LONG-TERM YIELD ASSESSMENT

TUVALU WIND FARM, TUVALU

28/02/2023
REV00

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Glossary

AEP	Annual Energy Production
AGL / ASL	Above Ground Level / Above Sea Level
BOP	BOP (Balance of Plant) corresponds to civil and electrical infrastructures inside the wind farm (inter-array cables, junction boxes, foundations, etc.).
Displacement height	Large areas of tall obstacles affect the wind shear, lifting the zero velocity theoretical height by a value called the displacement height.
ERA-5	ERA-5 is an hourly reanalysis dataset produced by the European Centre for Medium-Range Weather Forecast (ECMWF) cover a period from 1979 to the present. It extends to the whole of earth on a grid of 30km, resolving the atmosphere using 137 levels from the surface up to a height of 80km.
HH	Hub height
Mann-Kendall test	The Mann-Kendall test is a statistical test widely used for the analysis of trends in climatologic time series. The purpose of the test is to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time.
MCP	Measure-correlate-predict (MCP) algorithms are used to extrapolate wind measurement time series to the long-term. MCP methods first model the relationship between the site wind measurements (speed and direction) and the long-term reference wind data. It then applies this relationship to the whole reference data in order to construct a long-term time series of wind speed and direction at the site.
MERRA-2	MERRA-2, the Modern Era Retrospective Analysis for Research and Applications is a reanalysis dataset from NASA. It covers the period from 1980 to present with a resolution of 1/2° x 0.625° (latitude x longitude).
RD	Rotor diameter
Reanalysis	Reanalysis data are the results of a meteorological data assimilation process that aims to assimilate historical observational data spanning an extended period, using a single consistent assimilation (or "analysis") scheme throughout this period.
RIX	The ruggedness index (RIX) at a specific location is the percentage of the ground surface that has a slope above a given threshold (e.g. 40%) within a certain distance.
RP	Rated power
SNHT test	The SNHT test (Standard Normal Homogeneity Test) was initially developed to detect a change in a series of rainfall data. It has been used in a number of studies for climate data homogenization.

Turbine interaction losses	Combined production losses due to interaction effects (wake and blockage) between wind turbines within a wind farm.
Wake losses	The wake losses are production losses due to the mutual interaction of wind turbines, caused by the wind energy deficit downstream of the wind turbine rotors.
WAsP	WAsP (Wind Atlas Analysis and Application Program) is a software package that simulates wind flows for predicting wind climates, wind resources, and power productions from wind turbines and wind farms. WAsP is developed and distributed by DTU Wind Energy, Denmark. It has become the wind power industry-standard PC-software for wind resource assessment.
Weibull distribution	In probability theory and statistics, the Weibull distribution is a continuous probability distribution function with two parameters: k (shape) and A (scale). It is widely used in the wind power community as an approximation of the frequency distribution of wind speeds from a time series.
Wind farm blockage loss	Difference in production due to the accumulated induction effect of the wind farm between a turbine when operating in isolation and when operating in an array.
Wind Index	The wind index of a period quantifies the windiness of this period compared to a long-term reference period. It is usually done in terms of wind turbine power output. The long-term period is given an index of 100. Hence, a period with an index of 105 is 5% windier than the long-term. In this case, the long-term correction factor is 0.95.
Wind regime	In the WAsP methodology, the wind rose is divided into 12 sectors et the wind speed distribution in each sector is approximated by a Weibull distribution defined by 2 parameters A & k. A wind regime is defined by these parameters A & k, as well as the weight of each wind sector.
Wind shear	The wind shear is a measure of how the wind speed decreases in the lower atmosphere close to the ground. This phenomenon is due to the drag forces exerted by the ground and its roughness on the air flow. It shapes the wind speed and turbulence profiles, the former of which is often described with a logarithmic or exponential law.
WindPRO	WindPRO is a software package for designing and planning wind farm projects. It uses WAsP to simulate wind flows. It is developed and distributed by the Danish energy consultant EMD International A/S. It is trusted by many investment banks to create wind energy assessments used to determine financing for proposed wind farms.

Summary

The World Bank in collaboration with Pacific Power Association (PPA) is supporting the development of renewable assets in the region. In total 5 LiDAR's were installed on 5 islands for the purpose of validation of the mesoscale data for building a wind atlas, and collection of data for yield estimations.

This report, presents the results of the preconstruction long-term energy yield assessment of the Tuvalu wind project, located on the Fongafale islet, in Tuvalu. A single wind farm configuration was considered, comprising 1 Enercon E44 900 kW wind turbine with 44 m rotor diameter and 45 m hub height for a total installed capacity of 900 kW.

15.2 months of data from a Lidar installed at the site were available to 3E. After data processing and analysis, the 7.8 months period 01/03/2020 - 23/10/2020 was selected for being the most representative of the short-term wind regime at site. Over that period, the average measured wind speed was 5.17 m/s at 40 m above ground level (AGL), with the prevailing wind directions east.

Short-term measurements were then correlated to long-term reference data to compensate for seasonal and annual wind variations. ERA5 8.5°S 179.25°E at 100 m and the Linear regression MCP method were selected. The expected long-term mean wind speed at 40 m AGL at Lidar location is of 5.45 m/s, with the prevailing wind direction east, east-southeast.

The terrain at site was modelled (elevation, roughness and obstacles to the wind flow) and the wind flow model WAsP was used to extrapolate the wind regime to the hub height of the wind turbine. The calculation model was also validated using the available wind measurements. The expected Weibull mean wind speed at the location of wind turbine E01 at 45 m AGL is of 5.58 m/s, with prevailing wind direction east, east-southeast.

The wind regime at the location and hub height of the wind turbine was then combined with the air density-adjusted power curve of the considered wind turbine type, to assess its gross energy production. Energy production losses were assessed and deducted from the gross energy production of the wind turbine, resulting in its expected net annual energy production ('AEP'). No curtailment was taken into account for this project.

Energy production losses taken into account in this study equal 6.6 % and break down as follows:

Configuration		E44, 900kW @45m
Unavailability losses	**[%]**	**3.5**
Turbine	[%]	3.0
BOP	[%]	0.2
Grid	[%]	0.3
Performance losses	**[%]**	**1.0**
Non-standard wind flow conditions	[%]	0.8
Turbine control limitation	[%]	0.2
Electrical losses	**[%]**	**2.0**
Environmental losses	**[%]**	**0.3**
Performance degradation not due to icing	[%]	0.3
Curtailment losses	**[%]**	**0.0**
Total losses	**[%]**	**6.6**

Finally, energy productions estimations are displayed in the table below.

Table 1: Expected wind farm energy production figures

Configuration		E44, 900kW @45m
Mean wind speed	[m/s]	5.58
Gross energy production	[MWh/y]	1,085
Wake losses	[%]	0.0
Curtailment losses	[%]	0.0
Other losses	[%]	6.6
Total energy production losses	[%]	6.6
Net energy production (AEP)	**[MWh/y]**	**1,013**
Net full load equivalent hours	[h/y]	1,126
Net capacity factor	[%]	12.8

3E would like to remind the reader that the results presented in this report, are only valid if the following aspects considered in the study are consistent with those of the turbine supply agreement: Power curve.

1. Introduction

1.1. Objectives

The World Bank in collaboration with Pacific Power Association (PPA) is supporting the development of renewable assets in the region. In total 5 LiDAR's were installed on 5 islands for the purpose of validation of the mesoscale data for building a wind atlas, and collection of data for yield estimations.

This report, presents the results of the preconstruction long-term energy yield assessment of the Tuvalu wind project, located in Fongafale islet, in Tuvalu. A single wind farm configuration was considered, comprising 1 Enercon E44 900 kW wind turbine with 44 m rotor diameter and 45 m hub height for a total installed capacity of 900 kW.

1.2. Methodology

This study is carried out according to the best industry practices [1][2]. and managed according to the ISO 9001:2008 standard, under which 3E has been certified since 2010.

1.3. Outline of the report

- Section 2 details the site and project, including the site location and environment, the available wind measurements, and the wind farm configuration to be studied,
- Section 3 details the processing of wind data into a representative wind regime meant for energy production calculations,
- Section 4 details wind flow modelling,
- Section 5 details energy production calculations,
- Section 6 summarizes the findings of the study and provides recommendations.

