushi

Hoarafushi preliminary layout		Vergnet GEV MP C	Generic 3MW	
Hub height		50	100	m
Wind Farm Rated Power		0.275	3.0	MW
Gross Energy Output		0.312	4.4	GWh/ annum
1	Wake effect	100.0	100.0	%
1a	Internal wake effect	100.0	100.0	% Project specific
1b	External wake effect	100.0	100.0	% Project specific
1c	Future wake effect	100.0	100.0	% Project specific
2	Availability	92.4	92.4	%
2a	Turbine availability	95.2	95.2	% DNV GL standard
2b	Balance of Plant availability	99.0	99.0	% DNV GL standard
2c	Grid availability	98.0	98.0	% DNV GL standard
3	Electrical efficiency	97.0	97.0	%
3a	Operational electrical efficiency	97.0	97.0	% DNV GL standard
3b	Wind farm consumption	100.0	100.0	% DNV GL standard
4	Turbine Performance	97.1	95.9	%
4a	Generic power curve adjustment	100.0	100.0	% DNV GL standard
4b	High wind speed hysteresis	100.0	100.0	% Project specific
4c	Site specific power curve adjustment	99.1	97.8	% Project specific
4d	Sub-optimal performance	99.0	99.0	% DNV GL standard
4e	Turbine degradation	99.0	99.0	% DNV GL standard
5	Environmental	100.0	100.0	%
5a	Icing degradation	100.0	100.0	% Not considered
5b	Icing shutdown	100.0	100.0	% Not considered
5c	Temperature shutdown	100.0	100.0	% Not considered
5d	Site access	100.0	100.0	% Not considered
5e	Tree growth	100.0	100.0	% Not considered
6	Curtailments	100.0	100.0	%
6a	Wind sector management	100.0	100.0	% Not considered
6b	Grid curtailment	100.0	100.0	% Not considered
6c	Noise, visual and environmental curtailment	100.0	100.0	% Not considered
Net Energy Output¹		0.271	3.8	GWh/annum
Net Capacity Factor		11.2	14.3	%

NOTES: 1. Energy figures are derived for a 20-year period using the DNV GL Monte Carlo uncertainty model, which includes the effect of asymmetric probability distributions. Net energy is therefore not a direct product of gross energy and P50 losses.

Table 5-2 Energy production summary: Thulusdhoo

Thulusdhoo preliminary layout		Vergnet GEV MP C	Generic 3MW		
Hub height		50	100	m	
Wind Farm Rated Power		0.275	3	MW	
Gross Energy Output		0.400	5.3	GWh/ annum	
1	Wake effect	100.0	100.0	%	
1a	Internal wake effect	100.0	100.0	%	Project specific
1b	External wake effect	100.0	100.0	%	Project specific
1c	Future wake effect	100.0	100.0	%	Project specific
2	Availability	92.4	92.4	%	
2a	Turbine availability	95.2	95.2	%	DNV GL standard
2b	Balance of Plant availability	99.0	99.0	%	DNV GL standard
2c	Grid availability	98.0	98.0	%	DNV GL standard
3	Electrical efficiency	97.0	97.0	%	
3a	Operational electrical efficiency	97.0	97.0	%	DNV GL standard
3b	Wind farm consumption	100.0	100.0	%	DNV GL standard
4	Turbine Performance	96.5	95.7	%	
4a	Generic power curve adjustment	100.0	100.0	%	DNV GL standard
4b	High wind speed hysteresis	100.0	100.0	%	Project specific
4c	Site specific power curve adjustment	98.5	97.6	%	Project specific
4d	Sub-optimal performance	99.0	99.0	%	DNV GL standard
4e	Turbine degradation	99.0	99.0	%	DNV GL standard
5	Environmental	100.0	100.0	%	
5a	Icing degradation	100.0	100.0	%	Not considered
5b	Icing shutdown	100.0	100.0	%	Not considered
5c	Temperature shutdown	100.0	100.0	%	Not considered
5d	Site access	100.0	100.0	%	Not considered
5e	Tree growth	100.0	100.0	%	Not considered
6	Curtailments	100.0	100.0	%	
6a	Wind sector management	100.0	100.0	%	Not considered
6b	Grid curtailment	100.0	100.0	%	Not considered
6c	Noise, visual and environmental curtailment	100.0	100.0	%	Not considered
Net Energy Output¹		0.346	4.6	GWh/annum	
Net Capacity Factor		14.3	17.4	%	

NOTES: 1. Energy figures are derived for a 20-year period using the DNV GL Monte Carlo uncertainty model, which includes the effect of asymmetric probability distributions. Net energy is therefore not a direct product of gross energy and P50 losses.

Table 5-1 and Table 5-2 include potential sources of energy loss that have been either assumed to be the DNV GL standard values or estimated for this project. Project specific aspects of the loss estimates are provided in the following bullets:

- Wake effect – The wake effects have been calculated using the WindFarmer Analyst wake model and consider internal and external wake effects. Since there is only one turbine per layout and no neighbouring or known wind farms planned for the future, no internal, external or future wake losses are considered.

- Availability – This category considers turbine availability, balance of plant, and grid availability. A turbine availability value of 95.2% averaged over a 20-year period was used in accordance with DNV GL's standard method. Standard values were used to estimate balance of plant and grid availability losses.
- Operational electrical efficiency – Details of the specific balance of plant infrastructure and grid connection point have not been considered. Therefore, DNV GL has considered a standard loss factor of 97%.
- Turbine performance – As part of the turbine performance category, DNV GL has estimated the site-specific power curve adjustment, which considers the impact of site-specific conditions such as turbulence and wind shear on turbine performance. Standard values were used to estimate turbine sub-optimal performance and performance degradation over time.
- Environmental – Detailed environmental losses were not considered in this analysis.
- Curtailments – Detailed curtailment losses were not considered in this analysis.

5.2 Seasonal and diurnal distributions

Based on the meteorological measurements made at the Lidar units at both sites over the 12-month period, DNV GL has estimated the net hourly and 10-minute energy production for the proposed wind farm layout using both turbine options considered.

Figure 5-1 presents a comparison of the estimated net hourly output based on the generic 3 MW turbine at Thulusdhoo and the average hourly load data from the Thulusdhoo grid. The load data represents the average value for the given time of day based on data for the period from July to December 2017 provided to DNV GL [8].

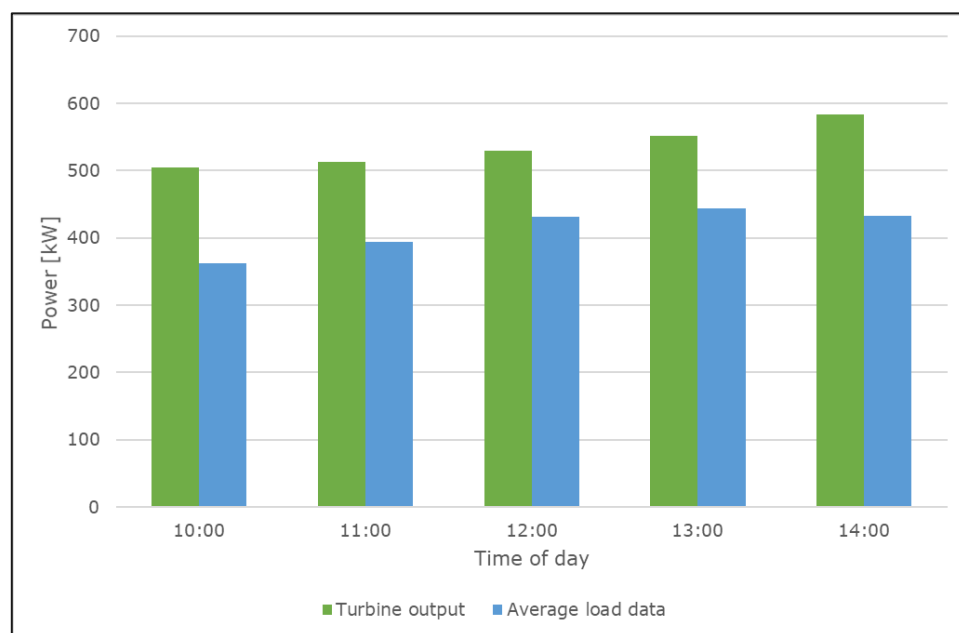


Figure 5-1 Comparison of average hourly turbine net production and grid load – Thulusdhoo

The estimated production time series were used to predict the expected seasonal and diurnal variation in energy production at both sites using both turbine options. The results for each case are presented in Appendix E in the form of a 12-month by 24-hour (12 x 24) matrix.

A representative monthly production profile for both sites using the generic 3 MW turbine option with 100 m hub height is presented in Figure 5-2 below. It is noted that the uncertainty associated with the prediction of any given month or hour of day is significantly greater than that associated with the prediction of the annual energy production.