2. Site and Project Description

2.1. Site Description

The site is located on the Fongafale islet, as indicated in Figure 1. The site is nearby the runaway of the airport, the city center of Vaiaku and the Tarasal lake, with the beaches on the Pacific ocean on both east and west of the site, as illustrated in ANNEX A. The terrain is flat within the project boundaries.

The configuration displayed in this report acts as an estimation of the energy production, given the wind resources at the site. No site constraints have been taken into account.

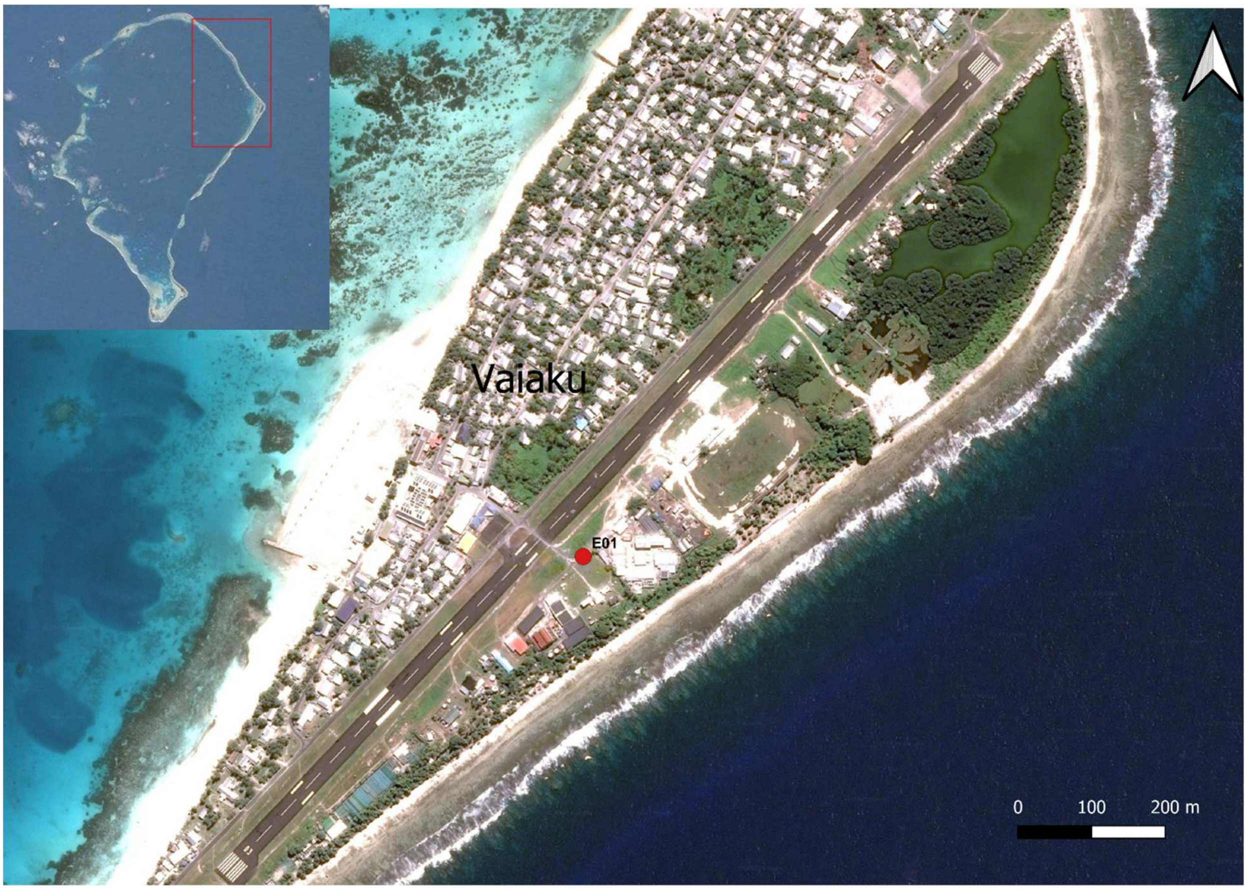

Figure 1: Site location (Source: Google Earth)

2.2. Available wind measurements

The client has provided 3E with wind measurements from a Lidar, located at the site, as indicated in Figure 1, the Lidar being placed at the same location as the wind turbine E01.

Table 2: LiDAR characteristics

Site	WLS7-1131
Commissioning date	03/03/2020
Fencing	Around lidar
Longitude	179°11'47.28" E
Latitude	-8°31'30.35" N
UTM (south) (WGS84) Easting	741,786 (Zone 60L)
UTM (south) (WGS84) Southing	9,056,964 (Zone 60L)
UTM zone	60L
Elevation	0m

2.3. Wind farm configuration

In this report, a configuration refers to the combination of a wind farm layout and a wind turbine type (turbine model + hub height). 1 configuration is considered, comprising 1 turbine for a total installed capacity of 900 kW. The configuration to be studied is detailed in Table 1. The wind farm layout is illustrated in Figure 1, whereas the wind turbine coordinates are listed in ANNEX B.

Table 3: Wind farm configuration

Configuration		E44, 900kW @45m
Wind turbine manufacturer	[-]	Enercon
Wind turbine type	[-]	E44
Number of wind turbines	[-]	1
Rated power per turbine	[kW]	900
Total rated power	[kW]	900
Rotor diameter	[m]	44
Hub height	[m]	45

3. Wind Data Processing

3.1. Short-term wind regime

3.1.1. Lidar WLS7-1131

The Lidar configuration does not fully comply with best practices. The period selected for the following steps of the study covers 7.8 months (01/03/2020 - 23/10/2020). Over this period, the mean wind speed is of 5.17 m/s at 40 m AGL.

Configuration of measurement device

The lidar was installed at the site by 3E on 25/02/2020. It is a Windcube V2.1 Lidar, configured to measure the wind speed and direction at nine levels (from 40 m to 200 m AGL). An installation report [4], a maintenance report [5], and raw 10-minute measurement data covering the period from 25/02/2020 to 01/06/2021 (15.2 months) are available for the yield assessment. The Lidar's coordinates and configuration details are provided in ANNEX B.

The Lidar configuration does not fully comply with best practices [1][2]. The following divergences from best practices are observed:

- Measurements do not cover 12 complete and consecutive months,
- Availability of the cleaned data is lower than 90 %

Data processing

Data are processed according to best practices [1][2]. The most significant changes applied to the data are the following:

- 10 min averages computed by the Lidar with less than 80% of data availability are discarded,
- 10 min averages computed by the Lidar with a CNR (Carrier-To-Noise) less than -23dB at the height of 100m are discarded,
- 10 min averages computed by the Lidar with a mean vertical wind speed less than -1.5 m/s or higher than 1.5 m/s are discarded.
- Magnetic declination offset on wind direction of 10.65° positive (from data on the 25/02/2020)

After data processing, a period covering 7.8 months (01/03/2020 - 23/10/2020) is identified as being of sufficient quality for the purpose of this study. Monthly mean wind speeds and data availabilities over that period can be found in ANNEX J.

Representativeness of the measurements for the site

Following best practices, Lidar measurements are only applicable for simple terrains (relatively flat and homogeneous) [6][7]. The terrain at site can be considered simple.

The distance between the Lidar and the furthest wind turbine is zero since the turbine is placed at Lidar location for this study. Considering the terrain characteristics, it can be concluded that the measurements are representative for the full extent of the site.

Short-term wind regime

Table 4 presents Weibull parameters of the short-term wind regime over the 7.8 months from 01/03/2020 - 23/10/2020. The Weibull mean wind speed at 40 m AGL is 5.10 m/s, in agreement with the measured mean wind speed of 5.17 m/s, which validates the approximation of the wind regime by a Weibull distribution.

ANNEX D presents the Weibull parameters per sector as well as charts of the short-term wind regime at 40 m AGL (wind speed distribution, mean wind speed, frequency and energy roses).

The wind predominantly blows from sectors east, where a higher mean wind speeds is also measured. Consequently, most of the wind energy is available from this sector.