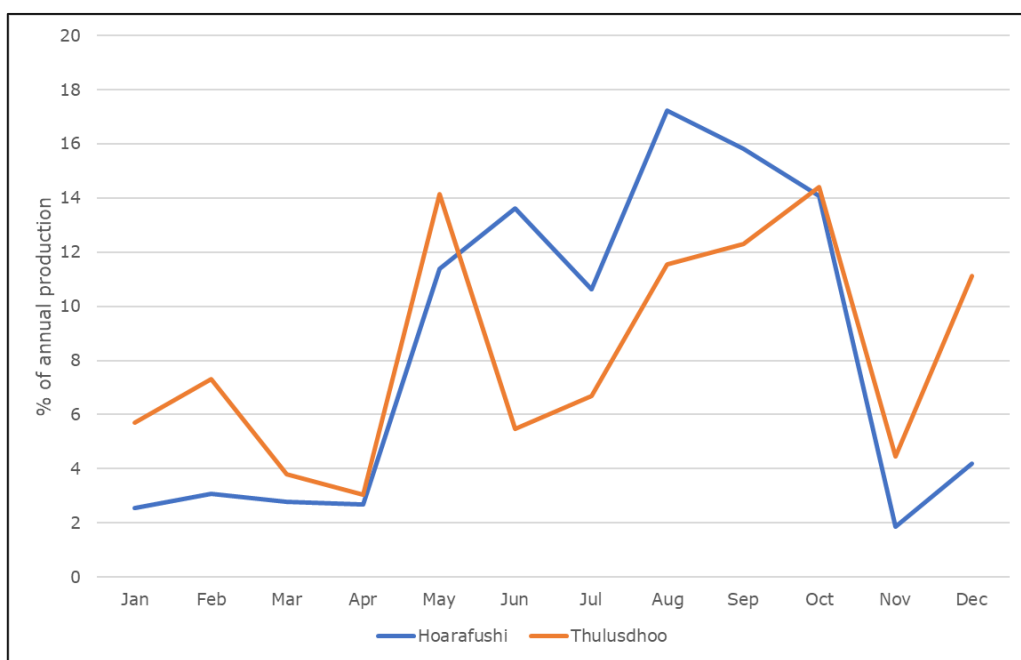


Figure 5-2 Monthly energy production profiles – 3 MW turbine option

6 UNCERTAINTY

The main sources of deviation from the central estimate (P50) have been quantified and combined using a probabilistic model, assuming full independence between the sources. The results of the probabilistic simulation of net energy production are summarised in Table 6-1 and detailed in Appendix F. The average calculated sensitivity ratios for variations of 10% on wind speed are shown in Table 6-2.

Table 6-1 Summary of project net average energy production for each site

Site	Hoarafushi [GWh/annum]				Thulusdhoo [GWh/annum]			
Turbine option	GEV MP C [275 kW]		Generic [3 MW]		GEV MP C [275 kW]		Generic [3 MW]	
Probability of exceedance	1-Year	20-year average	1-Year	20-year average	1-Year	20-year average	1-Year	20-year average
50%	0.268	0.271	3.74	3.77	0.343	0.346	4.53	4.56
75%	0.229	0.242	3.25	3.41	0.288	0.302	3.90	4.07
90%	0.195	0.218	2.82	3.11	0.240	0.264	3.35	3.65
95%	0.176	0.205	2.58	2.93	0.213	0.242	3.04	3.41
99%	0.142	0.180	2.15	2.61	0.166	0.202	2.50	2.98

Table 6-2 Site average sensitivity ratios

Site	Turbine option	Sensitivity ratio
Hoarafushi	GEV MP C [275 kW]	3.13
	Generic [3 MW]	2.68
Thulusdhoo	GEV MP C [275 kW]	2.96
	Generic [3 MW]	2.60

DNV GL notes that the calculated sensitivity ratios are relatively high, particularly for the Vergnet turbine option. This is due to the low hub height wind speeds.

7 SITE CONDITIONS

DNV GL has carried out a high level site conditions assessment for both the Hoarafushi and Thulusdhoo sites, encompassing the predicted turbulence intensity and extreme wind speeds.

It is noted that the assessment presented here provides a comparison of the on-site meteorological conditions to the limits of the wind class, using the assumption that both sites are Class III as defined by IEC 61400-1 [9]. The scope of this assessment is limited to the generic turbine model presented in Section 2.2, and therefore, a conclusion on the suitability of the turbine is not appropriate. However, it is recommended that any turbine manufacturer being considered for each site considers suitable margins in the context of confirming turbine suitability, turbine supply agreement and warranties, and that the results of this assessment are reviewed with consideration of the inherent uncertainties.

7.1 Turbulence Intensity

7.1.1 Ambient turbulence intensity at the turbine locations

Fatigue loading on wind turbines and their support structures is primarily the result of stochastic loading, originating from wind turbulence. In order to fully capture the turbulence conditions for the purposes of such load calculations, the cumulative effect of the ambient flow characteristics of the site and the wind farm must be taken into account. According to IEC 61400-1 [9], increased loading due to turbine wakes can be represented through the use of effective turbulence intensity, as defined by Frandsen [10]. This parameter characterises the effect of loading of ambient and wake induced turbulence.

However, since the wind farm layouts proposed at both sites consist of a single turbine, no wake-induced turbulence is considered, and therefore the Frandsen methodology is not applicable. DNV GL has determined that the ambient turbulence intensity at the Lidar location can be considered as a reasonable estimate of the ambient turbulence intensity at the proposed turbine location at each site.

Figure 7-1 and Figure 7-2 below present the ambient turbulence intensity as a function of wind speed at the 100 m Lidar measurement height at Hoarafushi and Thulusdhoo, respectively. The figures also include the profiles for the IEC turbulence subclasses. Tables of the predicted ambient turbulence intensity at both hub heights are presented in Appendix G.

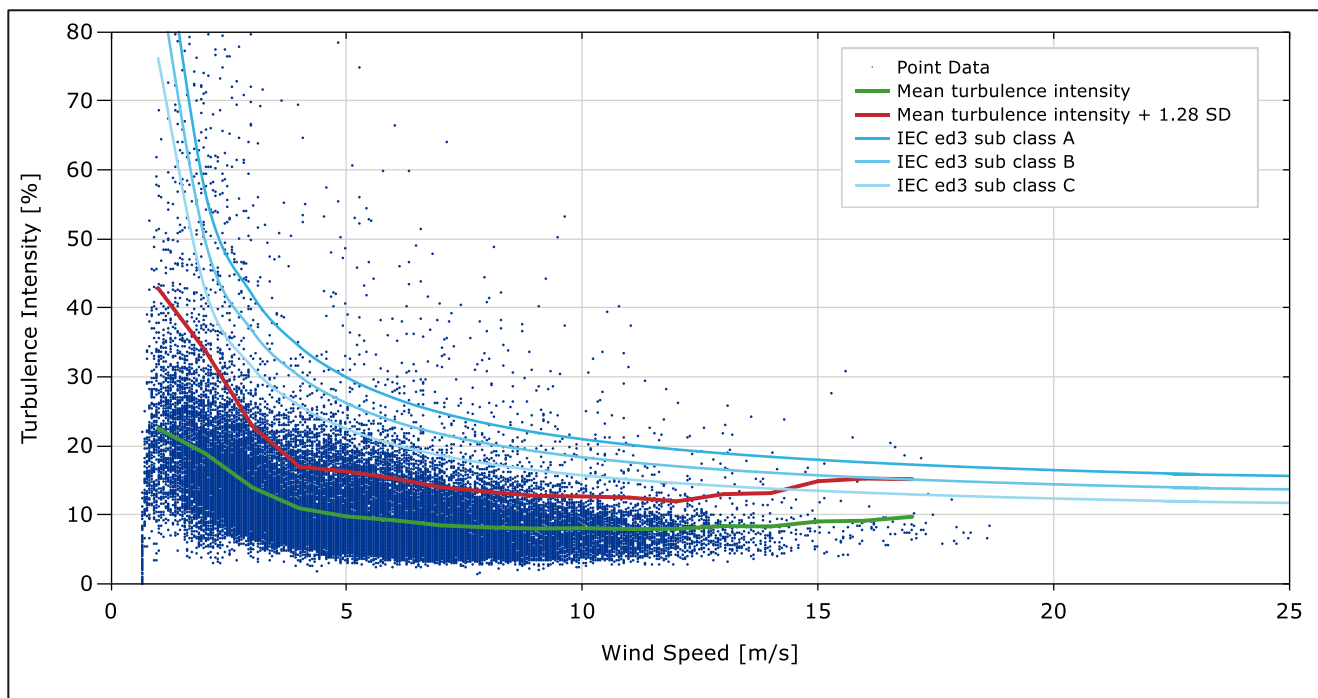


Figure 7-1 Ambient turbulence intensity as a function of wind speed at 100 m – Hoarafushi

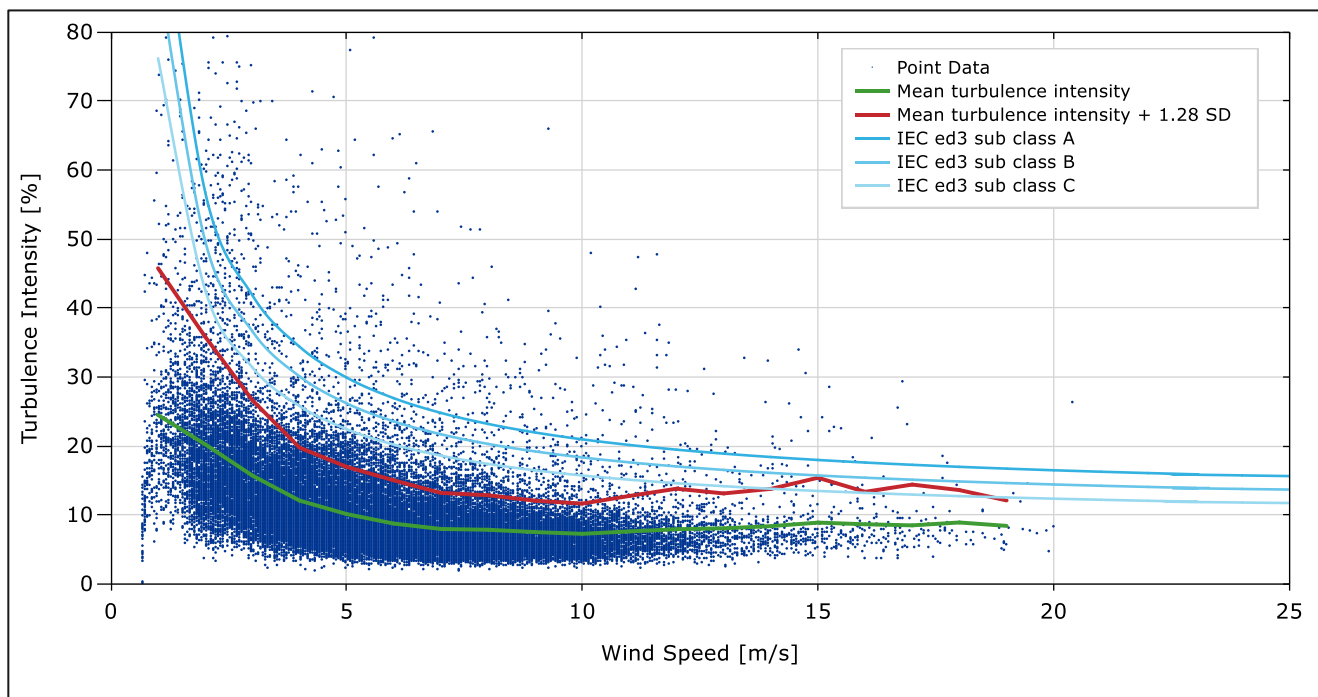


Figure 7-2 Ambient turbulence intensity as a function of wind speed at 100 m – Thulusdhoo

7.1.2 Uncertainty in turbulence prediction

It should be noted that there is scope for uncertainty in the application of the above turbulence intensity results to the specific site and turbine type considered in this study. A list of potential sources of uncertainty that should be considered when interpreting the results for load analysis is provided below:

- There is a relatively low data coverage of measurements available to define the turbulence intensity profile at high wind speeds, leading to increased uncertainty in these values.
- Statistical scatter in the turbulence at any mean wind speed may lead to non-linear impacts on wind turbine loads.
- There is uncertainty associated with turbulence intensity data recorded by remote sensing devices including Lidar, compared to data from meteorological masts.
- Uncertainty can also arise due to non-linear behaviour of the turbine, most notably in the control system and aerodynamics. Explicit time-domain simulations would be required to model these effects.
- It should be noted that the predictions of ambient turbulence intensity rely on the assumption that the standard deviation of wind speed recorded at the measurement location remains constant over the site area. Therefore, it is important that the measurement location is reasonably representative of the turbine location. Due to this assumption, the predictions do not include any estimation of the effects of the varying ground roughness around the turbines.
- The estimated ambient turbulence intensity values do not account for all the environmental parameters which influence turbine loads. The effect of wind shear, upflow angles and air density should all be included if a more rigorous load analysis is required. This would be achieved through explicit time-domain load simulations of the turbine at each site.
- The fatigue loading of a wind turbine is, in general, not a simple direct function of turbulence intensity but depends on other sources of loading including, but not limited to, gravity, centrifugal loads and dynamic response.

Due to these issues the turbulence predictions presented should be reviewed with consideration of the inherent assumptions and large uncertainties.

It should be noted that the methodology presented here provides only an estimate of the loading levels to be experienced at the turbine locations. For a detailed study of the fatigue loading at the turbines, explicit time-domain simulations would be required.

7.2 Extreme wind speeds

The extreme wind speed at a site is best determined by a Method of Independent Storms (MIS) or Gumbel analysis, using data recorded at the site over a period of at least seven years. At the sites, approximately one year of 10-minute mean wind speed data were available. This period is less than is required to obtain an accurate prediction. Despite this, estimates using the MIS method are provided below; however, it should be noted that the estimates are subject to a very high level of uncertainty given the limited on-site measurement period.

Furthermore, for indicative purposes the maximum wind speed values recorded on site are presented in Section 7.2.2.

7.2.1 Method of Independent Storms (MIS)

DNV GL has undertaken a Gumbel analysis, using the MIS approach defined by Cook [11] and further developed by Harris [12][13]. This method has been employed to provide an estimate based on the measured data available at the sites, as detailed below.

It is possible to use the MIS to determine a 10-minute mean extreme wind speed for a return period of 50 years from a continuous time series. Guidance within Cook recommends that a data set of at least seven years' duration is ideally used for an MIS analysis. As the site dataset used in this analysis is limited to a single year, caution must be exercised in the interpretation of the extreme gust wind speeds determined from this analysis. Using the code and inputs described above, DNV GL has undertaken an MIS analysis as follows.

The MIS procedure was applied to the time series of data measured at the Lidar units at the proposed hub height of 100 m. Using this method, the extreme 10-minute mean wind speed for a return period of 50 years was estimated at the Lidar locations.

The predicted 10-minute and 3-second gust extreme wind speeds for the turbine location at each site are presented in Table 7-1. It is noted that the predicted values at both sites are within the IEC Class III limits for 10-minute average and 3-second gust extreme wind speeds.

Table 7-1 Predicted extreme wind speeds by Method of Independent Storms (MIS) at proposed turbine locations

Site	Maximum 10-minute mean with a return period of 50 years at 100 m [m/s]	Maximum 3-second gust with a return period of 50 years at 100 m [m/s]
Hoarafushi	24.1	26.4
Thulusdhoo	23.7	34.2
Class III limit	37.5	52.5

The 10-minute values were predicted using the 10-minute average measurements, while the 3-second gust values were predicted using the 1-second maximum measurements, converted to 3-second values using a gust ratio calculated using the Wieringa equation which is defined as follows:

$$\gamma_t(t) = 1 + 0.42 \times I \times \ln\left(\frac{T}{t}\right)$$

Where: γ_t is the gust ratio;
 I is the turbulence intensity;
 T is the averaging period in seconds;
 t is the gust period in seconds.

7.2.2 Extreme wind speeds recorded at the sites

A review of the maximum wind speeds recorded on site was also undertaken. The ZephIR Lidar units on site are set up to record 1-second gust values and 10-minute averages.

The Wieringa equation has again been used to derive a conversion factor to adjust the predicted 1-second gusts measured at the Lidar locations to 3-second gusts. Using the measured period at the Lidar units, the maximum 10-minute mean wind speed and the maximum 3-second gust wind speed at each site are provided in Table 7-2.

Table 7-2 Maximum 10-min and 3-sec wind speeds at Lidar locations

Site	Maximum 10-minute mean wind speed at Lidar at 100 m [m/s]	Maximum 3-second wind speed measured at Lidar at 100 m [m/s]
Hoarafushi	23.9	27.0
Thulusdhoo	23.7	35.7

8 OBSERVATIONS AND RECOMMENDATIONS

DNV GL makes the following observations and recommendations regarding this analysis:

1. The Lidar units at the Hoarafushi and Thulusdhoo sites were sited in their current locations primarily for the purpose of validating the national Wind Atlas, upon completion of 24 months of data acquisition. While there may be potential for wind farm development at these locations (particularly at Thulusdhoo, due to the higher wind speeds recorded on site), DNV GL recommends that stakeholders wishing to develop a wind project in the Maldives not restrict their site selection to these two locations, as there may be other candidate locations across the country with potential for wind farm development.
2. Based on approximately one year of wind data, DNV GL evaluated the representativeness of the site data to the long-term wind regime based on a monthly wind index derived from the MERRA-2 and ERA-Interim reanalysis data sets. Adjustments were applied to the site wind data to adjust the data to represent long-term estimates. It is noted that the long-term wind speeds at both sites are estimated to be lower than the site measurement period wind speeds. The estimated long-term wind speeds are higher at Thulusdhoo than at Hoarafushi. It is also noted that there is a lack of viable ground station reference data to evaluate the consistency of the reanalysis and virtual datasets considered in this assessment. For this reason, and due to the short period of measurement data, there is increased uncertainty in the long-term wind regime at each site, which has been considered in the uncertainty analysis.
3. DNV GL examined the wind shear profile using the Lidar measurements at both sites. The results indicate that the shear profile at lower hub heights is impacted by seasonal effects caused by varying wind directions, and effects due to wind flow over surrounding land and ocean. However, it is expected that seasonal shear variation due to land effects is not significant at hub heights above 100 m.
4. The power curves used in this analysis include a Vergnet GEV MP C, and a Generic 3 MW turbine model that has been generated by DNV GL. However it is noted that there are turbine on the market now that may be more suitable for the wind regime in the Maldives, than those considered here. Given the preliminary nature of this analysis, DNV GL recommends that potential stakeholders conduct a thorough market review of available technologies when assessing a potential wind farm site in the Maldives.
5. There are a number of losses and uncertainties for which DNV GL's standard assumptions have been made at this stage, or for which an analysis was out of DNV GL's scope of work. It is recommended that The World Bank considers each of the loss categories carefully when using the results in this report for stakeholder engagement. They may vary materially from standard assumptions and can often be mitigated to some extent, especially in early years of the project, through appropriate contractual provisions.
6. DNV GL notes that aside from inter-annual variability, the uncertainty in the analysis is driven by uncertainty in the estimate of the long-term wind regime at both sites.