Table 4: Weibull parameters of the short-term wind regime

Wind measurement device	[-]	Lidar
Selected period	[-]	01/03/2020 - 23/10/2021
Height AGL	[m]	40
Arithmetic mean wind speed	[m/s]	5.17
Weibull mean wind speed	[m/s]	5.10
Weibull A	[m/s]	5.76
Weibull k	[-]	2.237
Prevailing wind direction	[-]	East
Wind direction with most energy content	[-]	East

3.2. Long-term extrapolation

The long-term extrapolation is performed in three steps: first, the most reliable reference datasets are identified, then the best combination of reference data and extrapolation method is selected. Eventually, the combination of dataset and method resulting in best correlation (cf. section 3.2.2) is selected.

3.2.1. Reference datasets

3E selects reference dataset from the following sources:

- MERRA-2 and post-processed ERA5 reanalysis data from WindPRO (4 closest grid points),

The following criteria are used to select reference datasets from these sources:

- **Agreement**: the reference dataset should agree with the measurements in terms of wind speed variations over time. This agreement is quantified by the Pearson correlation coefficient “r”.
- **Time resolution**: the time resolution of the reference dataset should be constant over time. In case time resolution varies, 3E resamples data to a constant time resolution.
- **Data availability**: missing periods should be limited and evenly distributed over time.
- **Consistency**: the reference dataset should not reveal any abrupt change or unrealistic trend. 3E applies a SNHT test [14] in order to identify discontinuities. If this happens, then the available period is limited to ensure homogeneity. 3E then also applies a Mann-Kendall test [15][16] (90% confidence interval) in order to identify possible trends. Again, the available period is limited to ensure the absence of a trend.

When several reference datasets from the same reanalysis project are considered, 3E only selects the one providing the best r (all data) and the one providing the best r (monthly averages).

The datasets eventually selected as reference are highlighted in bold in Table 5. Their long-term behaviours in terms of windiness are illustrated in Figure 2, whereas their geographical locations are indicated in ANNEX E. Please note that no ground meteorological stations have been kept for the following steps of the process since none of them in the vicinity of the project had concurrent data with the on-site measurements.

Table 5: Selection of reference datasets

Name	Type	Time shift[1] [h]	r (all data)	r (monthly averages)	Long-term period[2]	Concurrent period [years]	Time resolution [h]	Data availability [%]	Trend test results[3] [%]
MERRA2 S08.000 E179.375	MERRA2	+1h	0.656	0.937	01/01/2003 - 31/12/2022	0.65	1	100	OK
MERRA2 S08.500 E178.750	MERRA2	+1h	0.687	0.964	01/01/2003 - 31/12/2022	0.65	1	100	OK
MERRA2 S08.500 E179.375	MERRA2	+1h	0.688	0.973	01/01/2003 - 31/12/2022	0.65	1	100	OK
MERRA2 S09.000 E179.375	MERRA2	+1h	0.677	0.98	01/01/2003 - 31/12/2022	0.65	1	100	OK
ERA5CDS S08.25 E179.25	ERA5	0h	0.765	0.906	16/01/2003 - 15/01/2023	0.65	1	100	OK

[1] Time shift providing best r (all data). By default, 3E assumes it to be 0h. In cases where there is ambiguity on the time definition of the site wind measurements, or if the agreement of site wind measurements is insufficient, then 3E considers the benefit of applying a time shift comprised between -3 and +3h

[2] After eventual filtering to ensure consistency of time resolution and availability, as well as the absence of any discontinuity (SNHT test)

[3] Result of a Mann-Kendall test

Name	Type	Time shift[1] [h]	r (all data)	r (monthly averages)	Long-term period[2]	Concurrent period [years]	Time resolution [h]	Data availability [%]	Trend test results[3] [%]
ERA5CDS S08.50 E179.00	ERA5	0h	0.774	0.942	16/01/2003 - 15/01/2023	0.65	1	100	OK
ERA5CDS S08.50 E179.25	**ERA5**	**0h**	**0.775**	**0.937**	**16/01/2003 - 15/01/2023**	**0.65**	**1**	**100**	**OK**
ERA5CDS S08.75 E179.25	ERA5	0h	0.773	0.959	16/01/2003 - 15/01/2023	0.65	1	100	OK

Figure 2: Annual windiness relative to last concurrent year

3.2.2. Best combination of reference data and extrapolation method

3E considers 3 state-of-the-art long-term extrapolation methods: Linear regression MCP, Matrix MCP and Wind Index.

For each selected reference dataset, 3E applies the applicable extrapolation method(s), depending on r (all data) and r (monthly averages).

For 'Lidar WLS7-1131': the best correlation factor on wind speed is obtained from ERA5 8.5°S 179.25°E using the Linear regression MCP method, which is therefore the selected combination of reference data and extrapolation method.

The result of the long-term extrapolation based on the MCP method is a new time series of expected wind speeds and directions, over the 20-year period 16/01/2003 - 15/01/2023. The Weibull parameters of this new time series are given in Table 6. Weibull parameters per sector at 40 m AGL and charts of the long-term wind regime (wind speed distribution, mean wind speed, frequency and energy roses) are provided in ANNEX G. The mean wind speed expected over the long-term is slightly higher measured over the short-term (5.47 m/s compared to 5.17 m/s); the prevailing wind direction is east and east-southeast, which is similar to what is observed over the short-term (east).

Table 6: Long-term extrapolation results

Wind measurement device	[-]	Lidar
Long-term period	[-]	2003-2023
Height AGL	[m]	40
Arithmetic mean wind speed	[m/s]	5.45
Weibull mean wind speed	[m/s]	5.51
Weibull A	[m/s]	6.22
Weibull k	[-]	2.205
Prevailing wind direction	[-]	East, east-southeast
Wind direction with most energy content	[-]	East, east-southeast

4. Wind Flow Modelling

4.1. Terrain model

Terrain features influence the wind flow and thus play a significant role in the spatial extrapolation of the wind regime. The software package WindPRO and the WAsP wind flow model are used in the present study. WAsP requires a terrain model describing elevation, roughness and other relevant obstacles to the wind flow that are not modelled as roughness (cf. ANNEX H).

The terrain model used in this study represents the current conditions, which are assumed to remain the same over the wind farm lifetime.

4.1.1. Elevation

The wind regime can be highly influenced by elevation differences across the site. For this study, terrain elevation is modelled within a radius of 15 km (in line with WAsP recommendations [8]) based on DEM GLO-30 data. Height contour lines are then generated with an elevation difference of 5 m between two successive lines.

WAsP is designed for ΔRIX values close to 0, where RIX quantifies the complexity of the elevation model and ΔRIX the difference in complexity between two locations. The validity of the WAsP model is checked according to WAsP recommendations [8], by computing ΔRIX between each wind turbine location and the location of the measurement device used for wind flow simulations.

The ΔRIX value is equal to 0 for this project, which allows WAsP to be used for wind flow simulations.

4.1.2. Roughness length

Roughness length is a key parameter of the equation that governs wind shear. Changes in roughness length cause variations of wind shear, which propagate vertically as the air flows over the site. The impact at measurement or hub height therefore varies with distance to roughness changes but is also related to atmospheric conditions.

Given that roughness length is closely related to land use, terrain roughness is typically modelled using a land-use database. However, no suitable existing database could be considered for this study. Therefore, the shapes of areas of different land use are drawn manually in WindPRO, Then, roughness lengths values appropriate for each area are applied according to 3E's methodology [9]. Shapes of land use areas and roughness lengths are determined based on aerial imagery. The aerial imagery from Google Earth and dated 2017 is used for this purpose and is assumed representative of the site conditions at the time of writing this report.

Following WAsP recommendations, the terrain roughness is modelled within a radius of 20 kilometres.

4.1.3. Large obstacles to the wind flow

Terrain roughness does not properly take into account the disturbance of the wind flow caused by tall, isolated obstacles. Such obstacles should therefore be modelled separately.

According to WAsP recommendations, isolated obstacles should be modelled separately if they are located within a radius of 50 times their height from any measurement device or wind turbine, and if their height exceeds one third of any measurement or hub height.

In this study, no obstacles meet this criterion; hence no obstacle is modelled separately.

4.1.4. Displacement height

When a measurement device or wind turbine is located within or close to a large obstacle (forest, industrial area, urban area, etc.), the wind is blocked and flows over the obstacles. In this case, a displacement height needs to be applied, according to WAsP recommendations.

Applying a displacement height consists in reducing the measurement or hub height by the value of the displacement height. 3E applies a displacement height if an area of obstacles having an average height over 10 m is located within 1 km from any measurement device or wind turbine and obstructs at least one of the twelve 30° sectors. Displacement heights are evaluated following best practices [10].

In this study, the urban areas located west of E01 can be considered as large areas of obstacles and displacement heights are therefore applied. Table 7 summarizes the displacement height value applied to the measurement device and wind turbine.

Table 7: Displacement height

Object	Displacement height
[-]	[m]
E01/ Lidar	0.78

4.2. Wind flow model

WAsP is used to extrapolate the wind regime to the location and hub height of the wind turbine. It involves two steps: a vertical extrapolation of the wind regime to hub height and a horizontal extrapolation of the wind regime to the wind turbine location.

4.2.1. Vertical extrapolation of the wind regime

By default, WAsP is configured for atmospheric conditions typical of Northwestern Europe. Therefore, parameters sometimes need to be adapted. In particular, some parameters strongly affect the vertical extrapolation of the wind regime and can be validated and calibrated, if necessary, by comparison of the measured and calculated wind shears.

In this study, given the limited difference between the measured height (40m AGL) and the wind turbine hub height (45m AGL), and in combination with a close approximation of the WAsP model and measured wind shear no specific model calibration has been implemented.

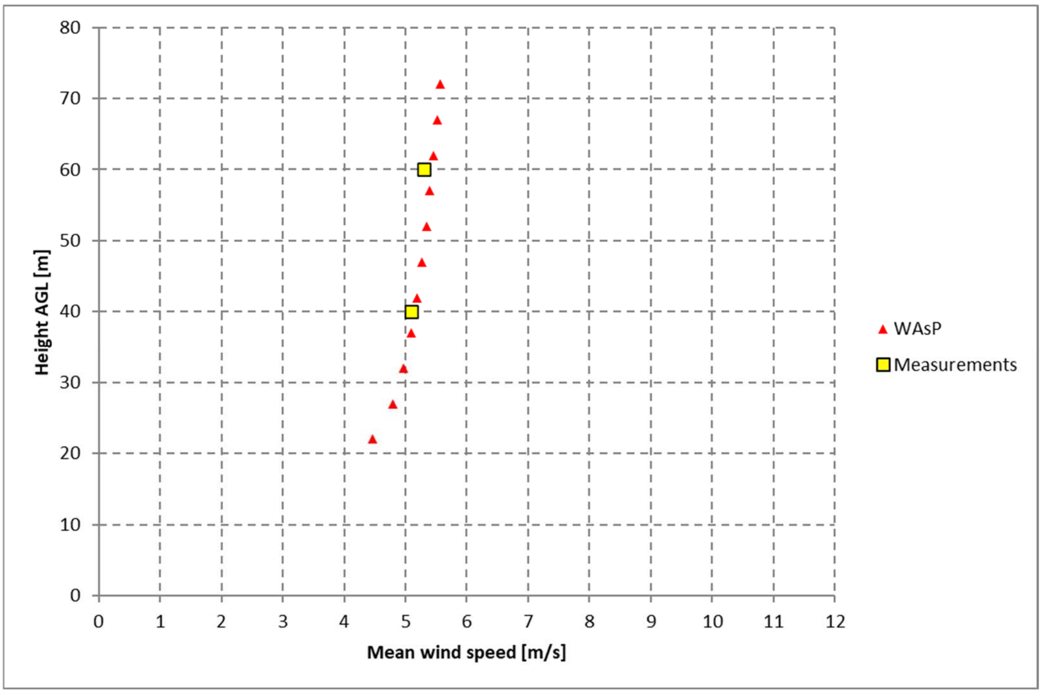

Figure 3: Mean wind speeds measured over the short-term period limited to 7.8 months and vertical wind speed profile calculated by WAsP using measurements at 40,60 m AGL

4.3. Wind regime at site

The long-term wind regime at the representative height of 45 m AGL at the location of wind turbine E01 is presented in Table 8 and Figure 4.

Table 8: Long -term wind regime at the site

Location	[-]	E01
Height AGL	[m]	45
Weibull mean wind speed	[m/s]	5.58
Weibull A	[m/s]	6.30
Weibull k	[-]	2.198
Prevailing wind direction	[-]	East, east-southeast
Wind direction with most energy content	[-]	East, east-southeast

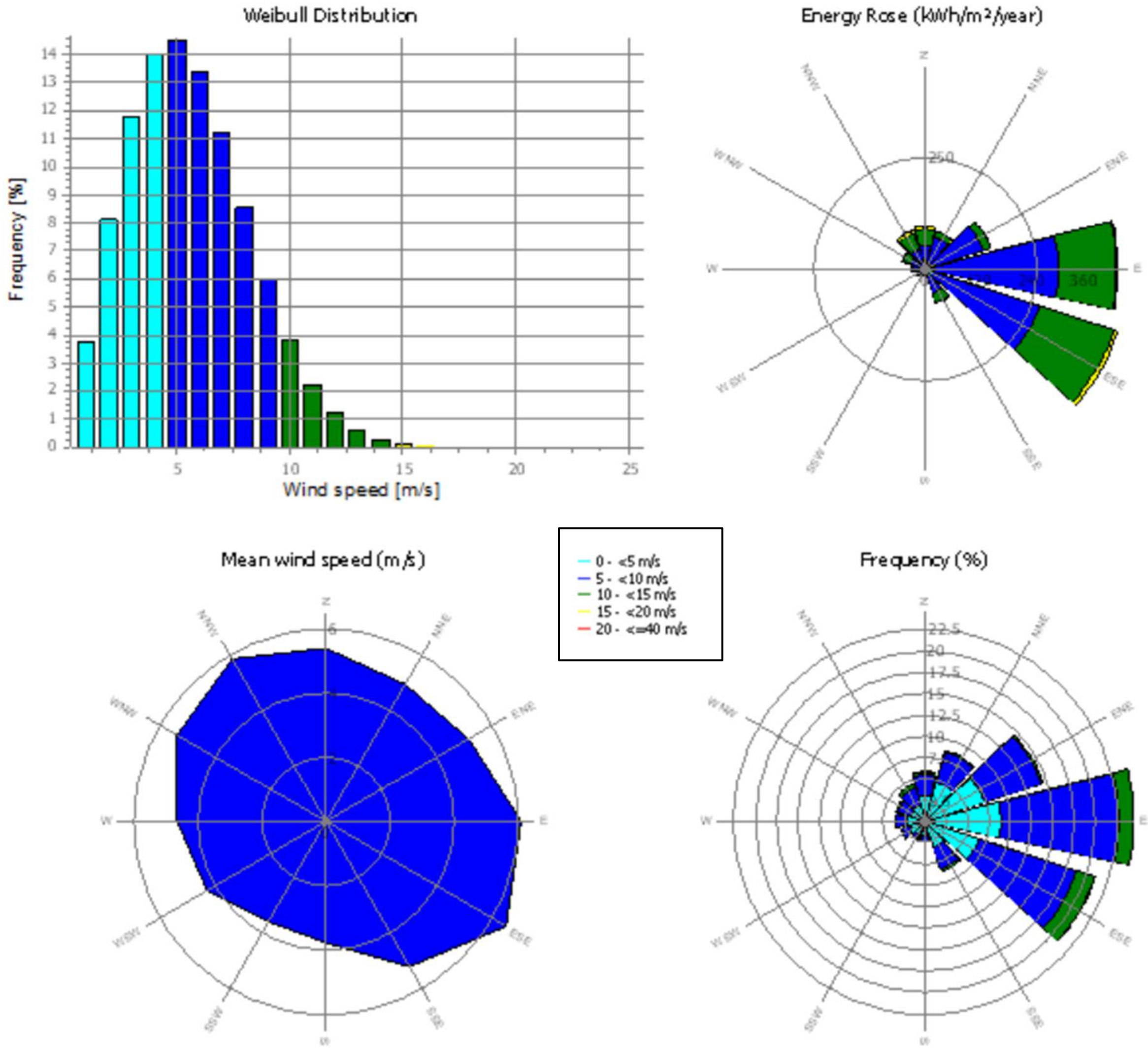

Figure 4: Long -term wind regime at the site

4.4. Turbulence analysis

The measured turbulence at 40 m AGL compared to the IEC curves is depicted in the figures below.