9 CONCLUSION

The overall ESMAP program for the Maldives originally consisted of providing a validated mesoscale wind atlas for the country, including associated datasets. As part of this program, meteorological data is collected using Lidar units at Hoarafushi and Thulusdhoo over a 24-month period. To date, 12 months of site measurements have been made, which have formed the basis for the interim wind resource statistics and preliminary energy production estimates at both sites.

A key conclusion from this study is that there are now two locations with state-of-the-art remote sensing wind measurement systems in the Maldives that can be used to support stakeholder wind analysis activities and future utility-scale wind development in the country. The data collected from the Lidar units at both sites are considered good both in terms of data quality and data coverage.

In the future, the datasets obtained from these locations could be supplemented with measurements from additional meteorological masts, and/or Lidar monitoring at other potential sites. This would provide the industry with additional sources of site data which could greatly reduce uncertainties for potential developers.

The primary goal of the Lidar site measurements was to validate a country-wide wind map rather than provide potential wind farm locations. Further investment by stakeholders in well-organised measurement campaigns and in feasibility analysis focused on reducing uncertainties will help support the future growth of wind energy developments in the Maldives.

10 REFERENCES

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APPENDIX A WIND DATA STATISTICS

Table A-1 Hoarafushi monthly statistics and data coverage

Month	Mean wind speed [m/s]					Wind speed data coverage [%]					Wind direction data coverage [%]				
Height [m] ¹	11	50	80	100	200	11	50	80	100	200	11	50	80	100	200
Apr-17	2.4	4.5	4.8	4.9	5.0	65	66	65	66	65	65	66	65	66	65
May-17	2.2	5.5	5.8	5.9	6.0	68	95	95	95	93	68	95	95	95	93
Jun-17	2.4	6.6	6.9	7.0	7.3	61	97	96	95	94	61	97	96	95	94
Jul-17	2.6	5.9	6.4	6.5	6.8	67	96	92	91	87	67	96	92	91	87
Aug-17	2.9	7.0	7.5	7.6	7.8	54	95	94	94	93	54	95	94	94	93
Sep-17	3.0	7.2	7.6	7.7	7.9	54	98	97	96	96	54	98	97	96	96
Oct-17	2.2	6.1	6.5	6.5	6.7	52	98	98	98	98	52	98	98	98	98
Nov-17	2.3	3.3	3.3	3.4	3.4	94	96	97	97	97	94	96	97	97	97
Dec-17	2.9	4.3	4.4	4.5	4.5	90	96	97	96	96	90	96	97	96	96
Jan-18	3.0	3.7	3.7	3.7	3.8	97	99	99	99	99	97	99	99	99	99
Feb-18	3.3	4.0	4.1	4.1	4.2	96	97	97	97	97	96	97	97	97	97
Mar-18	2.9	3.8	3.8	3.9	3.9	94	97	96	97	96	94	97	96	97	96

1. Only statistics for key representative measurement heights shown.

Table A-2 Thulusdhoo monthly statistics and data coverage

Month	Mean wind speed [m/s]					Wind speed data coverage [%]					Wind direction data coverage [%]				
Height [m]	11	50	80	100	200	11	50	80	100	200	11	50	80	100	200
Apr-17	2.4	4.9	5.2	5.2	5.3	65	69	71	71	71	65	69	71	71	71
May-17	2.2	6.6	7.0	7.1	7.3	56	99	99	99	97	56	99	99	99	97
Jun-17	2.1	4.9	5.3	5.4	5.6	88	95	94	93	91	88	95	94	93	91
Jul-17	2.6	5.5	5.6	5.6	5.7	78	97	98	97	97	78	97	98	97	97
Aug-17	2.7	6.5	6.8	6.8	7.0	65	98	99	99	97	65	98	99	99	97
Sep-17	2.9	7.0	7.3	7.4	7.5	62	99	99	99	98	62	99	99	99	98
Oct-17	2.4	6.8	7.2	7.3	7.5	47	99	99	99	98	47	99	99	99	98
Nov-17	1.9	4.2	4.4	4.4	4.5	86	98	98	98	97	86	98	98	98	97
Dec-17	2.2	6.3	6.5	6.6	6.7	53	98	99	99	98	53	98	99	99	98
Jan-18	2.2	5.2	5.4	5.4	5.4	73	98	99	99	98	73	98	99	99	98
Feb-18	2.3	6.1	6.2	6.3	6.4	59	95	96	96	95	59	95	96	96	95
Mar-18	2.2	4.6	4.7	4.7	4.7	86	97	98	98	97	86	97	98	98	97

1. Only statistics for key representative measurement heights shown.

Table A-3 Hoarafushi seasonal and diurnal wind speed variation at 100 m – based on site measurement period

Hour	Average 100 m wind speed [m/s]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	3.5	3.7	3.5	3.9	5.8	6.6	6.4	7.4	7.5	6.4	2.8	4.5
0100	3.3	3.6	3.3	3.8	5.8	6.8	6.5	7.4	7.7	6.4	2.8	4.4
0200	3.3	3.6	3.1	4.0	5.8	7.1	6.4	7.5	7.8	6.8	2.7	4.5
0300	3.2	3.6	3.1	4.0	5.9	7.3	6.7	7.5	7.8	6.6	2.9	4.3
0400	3.1	3.6	3.1	4.0	5.9	7.3	6.7	7.1	7.5	6.6	3.2	4.1
0500	3.3	3.7	3.1	3.9	5.7	7.2	6.7	7.0	7.6	6.7	3.4	4.3
0600	3.3	3.7	3.5	3.9	5.7	7.5	6.7	7.1	7.8	6.6	3.5	4.3
0700	3.4	4.0	3.6	3.9	5.7	7.2	6.5	7.3	7.9	6.3	3.3	4.4
0800	3.6	4.0	3.8	4.0	5.7	6.9	6.5	7.2	7.8	6.3	3.5	4.6
0900	3.7	4.2	4.0	4.1	5.4	6.9	6.3	7.4	7.5	6.3	3.5	4.5
1000	4.0	4.3	4.1	4.2	5.2	7.2	6.4	7.5	7.3	6.7	3.5	4.4
1100	4.3	4.3	4.3	4.4	5.4	7.3	6.4	7.3	7.4	7.0	3.6	4.5
1200	4.3	4.4	4.4	4.4	5.8	7.5	6.4	7.7	7.6	6.8	3.7	4.5
1300	4.3	4.4	4.6	4.4	5.9	7.0	6.8	7.8	7.6	6.8	3.8	4.3
1400	4.1	4.6	4.7	4.5	5.9	7.1	6.6	7.8	7.7	7.1	3.8	4.4
1500	4.1	4.6	4.5	4.4	6.0	7.1	7.0	8.0	7.9	6.9	3.9	4.6
1600	3.9	4.6	4.3	4.3	6.1	7.1	7.1	7.8	7.9	6.9	3.6	4.6
1700	3.9	4.5	4.3	4.2	6.5	7.0	6.9	8.2	8.0	6.6	3.5	4.5
1800	4.0	4.4	4.2	4.1	6.2	7.0	6.6	8.1	8.0	6.4	3.5	4.7
1900	3.9	4.5	4.2	4.1	6.3	6.9	6.3	8.1	7.8	6.2	3.5	4.7
2000	3.9	4.4	3.9	4.0	6.3	6.6	6.2	7.9	7.6	6.2	3.3	4.4
2100	4.0	4.2	3.8	3.8	6.1	6.7	6.2	7.8	7.3	6.3	3.2	4.5
2200	3.9	4.0	3.7	3.9	5.8	6.8	6.2	7.6	7.3	6.0	3.0	4.5
2300	3.7	3.7	3.7	3.8	5.7	6.7	6.2	7.2	7.4	6.1	3.2	4.4

Table A-4 Thulusdhoo seasonal and diurnal wind speed variation at 100 m – based on site measurement period

Hour	Average 100 m wind speed [m/s]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	5.1	5.9	4.6	4.4	7.2	5.1	5.0	6.7	7.5	7.2	4.3	6.5
0100	5.0	5.6	4.4	4.4	7.3	5.2	5.1	7.2	7.7	7.4	4.1	6.5
0200	5.2	5.5	4.5	4.5	7.1	5.5	5.3	7.0	8.1	7.4	4.3	6.7
0300	5.2	5.5	4.5	4.2	7.0	5.8	5.6	6.9	7.8	7.4	4.5	6.7
0400	4.9	5.5	4.4	4.3	7.3	5.4	5.9	6.8	7.8	7.3	4.5	6.4
0500	4.8	5.5	4.3	4.3	7.1	5.2	5.6	6.7	7.8	7.4	4.4	6.7
0600	4.8	5.7	4.5	4.4	7.0	5.6	5.3	6.6	7.8	7.5	4.0	6.7
0700	4.8	5.8	4.5	4.2	6.6	5.7	5.3	6.5	7.3	7.3	3.8	6.5
0800	5.1	5.9	4.5	4.2	6.3	5.4	5.1	6.6	7.1	7.3	4.0	6.3
0900	5.2	6.0	4.4	4.2	6.3	5.6	5.1	6.7	6.7	6.9	4.2	6.5
1000	5.3	6.2	4.5	4.3	6.9	5.6	5.9	6.8	6.7	6.9	4.6	6.5
1100	5.4	6.3	4.6	4.5	7.0	5.4	5.7	6.8	6.7	7.2	4.8	6.3
1200	5.5	6.4	4.8	4.5	6.7	5.5	5.7	7.1	6.9	7.2	5.2	6.3
1300	5.6	6.6	5.2	4.3	6.8	5.6	6.1	7.2	7.2	7.5	4.8	6.3
1400	5.5	6.9	5.3	4.3	7.2	5.7	6.4	7.4	7.4	7.4	4.7	6.5
1500	5.8	6.7	5.4	4.6	7.3	5.5	6.4	7.2	7.4	7.6	4.7	6.8
1600	5.8	6.8	5.4	4.7	7.2	5.5	6.0	7.1	7.6	7.5	4.2	6.8
1700	6.0	6.8	5.1	4.7	7.6	5.2	6.0	6.8	7.5	7.4	4.1	6.7
1800	6.1	7.1	5.0	4.6	7.7	5.2	6.5	6.8	7.6	7.5	4.1	6.7
1900	5.9	6.9	4.8	4.6	7.5	5.1	6.1	6.5	7.0	7.3	4.5	6.8
2000	5.8	6.6	4.7	4.6	7.0	5.2	5.5	6.9	7.1	7.2	4.6	6.8
2100	5.6	6.8	4.6	4.4	7.1	5.3	5.3	6.7	7.2	7.2	4.5	6.7
2200	5.7	6.8	4.3	4.4	7.1	5.0	5.3	6.4	7.2	7.1	4.4	6.6
2300	5.7	6.5	4.4	4.5	7.2	5.1	5.3	6.5	7.4	6.9	4.4	6.5



APPENDIX B REFERENCE DATA CONSIDERED

MERRA-2 Reanalysis data

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

DNV GL has some concerns over the long-term consistency of reanalysis data and has conducted investigations into the consistency of the MERRA-2 dataset close to the site. On the basis of these investigations the long-term reference period considered for the MERRA-2 dataset is from January 2002 to the present.

ERA-Interim Reanalysis data

DNV GL has considered ERA-Interim data as part of this analysis. The ECMWF Interim Reanalysis (ERA-Interim) is a global atmospheric reanalysis product of the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA-Interim dataset uses weather measurements from a number of sources as inputs to a numerical atmospheric model in order to produce a description of the state of the atmosphere, including wind speed. The analysis is performed at a spatial resolution of 0.75° longitude by 0.75° latitude with a 6 hourly temporal resolution. DNV GL has some concerns over the long-term consistency of reanalysis data, and hence in order to mitigate against potential inclusion of inconsistent data in the long-term analysis, DNV GL has considered the same long-term reference period for the ERA-Interim dataset as for the MERRA datasets, i.e. from January 2002 to the present. DNV GL procured 6-hourly time series of two-dimensional diagnostic data, at a surface height of 10 m for the nearest grid points near the project site.

DNV GL Virtual Met Data (VMD)

The 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 new high-resolution inputs, such as MERRA, 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 typically produced as a virtual hourly time series on a 2 km horizontal resolution grid, centred on the subject wind farm site at the location of a the site measurement.



APPENDIX C WIND FARM SITE INFORMATION AND LAYOUTS

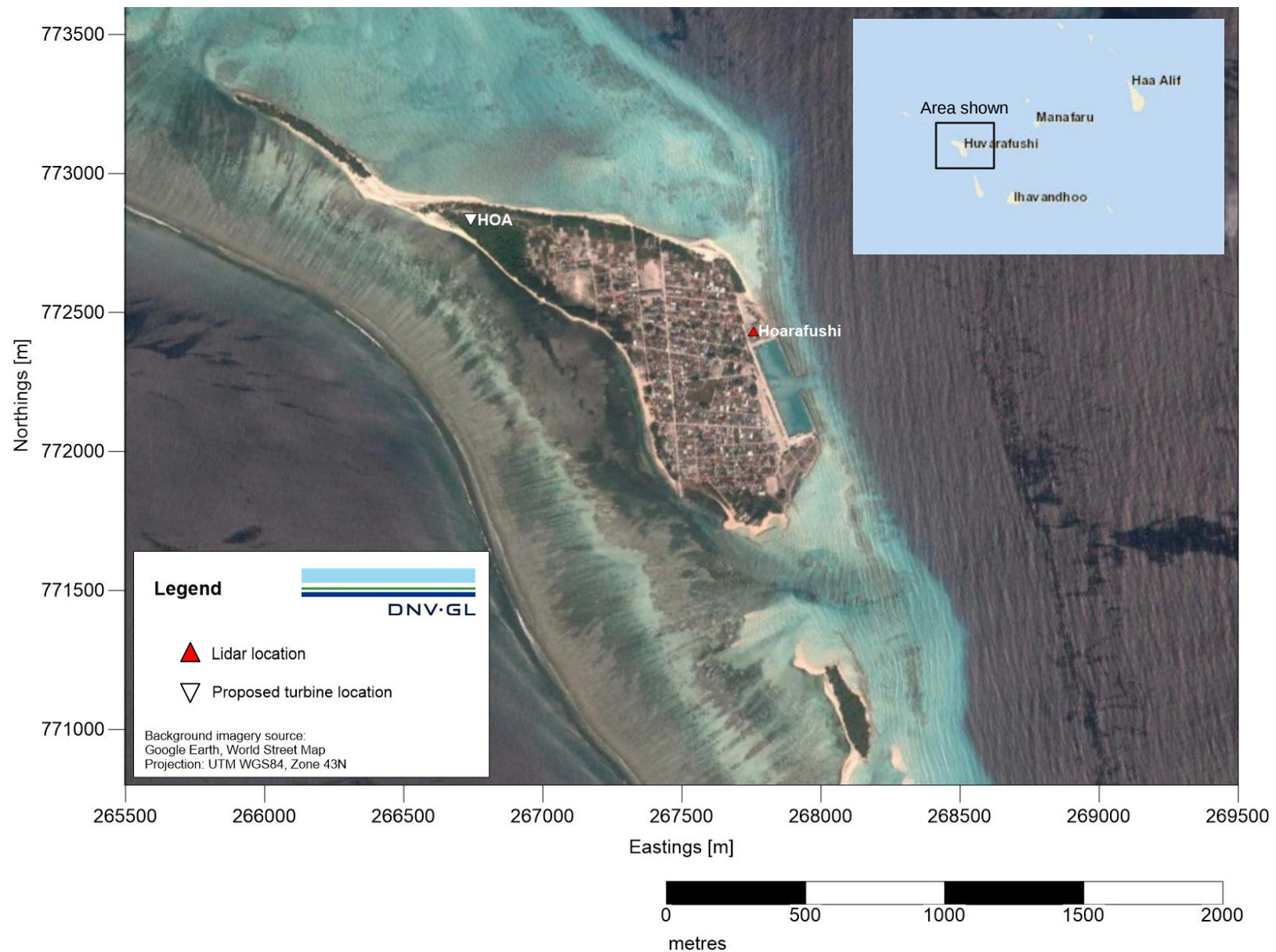


Figure C-1 Map of Hoarafushi site showing locations of Lidar monitoring and proposed turbine



Figure C-2 Map of Thulusdhoo site showing locations of Lidar monitoring and proposed turbine



APPENDIX D TURBINE LAYOUT RESULTS

Table D-1 Hoarafushi turbine layout with predicted wind speed and energy production

Turbine	Easting ¹	Northing ¹	Turbine base elevation ²	Turbine model	Hub height	Long-term wind speed at hub height ³	Energy output ⁴
	[m]	[m]	[m ASL]		[m]	[m/s]	[GWh/annum]
HOA	266742	772832	4	GEV MP C	50	5.0	0.271
				Generic 3 MW	100	5.2	3.77

Table D-2 Thulusdhoo turbine layout with predicted wind speed and energy production

Turbine	Easting ¹	Northing ¹	Turbine base elevation ²	Turbine model	Hub height	Long-term wind speed at hub height ³	Energy output ⁴
	[m]	[m]	[m ASL]		[m]	[m/s]	[GWh/annum]
THU	349366	483312	2	GEV MP C	50	5.6	0.345
				Generic 3 MW	100	5.8	4.56

Notes

1. Coordinate system is UTM Zone 43N, WGS84 datum.
2. Estimate based on SRTM1 elevation data.
3. Wind speed at the location of the turbine.
4. Individual turbine output figures including all wind farm losses.