The effective turbulence intensity measured by the Lidar at 40 m AGL is below the representative turbulence intensity of Class A wind turbines (IEC 61400-1, ed. 3.0) [9] for the wind speed range above 3.5 m/s and below the 14.5 m/s. Graphs for turbulence values can be seen in Figure 5.

The turbulence measurements from a Lidar are based on volume measurements. The IEC standard requires point measurements and therefore the figure below is a guideline towards turbulence compliance.

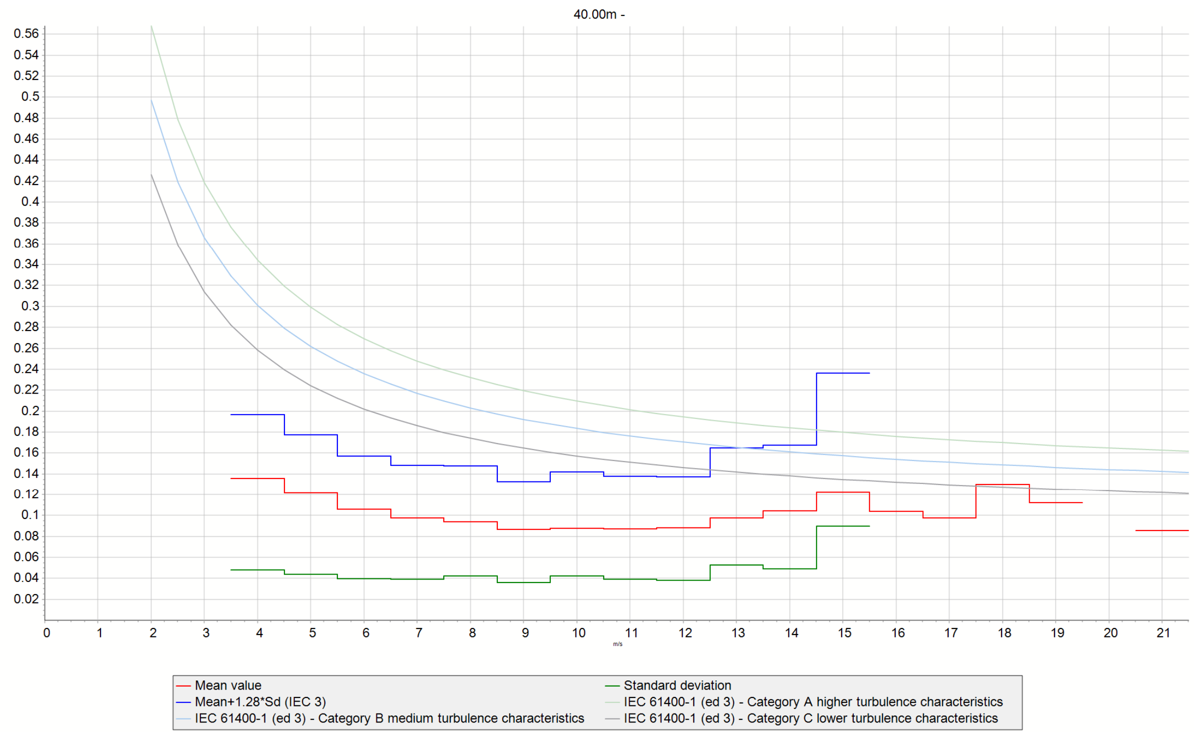

Figure 5: Turbulence at 40 m AGL compared to the IEC curves

4.5. Suitable turbine suggestions

For wind projects turbine selection is one of the most important issues when considering the efficiency of the project. In the project, an average turbine type that can adapt to all sites has been selected so that resource reports of different sites can be compared with each other easily and objectively. This turbine type is defined as an Enercon E44.

However, when wind speed and turbulence intensity values of specific sites are taken into consideration, most suitable turbine types may differ from each other.

4.6. Wind Resource Mapping

Based on the measurement data from the lidar, a wind resource map was generated in a 20 km radius around the site at 45 meters above ground level (AGL) and with a resolution of 100 meters. The figure in the subsequent section presents the wind energy content for the site. Figure 6 shows the wind energy map for the site.

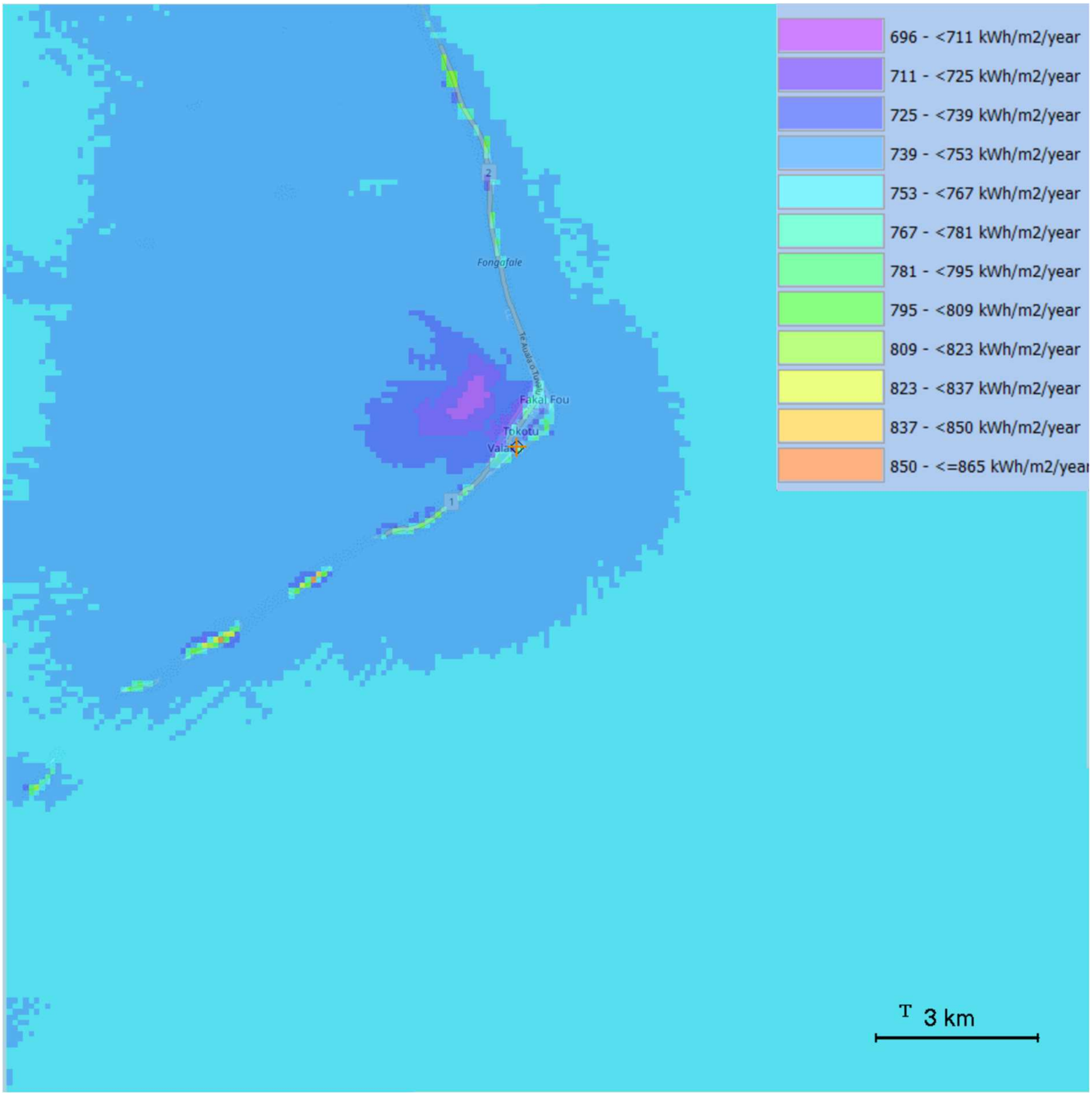

Figure 6: Ressource map at 45 m AGL for 20 km area around site center

5. Energy Production Losses

5.1. Gross energy production

A gross energy production refers to the theoretical energy production that would be achieved if there was no operational loss. It is calculated by combining the wind regime at a wind turbine location and hub height to the power curve specific to the considered wind turbine type and corrected for local hub height air density. This is done using the software WindPRO. For ease of reading, these results are provided in section 5.3. Power curves are provided in ANNEX H.