Table D-3 Vergnet GEV MP C turbine power curve

		Hub height wind speed [m/s]	Electrical power [kW]	Thrust coefficient [Ct]
Manufacturer	Vergnet			
Turbine	GEV MP C	1	0	0.00
Power Control	Pitch	2	0	0.00
Rated power	275 kW	3	0	0.00
Diameter	32 m	4	3	0.93
Hub height	50 m	5	18	0.86
Rotor speed	31 - 46 rpm	6	36	0.78
Air Density	1.225 kg/m ³	7	58	0.70
Peak Cp	0.39	8	98	0.86
Cut out 10-minute mean wind speed	25 m/s	9	141	0.80
Restart 10-minute mean wind speed	22.5 m/s	10	189	0.74
		11	243	0.60
		12	272	0.45
		13	275	0.37
		14	275	0.29
		15	275	0.21
		16	275	0.18
		17	275	0.15
		18	275	0.12
		19	275	0.11
		20	275	0.09
		21	275	0.08
		22	275	0.07
		23	275	0.06
		24	275	0.05
		25	275	0.04

The graph displays three performance metrics of the Vergnet GEV MP C turbine as a function of wind speed (0 to 25 m/s). The left y-axis represents Power in kW (0 to 300), and the right y-axis represents the thrust coefficient (Ct) and power coefficient (Cp) from 0 to 1. The Power curve (red) begins at 3 m/s, reaches the rated power of 275 kW at 12 m/s, and maintains this level through the cut-out speed of 25 m/s. The Ct curve (green) shows a peak of 0.93 at 4 m/s before declining. The Cp curve (blue) peaks at 0.39 at 8 m/s and then decreases.

Table D-4 Generic 3 MW turbine power curve

		Hub height wind speed [m/s]	Electrical power [kW]	Thrust coefficient [Ct]
Manufacturer	Generic			
Turbine	Generic	1	0	0.00
Power Control	Pitch	2	0	0.00
Rated power	3000 kW	3	29	0.85
Diameter	100 m	4	117	0.85
Hub height	100 m	5	255	0.85
Rotor speed	6 - 16 rpm	6	458	0.85
Air Density	1.225 kg/m ³	7	738	0.85
Peak Cp	0.45	8	1102	0.85
Cut out 10-minute mean wind speed	25 m/s	9	1571	0.82
Restart 10-minute mean wind speed	22.5 m/s	10	2117	0.75
		11	2677	0.69
		12	2931	0.52
		13	2990	0.38
		14	3000	0.30
		15	3000	0.24
		16	3000	0.20
		17	3000	0.16
		18	3000	0.14
		19	3000	0.12
		20	3000	0.10
		21	3000	0.09
		22	3000	0.08
		23	3000	0.07
		24	3000	0.06
		25	3000	0.05

The graph illustrates the performance characteristics of a generic 3 MW turbine. The x-axis represents Wind Speed in m/s, ranging from 0 to 25. The left y-axis represents Power in kW, ranging from 0 to 3500. The right y-axis represents the thrust coefficient (Ct) and power coefficient (Cp), ranging from 0 to 0.9. Three curves are plotted: Power (red), Ct (green), and Cp (blue). The Power curve shows the electrical power output, which begins to rise at 3 m/s and reaches its rated value of 3000 kW at 12 m/s, remaining constant thereafter. The Ct curve shows the thrust coefficient, which peaks at 0.85 at 8 m/s and then decreases as wind speed increases. The Cp curve shows the power coefficient, which peaks at 0.45 at 8 m/s and then decreases as wind speed increases.



APPENDIX E MONTHLY AND DIURNAL PRODUCTION PROFILES

Table E-1 Hoarafushi monthly and diurnal production matrix – Vergnet GEV MP C turbine option

Hour	Energy Production ^a [%]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	0.07	0.07	0.11	0.08	0.52	0.52	0.41	0.70	0.69	0.64	0.03	0.17
0100	0.09	0.07	0.08	0.06	0.52	0.65	0.49	0.74	0.72	0.57	0.04	0.15
0200	0.08	0.09	0.08	0.08	0.57	0.64	0.40	0.73	0.76	0.70	0.05	0.12
0300	0.06	0.09	0.04	0.07	0.63	0.73	0.47	0.82	0.77	0.64	0.06	0.13
0400	0.06	0.07	0.04	0.07	0.59	0.71	0.41	0.65	0.66	0.67	0.13	0.12
0500	0.06	0.08	0.03	0.07	0.45	0.68	0.47	0.67	0.72	0.64	0.07	0.12
0600	0.06	0.09	0.06	0.07	0.49	0.79	0.38	0.70	0.78	0.64	0.08	0.13
0700	0.07	0.11	0.07	0.06	0.48	0.67	0.34	0.65	0.72	0.56	0.05	0.22
0800	0.08	0.11	0.08	0.07	0.41	0.64	0.35	0.65	0.72	0.58	0.15	0.23
0900	0.09	0.10	0.09	0.07	0.37	0.59	0.37	0.61	0.69	0.54	0.05	0.23
1000	0.13	0.15	0.10	0.08	0.44	0.54	0.38	0.66	0.61	0.58	0.06	0.12
1100	0.14	0.12	0.10	0.12	0.39	0.75	0.45	0.70	0.66	0.64	0.07	0.22
1200	0.16	0.16	0.15	0.11	0.40	0.66	0.38	0.70	0.70	0.55	0.09	0.22
1300	0.14	0.12	0.18	0.12	0.50	0.56	0.38	0.72	0.69	0.59	0.06	0.19
1400	0.12	0.17	0.18	0.13	0.50	0.61	0.40	0.56	0.69	0.66	0.08	0.19
1500	0.13	0.16	0.13	0.11	0.57	0.56	0.40	0.81	0.81	0.55	0.08	0.11
1600	0.11	0.19	0.14	0.11	0.55	0.51	0.48	0.71	0.67	0.60	0.06	0.20
1700	0.12	0.16	0.17	0.10	0.69	0.47	0.43	0.75	0.77	0.54	0.07	0.22
1800	0.12	0.16	0.11	0.10	0.56	0.58	0.40	0.84	0.80	0.52	0.05	0.14
1900	0.09	0.15	0.14	0.10	0.61	0.55	0.35	0.76	0.64	0.50	0.07	0.26
2000	0.10	0.18	0.13	0.11	0.51	0.51	0.40	0.77	0.61	0.52	0.05	0.18
2100	0.09	0.16	0.13	0.09	0.51	0.52	0.38	0.81	0.60	0.54	0.05	0.17
2200	0.06	0.13	0.07	0.07	0.48	0.52	0.37	0.75	0.65	0.52	0.03	0.15
2300	0.08	0.08	0.13	0.05	0.45	0.52	0.33	0.71	0.60	0.53	0.13	0.16
All	2.32	2.97	2.55	2.12	12.19	14.50	9.63	17.17	16.74	14.04	1.64	4.12

a. Energy figures do not include availability, electrical efficiency or turbine performance losses.

Table E-2 Hoarafushi monthly and diurnal production matrix – Generic 3 MW turbine option

Hour	Energy Production ^a [%]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	0.09	0.08	0.12	0.11	0.48	0.54	0.45	0.72	0.65	0.59	0.04	0.18
0100	0.09	0.08	0.08	0.09	0.48	0.58	0.51	0.77	0.65	0.52	0.05	0.16
0200	0.08	0.10	0.08	0.10	0.52	0.58	0.42	0.73	0.69	0.71	0.06	0.16
0300	0.07	0.10	0.05	0.11	0.49	0.63	0.48	0.80	0.71	0.63	0.07	0.14
0400	0.07	0.08	0.06	0.10	0.55	0.70	0.43	0.63	0.62	0.63	0.12	0.14
0500	0.07	0.09	0.05	0.10	0.44	0.59	0.46	0.66	0.69	0.62	0.08	0.12
0600	0.07	0.10	0.08	0.11	0.44	0.74	0.44	0.69	0.72	0.64	0.09	0.15
0700	0.08	0.12	0.09	0.09	0.47	0.64	0.41	0.67	0.66	0.56	0.06	0.21
0800	0.10	0.13	0.10	0.10	0.38	0.58	0.45	0.60	0.65	0.54	0.13	0.21
0900	0.10	0.11	0.11	0.10	0.35	0.50	0.42	0.62	0.62	0.54	0.07	0.21
1000	0.13	0.15	0.12	0.11	0.34	0.52	0.41	0.63	0.56	0.59	0.07	0.13
1100	0.15	0.12	0.12	0.12	0.39	0.65	0.42	0.64	0.61	0.64	0.08	0.20
1200	0.16	0.16	0.15	0.13	0.45	0.60	0.40	0.70	0.65	0.56	0.10	0.21
1300	0.15	0.13	0.18	0.14	0.43	0.50	0.43	0.73	0.61	0.60	0.08	0.19
1400	0.13	0.17	0.19	0.15	0.45	0.53	0.44	0.59	0.63	0.68	0.09	0.18
1500	0.13	0.16	0.15	0.14	0.50	0.54	0.44	0.78	0.73	0.58	0.09	0.12
1600	0.12	0.18	0.15	0.13	0.47	0.51	0.51	0.70	0.64	0.61	0.08	0.19
1700	0.13	0.16	0.17	0.13	0.65	0.50	0.48	0.78	0.73	0.54	0.08	0.20
1800	0.13	0.16	0.12	0.12	0.53	0.57	0.47	0.83	0.80	0.54	0.06	0.15
1900	0.10	0.15	0.14	0.14	0.62	0.55	0.42	0.83	0.64	0.53	0.08	0.25
2000	0.11	0.17	0.14	0.12	0.54	0.50	0.45	0.82	0.65	0.55	0.06	0.19
2100	0.11	0.15	0.14	0.10	0.52	0.52	0.53	0.88	0.65	0.59	0.06	0.18
2200	0.08	0.13	0.09	0.09	0.49	0.56	0.42	0.74	0.65	0.53	0.04	0.16
2300	0.09	0.09	0.13	0.08	0.42	0.52	0.35	0.69	0.61	0.56	0.13	0.16
All	2.57	3.08	2.80	2.68	11.38	13.63	10.64	17.23	15.83	14.09	1.87	4.20

a. Energy figures do not include availability, electrical efficiency or turbine performance losses.