Since the energy content of the wind varies proportionally to air density, power curves are adapted accordingly before being used in calculations. The adaptation is done using the new recommended WindPRO method (adjusted IEC 61400-12 method, improved to match turbine control) [11].

For this project, air density at hub height is equal to 1.159 kg/m³. Air density is calculated by WindPRO based on temperature and pressure measurements from the weather station at Funafuti, located 3 km from the site and a relative humidity value of 50% according to IEC 61400-12 [3]. According to the experience of 3E, this calculation is accurate enough for the scope of this study.

Important Note: AEP calculation results are specific to the considered wind turbine power curve. Therefore, when procuring the wind turbines for the project, it should be verified that the power curve guaranteed by the manufacturer in the procurement contract corresponds to the one used in this study. Any change to the power curve may require the recalculation of the AEP.

5.2. Energy production losses

In addition to energy conversion losses taken into account in the power curve, other losses affect the electrical power expected to be delivered to the grid. The following losses are taken into account in this study and are summarised in Table 9 further below. Other losses may apply but are considered negligible in this study.

Unavailability losses

Unavailability losses are due to downtime of the wind turbines or balance of plant (maintenance or technical incidents) as well as downtime of the power grid as follows:

- Losses due to maintenance and technical incidents on the turbines are typically evaluated by 3E as 3.0 % of the energy production. This is considered an industry standard but conservative estimate, based on availability guarantees often being around 97 % in operation and maintenance (O&M) contracts.
- Losses due to maintenance and technical incidents on the Balance of Plant (BoP) are typically evaluated by 3E as 0.2 % of the energy production.
- Grid unavailability loss is considered to be 0.3 % for this project. This value is based on the analysis of data from a large portfolio of operational wind farms.

It should be noted that the selected value is not the result of a detailed study and an update might be needed in a later phase of the project.

Performance losses

Turbine performance losses are typically due to high wind hysteresis, yaw misalignment, wind flow inclination, turbulence, wind shear and other differences between turbine power curve test conditions and actual conditions at the project site:

- Turbine control limitations correspond to the following losses:
    - High wind hysteresis losses are considered to be negligible for this project for two reasons. Firstly, because the Enercon turbines are equipped with a control mechanism that does not stop the turbine but gradually reduces the output of the turbine, and secondly because the wind distribution at the site is such that this type of event is not likely to occur very often.
    - Sub-optimal turbine performance due to limitations of the turbine system are considered to be 0.2% regardless of the simplicity of the site. This loss is based on the analysis of operational data from a large number of wind farms. It is related to the unwinding of the cables, the configuration of the wind turbine and the physical limits of its control.
- An additional loss of 0.8 % is considered in this study, to account for terrain characteristics, which are likely to create non-standard wind flow conditions. This loss is estimated based on 3E's experience.

Electrical losses

Electrical losses occur in cables and transformers ensuring electrical transmission to the wind farm substation. 3E typically evaluates them as 2 % of the energy production for a wind farm of this size and layout. This value is based on the analysis of data from a large portfolio of operational wind farms.

Environmental losses

Environmental losses account for the performance degradation of the wind turbines due to environmental conditions:

- Aerodynamic performance degradation of turbine blades due to dirt accretion (excluding icing) is estimated at 0.25 % for this study,
- At this stage, 3E does not consider any loss for potential turbine shutdowns due to lighting or hail. If specific shutdown rules are enforced, their impact on the production should be evaluated separately.

5.2.1. Curtailment losses

These losses are due to modifications of wind turbine operation for technical or environmental reasons (e.g. related to noise or shadow flicker constraints, birds or bats preservation, etc.). No curtailment was communicated by the client.

5.2.2. Losses summary table

The energy production losses defined in the preceding sub-sections are summarised in Table 9.

Important note: some losses taken into account in this study are industry standard values that 3E estimates relevant for the project. They are not all based on contractual documents or specific studies and they should be reviewed for the financial closing of the project.

Table 9: Expected energy production losses

Configuration		E44, 900kW @45m
Unavailability losses	**[%]**	**3.5**
Turbine	[%]	3.0
BOP	[%]	0.2
Grid	[%]	0.3
Performance losses	**[%]**	**1.0**
Non-standard wind flow conditions	[%]	0.8
Turbine control limitations	[%]	0.2
Electrical losses	**[%]**	**2.0**

Configuration		E44, 900kW @45m
Environmental losses	**[%]**	**0.3**
Performance degradation not due to icing	[%]	0.3
Curtailment losses	**[%]**	0.0
Total losses	**[%]**	**6.6**

(*) THE PRODUCTION LOSSES IN % ARE COMBINED AS: $Total = 100 - \frac{\prod_i (100 - Loss_i)}{100^{(N-1)}}$

5.3. Net energy production

Energy production losses are then applied to the expected annual gross energy production, resulting in the expected net Annual Energy Production (AEP).

The expected AEP and other energy production figures are presented in Table 10. The following results are provided:

- **Mean wind speed**: corresponds to the lowest and highest mean wind speeds expected at the location and hub height of wind turbines.
- **Gross energy production**: corresponds to the theoretically recoverable annual energy production at the outlet side of the generator, without production losses.
- **Energy production losses**: as calculated in Section 5.3.
- **Net energy production (AEP)**: corresponds to the annual energy production expected to be delivered to the grid (taking into account all energy production losses).
- **Net full load equivalent hours**: is the amount of time it would take for the wind farm to yield its annual production if it was able to constantly produce at full load.
- **Net capacity factor**: is the net full load equivalent hours divided by the total number of hours in a year. It represents the usage of the installed capacity.

Table 10: Expected wind farm energy production figures

Configuration		E44, 900kW @45m
Mean wind speed	[m/s]	5.58
Gross energy production	[MWh/y]	1,085
Wake losses	[%]	0.0
Curtailment losses	[%]	0.0
Other losses	[%]	6.6
Total energy production losses	[%]	6.6
Net energy production (AEP)	**[MWh/y]**	**1,013**
Net full load equivalent hours	[h/y]	1,126
Net capacity factor	[%]	12.8

6. Conclusion and Recommendations

3E has calculated the expected energy production for the proposed configuration of the Tuvalu wind farm project. The main production results expected for a 20-year period are summarised in the following table:

Table 11: 20 year expected AEP

Configuration		E44, 900kW @45m
Mean wind speed	[m/s]	5.58
Gross energy production	[MWh/y]	1,085
Wake losses	[%]	0.0
Curtailment losses	[%]	0.0
Other losses	[%]	6.6
Total energy production losses	[%]	6.6
Net energy production (AEP)	**[MWh/y]**	**1,013**
Net full load equivalent hours	[h/y]	1,126
Net capacity factor	[%]	12.8

Important notes:

- It should be noted that 3E assumes that any information communicated by the client is correct.
- The configurations of the Lidar WSL7-1131 does not fully comply with best practices. In particular, measurements do not cover 12 complete and consecutive months and availability of the cleaned data is lower than 90 %.
- Results of AEP calculations are specific to a wind turbine power curve. Therefore, when procuring the wind turbines for the project, it should be verified that the power curve guaranteed by the manufacturer and as provided in the procurement contract corresponds to the one used in this study. Any change to the power curve will require the recalculation of AEP.
- Several energy production losses taken into account in this study are industry standard values that 3E estimates relevant for the project. They are not all based on contractual documents or specific studies and they should be reviewed for the financial closing of the project.