Table E-3 Thulusdhoo monthly and diurnal production matrix – Vergnet GEV MP C turbine option

Hour	Energy Production ^a [%]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	0.19	0.25	0.17	0.11	0.66	0.16	0.14	0.46	0.58	0.57	0.14	0.45
0100	0.19	0.23	0.13	0.10	0.74	0.17	0.20	0.57	0.63	0.67	0.15	0.48
0200	0.19	0.22	0.13	0.13	0.61	0.20	0.21	0.54	0.62	0.67	0.15	0.52
0300	0.22	0.22	0.13	0.11	0.61	0.25	0.24	0.51	0.63	0.64	0.18	0.54
0400	0.18	0.21	0.10	0.10	0.63	0.19	0.33	0.48	0.66	0.63	0.21	0.48
0500	0.15	0.21	0.10	0.10	0.57	0.15	0.28	0.54	0.67	0.66	0.20	0.56
0600	0.15	0.22	0.12	0.10	0.58	0.19	0.20	0.46	0.64	0.65	0.16	0.54
0700	0.17	0.22	0.11	0.08	0.49	0.22	0.25	0.46	0.53	0.59	0.14	0.49
0800	0.18	0.26	0.12	0.07	0.42	0.19	0.21	0.49	0.46	0.58	0.16	0.45
0900	0.19	0.24	0.11	0.07	0.48	0.29	0.26	0.49	0.42	0.47	0.17	0.48
1000	0.22	0.29	0.12	0.10	0.57	0.23	0.33	0.49	0.36	0.51	0.19	0.52
1100	0.28	0.31	0.13	0.10	0.58	0.15	0.33	0.49	0.36	0.63	0.22	0.48
1200	0.24	0.36	0.13	0.11	0.52	0.13	0.32	0.49	0.42	0.55	0.29	0.46
1300	0.25	0.46	0.19	0.09	0.53	0.18	0.37	0.55	0.48	0.60	0.22	0.41
1400	0.28	0.45	0.24	0.08	0.58	0.22	0.37	0.60	0.51	0.59	0.17	0.49
1500	0.32	0.39	0.27	0.13	0.61	0.19	0.46	0.56	0.52	0.62	0.22	0.57
1600	0.31	0.44	0.24	0.12	0.59	0.16	0.33	0.55	0.55	0.61	0.16	0.53
1700	0.37	0.42	0.20	0.15	0.68	0.14	0.32	0.43	0.58	0.57	0.14	0.54
1800	0.33	0.44	0.21	0.14	0.71	0.13	0.42	0.46	0.57	0.63	0.14	0.50
1900	0.32	0.46	0.17	0.13	0.63	0.14	0.35	0.38	0.47	0.58	0.20	0.53
2000	0.26	0.37	0.15	0.10	0.59	0.13	0.25	0.46	0.48	0.54	0.20	0.51
2100	0.26	0.36	0.14	0.10	0.58	0.19	0.24	0.41	0.50	0.57	0.20	0.52
2200	0.25	0.37	0.12	0.11	0.61	0.14	0.21	0.40	0.49	0.53	0.23	0.50
2300	0.26	0.35	0.11	0.10	0.62	0.16	0.20	0.44	0.55	0.53	0.21	0.48
All	5.76	7.73	3.65	2.54	14.18	4.28	6.81	11.70	12.70	14.19	4.45	12.02

a. Energy figures do not include availability, electrical efficiency or turbine performance losses.

Table E-4 Thulusdhoo monthly and diurnal production matrix – Generic 3 MW turbine option

Hour	Energy Production ^a [%]											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0000	0.20	0.26	0.17	0.13	0.60	0.21	0.19	0.47	0.56	0.58	0.16	0.44
0100	0.20	0.23	0.13	0.12	0.67	0.23	0.20	0.54	0.58	0.69	0.15	0.45
0200	0.20	0.22	0.13	0.15	0.61	0.25	0.22	0.50	0.62	0.63	0.17	0.48
0300	0.22	0.22	0.13	0.12	0.59	0.31	0.25	0.52	0.60	0.61	0.20	0.48
0400	0.19	0.22	0.12	0.12	0.62	0.22	0.29	0.49	0.57	0.61	0.20	0.45
0500	0.16	0.21	0.12	0.11	0.58	0.18	0.27	0.50	0.62	0.63	0.20	0.51
0600	0.16	0.22	0.13	0.13	0.58	0.26	0.21	0.47	0.59	0.66	0.16	0.49
0700	0.16	0.22	0.13	0.11	0.47	0.27	0.25	0.45	0.49	0.61	0.15	0.44
0800	0.19	0.23	0.14	0.10	0.45	0.23	0.22	0.47	0.47	0.60	0.16	0.42
0900	0.20	0.24	0.13	0.11	0.49	0.26	0.25	0.47	0.40	0.53	0.16	0.46
1000	0.22	0.28	0.13	0.13	0.59	0.24	0.30	0.48	0.40	0.52	0.20	0.46
1100	0.24	0.28	0.14	0.14	0.60	0.22	0.31	0.45	0.37	0.60	0.22	0.44
1200	0.23	0.32	0.16	0.13	0.51	0.21	0.31	0.53	0.43	0.57	0.27	0.43
1300	0.25	0.39	0.19	0.12	0.55	0.24	0.33	0.53	0.47	0.63	0.21	0.41
1400	0.26	0.40	0.22	0.10	0.62	0.25	0.36	0.58	0.51	0.60	0.17	0.46
1500	0.29	0.39	0.23	0.15	0.60	0.23	0.40	0.54	0.51	0.66	0.20	0.51
1600	0.27	0.41	0.23	0.14	0.60	0.22	0.31	0.52	0.55	0.60	0.15	0.49
1700	0.33	0.37	0.21	0.16	0.66	0.20	0.29	0.46	0.56	0.61	0.15	0.47
1800	0.32	0.43	0.20	0.14	0.69	0.20	0.40	0.46	0.57	0.62	0.16	0.48
1900	0.29	0.42	0.18	0.15	0.65	0.20	0.35	0.37	0.48	0.58	0.19	0.46
2000	0.31	0.32	0.16	0.13	0.60	0.21	0.26	0.47	0.48	0.57	0.20	0.49
2100	0.25	0.35	0.15	0.12	0.57	0.24	0.25	0.43	0.47	0.59	0.20	0.49
2200	0.29	0.37	0.13	0.12	0.61	0.20	0.22	0.41	0.48	0.55	0.22	0.48
2300	0.26	0.34	0.13	0.12	0.61	0.23	0.21	0.44	0.53	0.55	0.20	0.47
All	5.70	7.32	3.80	3.05	14.14	5.48	6.68	11.53	12.30	14.42	4.46	11.13

a. Energy figures do not include availability, electrical efficiency or turbine performance losses.



APPENDIX F UNCERTAINTY ANALYSIS

Table F-1 Uncertainty in the projected energy output for the Hoarafushi site – GEV MP C turbine option

Source of uncertainty/variability	[GWh/annum]		Equivalent standard deviation [%]	
Measurement accuracy	0.019		6.9%	
Long-term measurement height wind regime	0.030		11.0%	
Vertical extrapolation	0.00		0.0%	
Spatial extrapolation	0.009		3.3%	
Loss factors	0.013		4.7%	
Inter-annual variability	0.042		15.6%	
<i>Future period under consideration</i>	<i>1 year</i>	<i>20 year</i>	<i>1 year</i>	<i>20 year</i>
Overall energy uncertainty	0.057	0.041	20.9%	15.1%

Table F-2 Uncertainty in the projected energy output for the Hoarafushi site – Generic turbine option

Source of uncertainty/variability	[GWh/annum]		Equivalent standard deviation [%]	
Measurement accuracy	0.23		6.1%	
Long-term measurement height wind regime	0.39		10.4%	
Vertical extrapolation	0.00		0.0%	
Spatial extrapolation	0.11		2.9%	
Loss factors	0.15		4.1%	
Inter-annual variability	0.53		14.0%	
<i>Future period under consideration</i>	<i>1 year</i>	<i>20 year</i>	<i>1 year</i>	<i>20 year</i>
Overall energy uncertainty	0.71	0.51	19.0%	13.6%

Table F-3 Uncertainty in the projected energy output for the Thulusdhoo site – GEV MP C turbine option

Source of uncertainty/variability	[GWh/annum]		Equivalent standard deviation [%]	
Measurement accuracy	0.023		6.6%	
Long-term measurement height wind regime	0.054		15.7%	
Vertical extrapolation	0.000		0.0%	
Spatial extrapolation	0.012		3.5%	
Loss factors	0.016		4.5%	
Inter-annual variability	0.052		15.1%	
<i>Future period under consideration</i>	<i>1 year</i>	<i>20 year</i>	<i>1 year</i>	<i>20 year</i>
Overall energy uncertainty	0.080	0.064	23.2%	18.5%