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ANNEX A Site Description Illustrations

Figure 7: Typical site environment and Lidar location

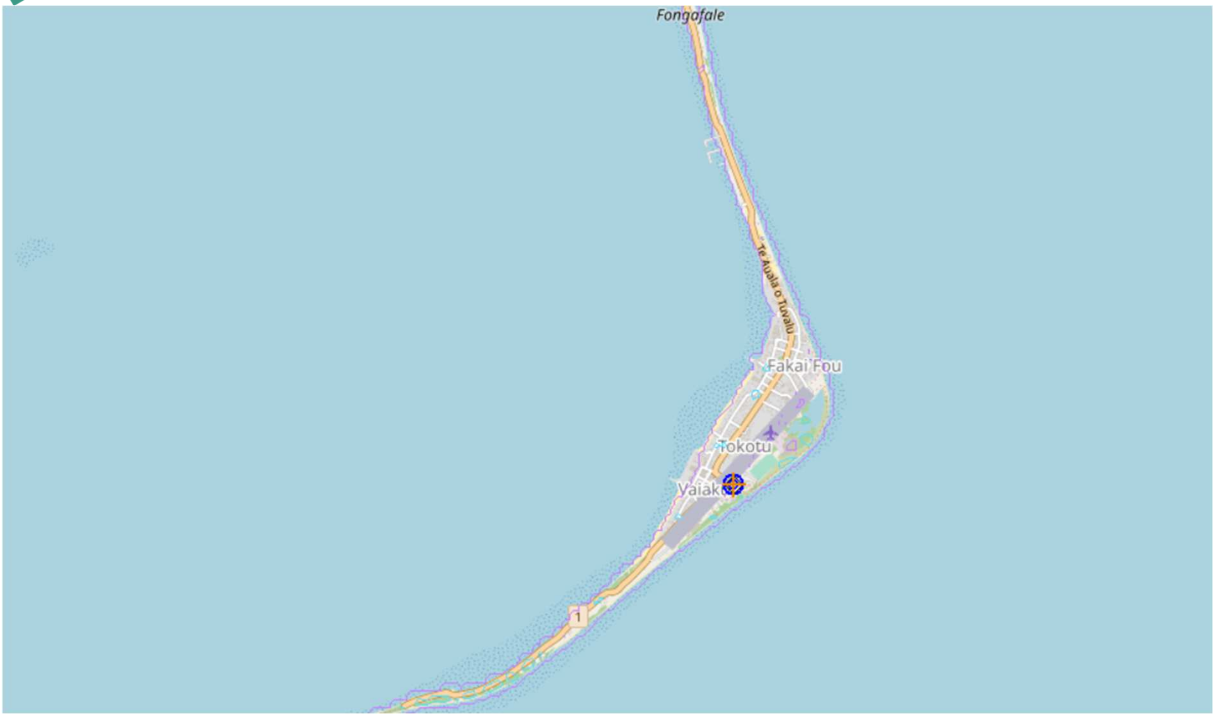

Figure 8: Site elevation (contour lines every 5 metres, and wormer colours denote higher elevations)

ANNEX B Wind Turbine Coordinates

Table 12: Wind turbine coordinates and altitude (coordinate system: WGS84 – UTM (south) Zone 60L)

Turbine	Easting (X)	Souhing (Y)	Altitude
	[m]	[m]	[m]
E01	741,786	9,056,964	0

ANNEX CConfiguration of Measurement Device

Table 13: Characteristics of measurement device (coordinate system: WGS84 – UTM (south) Zone 60L)

Measurement device	WLS7-1131
Easting (X)	741,786 m
Southing (Y)	9,056,964 m
Altitude	0m
Measurement heights AGL	40 m, 60 m, 80 m, 100 m, 120 m, 160 m, 180 m, 200 m
Date begin	25/02/2020
Date end	01/06/2021
Period length	15.2 months
Availability	68.3 %

ANNEX D Short-term Wind Regime

Table 14: Short-term wind regime at 40 m AGL at the Lidar

Sector	A - parameter	K - parameter	Frequency	Wind speed
[-]	[m/s]	[-]	[%]	[m/s]
Global	**5.76**	**2.237**	**100.0**	**5.10**
N	4.94	2.356	4.0	4.38
NNE	4.90	2.466	9.0	4.35
ENE	5.26	2.430	18.8	4.66
E	6.33	2.472	33.9	5.61
ESE	6.59	2.503	22.8	5.84
SSE	4.97	1.831	3.8	4.42
S	3.20	1.975	1.4	2.84
SSW	3.11	2.394	1.1	2.75
WSW	3.37	2.000	1.0	2.98
W	3.33	1.727	0.8	2.96
WNW	4.00	1.499	1.2	3.61
NNW	4.58	1.761	2.1	4.08

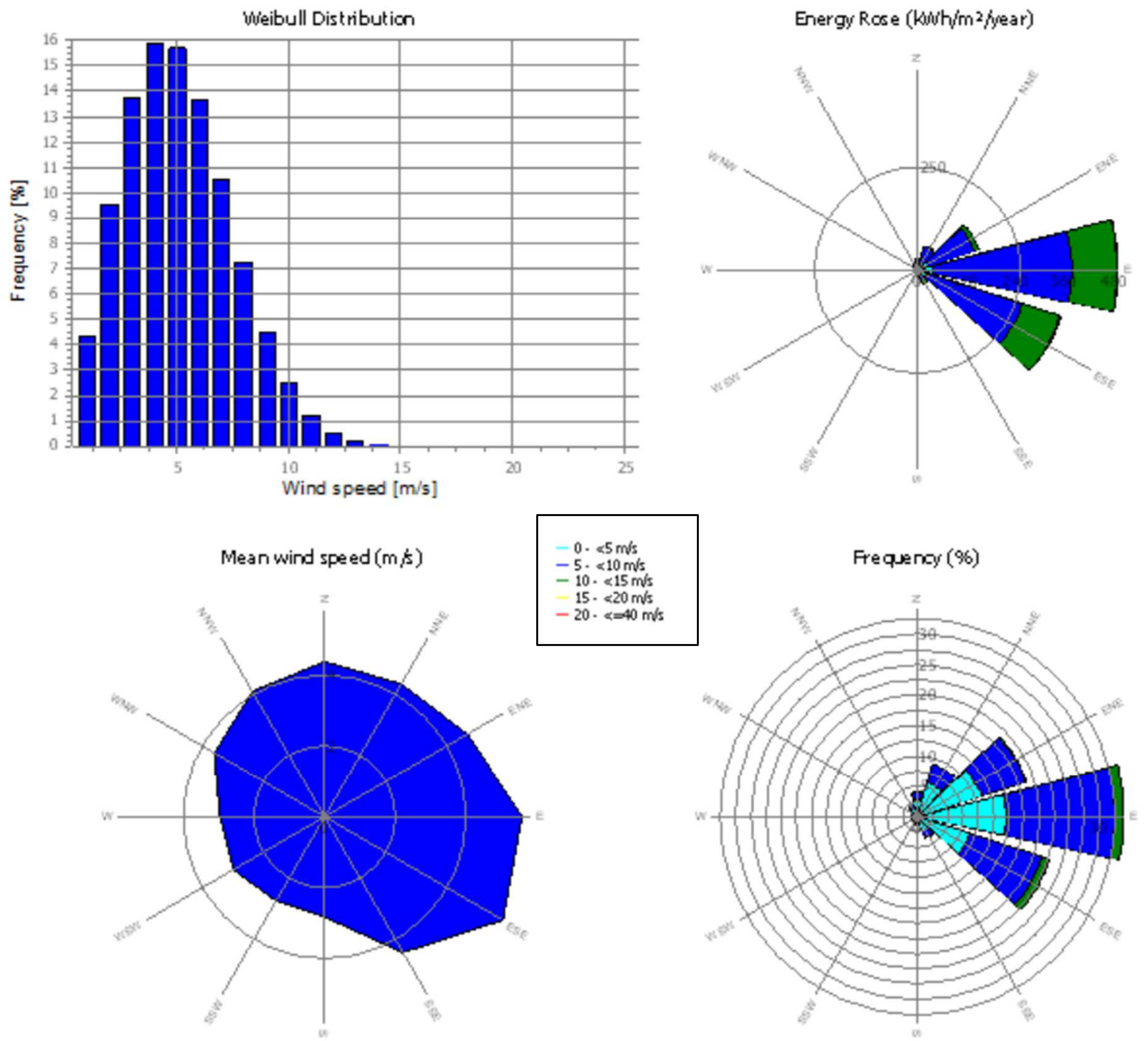

Figure 9: Short-term wind regime at 40 m AGL at the Lidar

ANNEX E Long-term Reference Datasets

Figure 10: Location of the considered long-term reference datasets with respect to the site. The selected dataset has been marked by a red square.

ANNEX F Long-term Extrapolation Methods

3E considers three state-of-the-art long-term extrapolation methods: Linear regression MCP, Matrix MCP and Wind Index.