Table F-4 Uncertainty in the projected energy output for the Thulusdhoo site – Generic turbine option

Source of uncertainty/variability	[GWh/annum]		Equivalent standard deviation [%]	
Measurement accuracy	0.27		5.9%	
Long-term measurement height wind regime	0.58		12.7%	
Vertical extrapolation	0.00		0.0%	
Spatial extrapolation	0.14		3.1%	
Loss factors	0.18		4.0%	
Inter-annual variability	0.62		13.7%	
<i>Future period under consideration</i>	<i>1 year</i>	<i>20 year</i>	<i>1 year</i>	<i>20 year</i>
Overall energy uncertainty	0.92	0.71	20.1%	15.6%



APPENDIX G SITE CONDITIONS

Table G-1 Predicted ambient turbulence intensity at the Hoarafushi Lidar location at a measurement height of 50 m

Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	All Direction
1	23.7	22.3	22.3	24.8	22.6	22.4	21.8	22.8	30.0	21.5	25.3	22.8	23.4
2	19.7	17.5	18.6	18.3	20.6	21.0	22.3	23.9	25.8	21.2	19.8	20.3	19.8
3	13.6	12.3	12.6	12.2	12.4	13.7	17.4	18.2	18.5	20.2	16.5	15.3	14.7
4	9.6	9.2	9.0	9.2	10.0	11.1	13.9	15.9	16.3	17.9	15.5	12.0	12.4
5	7.8	7.6	8.0	7.7	7.8	10.4	12.4	17.7	13.2	15.9	14.5	9.3	11.6
6	6.9	6.8	7.3	7.4	7.3	8.9	14.9	13.6	10.7	14.3	13.1	8.4	11.3
7	6.6	6.4	7.3	6.4	+	8.0	13.1	12.6	9.5	12.4	12.4	8.2	10.7
8	7.2	6.1	8.6	8.1	+	+	+	9.9	8.5	11.6	12.2	8.5	10.4
9	7.6	6.8	7.3	+	+	+	+	11.3	8.7	11.1	11.8	8.9	10.4
10	+	+	6.6	+	+		+	13.2	8.2	11.0	11.5	8.7	10.1
11	+		+	+		+	+	12.2	8.6	10.7	11.4	9.1	10.0
12			+					+	8.4	11.5	10.3	8.7	9.7
13						+		+	9.1	10.4	11.3	+	9.8
14	+							+	9.2	10.6	+	+	9.5
15									10.3	9.5	+		10.2
16								+	9.8	+	+	+	10.0
17									10.6	+			10.3
18									+	+			+
19													
20													
21													
22													
23													
24+													
5+	7.4	7.1	7.7	7.4	7.8	9.7	13.5	13.4	9.6	13.1	13.0	8.7	11.0

Table G-2 Predicted ambient turbulence intensity at the Hoarafushi Lidar location at a measurement height of 100 m

Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	All Direction
1	25.2	23.8	22.9	21.6	22.1	22.9	24.7	19.1	23.8	23.0	19.4	22.3	22.5
2	19.5	17.8	17.8	17.1	19.4	19.2	20.7	24.4	21.8	18.7	17.9	20.5	18.9
3	13.6	12.5	11.9	12.1	12.6	13.3	17.7	17.7	16.4	16.9	15.3	14.7	14.0
4	9.6	9.1	8.9	9.0	9.4	10.3	10.8	13.7	13.5	15.2	12.6	11.1	10.9
5	7.6	7.4	7.8	7.9	7.2	8.7	10.7	13.3	11.4	13.2	11.5	8.6	9.8
6	6.4	6.5	7.1	7.0	7.9	8.1	8.3	11.3	8.7	11.6	10.4	7.3	9.2
7	6.1	5.9	6.6	6.0	+	7.6	10.1	8.5	7.8	9.6	9.4	7.0	8.5
8	6.1	5.7	8.0	6.2	+	+	11.3	8.4	7.2	8.7	9.1	6.9	8.2
9	5.5	4.9	6.7	+	+	+	+	8.0	7.2	8.3	8.8	7.1	8.0
10	+	+	8.2	+	+	+	+	11.5	7.2	8.3	8.6	7.7	8.1
11	+	+	+	+	+	+	+	9.0	7.4	8.0	8.3	7.2	7.9
12			+				+	+	7.4	8.6	8.1	7.0	8.0
13	+							+	7.9	9.2	8.0	7.9	8.4
14						+		+	7.9	8.9	9.0	+	8.3
15								+	9.3	+	+		9.0
16									9.6	+	+	+	9.1
17								+	10.3	+	+		9.7
18									+	+			+
19									+				+
20													
21													
22													
23													
24+													
5+	7.0	6.7	7.4	7.1	7.3	8.5	10.1	10.0	8.0	9.9	9.8	7.7	8.8

Table G-3 Predicted ambient turbulence intensity at the Thulusdhoo Lidar location at a measurement height of 50 m

Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	All Direction
1	29.8	27.0	23.0	24.9	26.9	27.7	22.5	25.3	28.4	22.1	22.8	21.6	25.2
2	18.1	16.7	21.5	21.0	23.8	26.0	26.5	21.0	20.6	19.5	19.2	18.8	20.7
3	14.5	14.8	15.3	18.0	19.9	19.5	20.2	20.0	17.3	16.9	15.6	14.1	16.5
4	10.4	12.0	11.8	16.2	15.0	14.8	16.7	16.4	16.5	14.7	11.2	10.3	13.5
5	8.2	9.8	10.3	14.8	12.7	15.2	13.4	13.8	14.9	12.9	9.2	8.3	11.6
6	7.3	8.9	9.3	12.7	10.0	17.9	8.4	11.6	13.8	11.9	8.0	7.3	10.2
7	7.4	7.6	8.6	11.3	8.0	+	10.7	11.7	13.5	11.3	7.8	7.0	9.8
8	9.4	7.7	8.3	10.8	7.8	+	+	11.5	12.1	10.7	7.6	7.1	9.4
9	8.1	9.0	8.2	11.0	+	+	10.4	11.7	11.5	10.1	8.2	6.9	9.2
10	+	8.7	8.5	9.6	+	+	+	10.2	11.6	9.6	8.1	6.9	9.0
11	+	8.4	8.3	10.3	+	+	+	10.0	12.3	10.5	8.3	7.2	9.5
12	+	+	9.6	+	+	+	+	+	11.4	10.5	8.9	7.6	9.7
13		+	+	+	+	+	+	+	12.2	10.8	9.6	7.3	10.5
14		+	+		+			+	11.4	11.2	9.6	7.1	10.7
15		+	+						11.7	11.2	9.5	10.5	10.8
16									+	11.1	9.5	+	10.9
17									+	9.3	+	+	10.0
18									+	+	+		9.7
19										+	+	+	+
20												+	+
21											+		+
22													
23													
24+													
5+	7.9	8.9	8.8	12.5	10.5	15.9	11.6	12.4	13.4	11.4	8.3	7.5	10.2

Table G-4 Predicted ambient turbulence intensity at the Thulusdhoo Lidar location at a measurement height of 100 m

Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	All Direction
1	22.1	25.5	27.9	22.5	26.8	25.1	24.9	26.5	23.7	22.6	22.9	21.2	24.5
2	19.2	17.7	19.7	21.5	23.6	23.6	23.3	20.6	18.5	18.7	19.6	19.5	20.2
3	14.5	13.9	14.3	17.4	20.2	20.4	18.5	17.5	15.8	15.6	15.1	14.2	15.7
4	9.7	10.9	11.3	15.3	14.2	13.6	17.0	14.4	13.9	12.4	10.8	10.0	12.1
5	7.5	9.3	10.2	13.4	11.0	12.6	11.7	12.0	12.1	10.4	8.6	8.1	10.1
6	7.1	7.7	8.9	12.0	10.0	12.9	8.5	9.4	11.2	8.6	7.5	6.9	8.7
7	6.4	6.2	8.0	9.6	8.0	+	10.2	9.2	10.4	7.8	6.8	6.4	8.0
8	8.2	6.7	7.5	9.9	6.5	+	+	9.7	9.5	7.8	6.8	6.4	7.9
9	8.1	6.5	7.2	9.6	+	+	9.4	8.7	8.6	7.4	7.2	6.2	7.5
10	+	6.4	7.4	8.6	+		+	9.8	7.8	7.0	7.2	5.9	7.3
11	+	9.6	7.1	8.0	+			7.5	8.8	7.6	7.4	6.6	7.6
12	+	+	8.1	8.5	+			6.9	9.0	7.9	7.5	6.1	7.9
13		+	+	+	+			+	8.5	8.2	8.0	6.7	8.1
14		+	+	+				+	8.2	7.9	9.5	7.0	8.4
15			+						8.8	9.2	8.4	8.5	8.9
16		+							9.4	7.7	9.7	+	8.6
17									8.4	8.8	8.4	+	8.5
18									+	8.3	+	+	8.9
19									+	+	+		8.4
20									+	+	+	+	+
21											+		+
22													
23													
24+													
5+	7.3	7.8	8.2	11.1	9.8	12.6	10.5	10.2	10.2	8.3	7.6	7.0	8.5



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.