Both MCP methods establish relationships between the wind speeds and directions measured at the site and available in the long-term reference dataset. Then, the long-term reference time series is adjusted accordingly, so as to be representative of the long-term wind regime at the site. The MCP methods are the preferred long-term extrapolation methods because they reconstruct the long-term wind regime, including its wind rose. It is however not necessarily the best suited method to minimise the uncertainty because it is very sensitive to the quality of the agreement between on-site measurements and reference data.

The Wind Index method is more robust but is not meant to estimate the long-term wind regime, and assumes that the wind rose over the short-term is representative of the long-term. It only evaluates the windiness of the short-term period against the long-term in terms of energy production.

ANNEX G Long-term Wind Regime

Table 15: Long-term wind regime at 40 m AGL at the Lidar

Sector	A- parameter	k-parameter	Frequency	Wind speed
[-]	[m/s]	[-]	[%]	[m/s]
Global	**6.22**	**2.205**	**100.0**	**5.51**
N	5.98	1.844	5.9	5.31
NNE	5.42	2.296	8.7	4.80
ENE	5.69	2.572	14.6	5.05
E	6.77	2.564	24.6	6.01
ESE	7.23	2.540	21.0	6.42
SSE	5.79	2.080	6.1	5.13
S	4.09	1.578	2.3	3.67
SSW	3.96	1.687	2.2	3.54
WSW	4.80	2.107	3.0	4.25
W	5.19	2.078	3.6	4.59
WNW	5.98	1.982	3.6	5.30
NNW	6.54	1.913	4.4	5.81

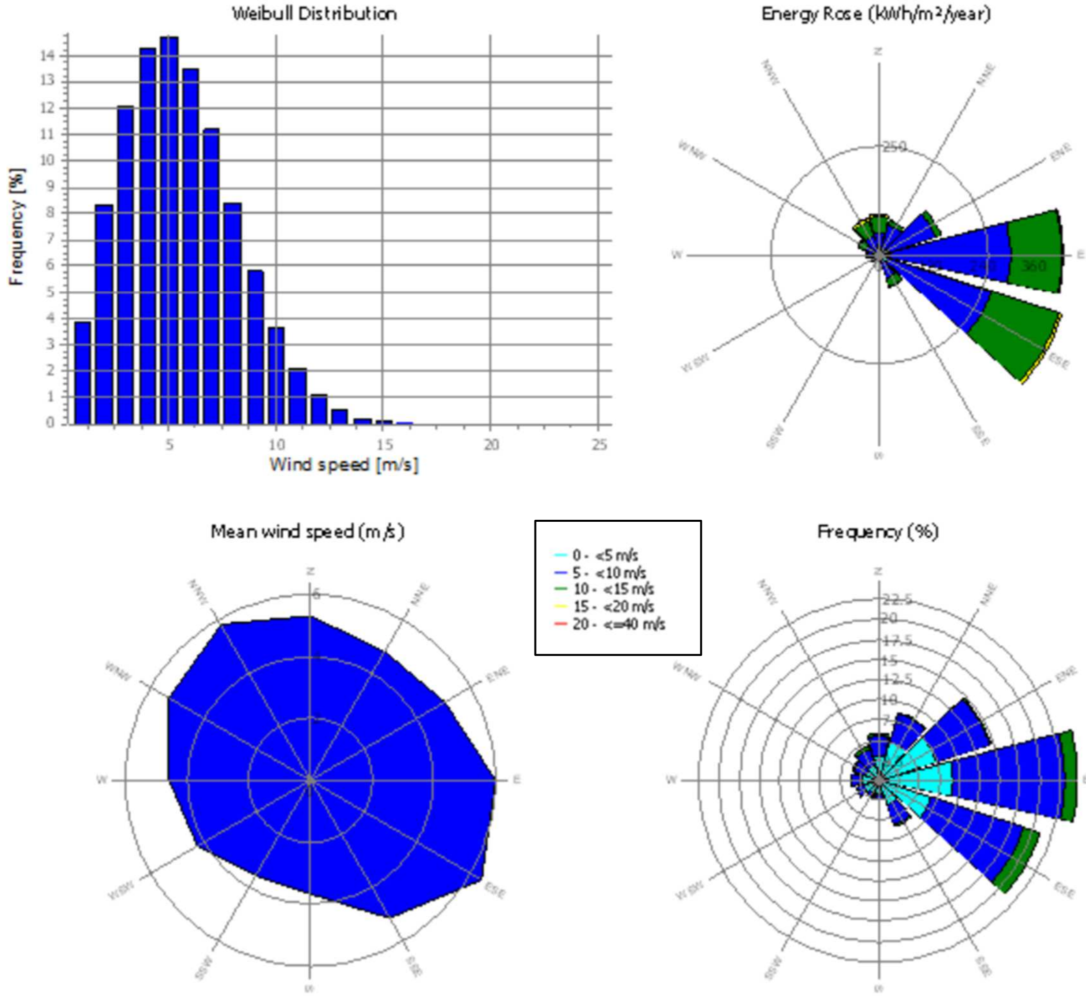

Figure 11: Long-term wind regime at 40 m AGL at the Lidar

ANNEX H The WAsP Model

The central point in the wind transformation model of WAsP – the so-called Wind Atlas Methodology – is the concept of a Regional or Generalized Wind Climate, or Wind Atlas. This Generalized Wind Climate is the hypothetical wind climate for an ideal, featureless and completely flat terrain with a uniform surface roughness, assuming the same overall atmospheric conditions as those of the measuring position. The basic "machine" of WAsP is a flow model, representing the effect of different terrain features:

- Terrain height variations,
- Terrain roughness,
- Sheltering obstacles.

To deduce the Generalized Wind Climate from measured wind in actual terrain, the WAsP flow model is used to remove the local terrain effects.

To deduce the wind climate at a location of interest from the Generalized Wind Climate, the WAsP flow model is used to introduce the effect of terrain features.

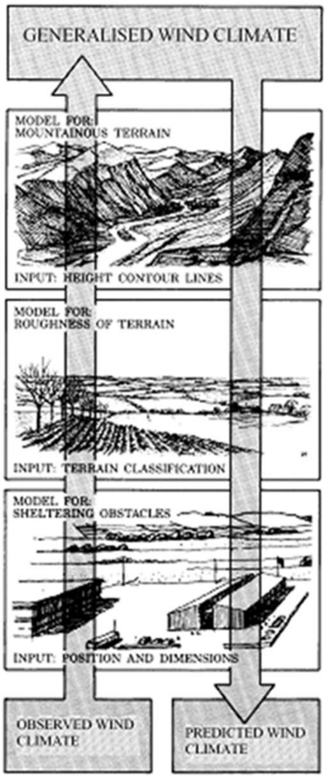

Figure 12: Wind Atlas methodology (Source: wasp.dk)

ANNEX I Power & Thrust Curve

Table 16: Power & thrust curves (PC & TC), air density = 1.225 kg/m³ [26]

Wind speed	E44	
	PC	TC
[m/s]	[kW]	[-]
1	0	0.00
2	0	0.00
3	4	1.00
4	20	0.99
5	50	0.97
6	96	0.94
7	156	0.91
8	238	0.88
9	340	0.87
10	466	0.84
11	600	0.82
12	710	0.8
13	790	0.76
14	850	0.5
15	880	0.39
16	905	0.31
17	910	0.25
18	910	0.21
19	910	0.18
20	910	0.15
21	910	0.13
22	910	0.12
23	910	0.1
24	910	0.09
25	910	0.08

ANNEX J Monthly Measurement Campaign Results

Table 17: Measured monthly mean wind speeds (MWS) and availabilities

	40 m		60 m	
Month	MWS	Avail.	MWS	Avail.
	[m/s]	[%]	[m/s]	[%]
Feb-20	2.95	100	3.04	100
Mar-20	4.75	91.8	5.01	91.8
Apr-20	4.44	61.6	4.65	61.6
May-20	4.36	98.3	4.56	98.3
Jun-20	4.9	97.1	5.09	97.1
Jul-20	5.9	98	6.07	98
Aug-20	6.17	98	6.39	98
Sep-20	5.82	97.9	6.07	97.9
Oct-20	4.52	96.1	4.75	96.1
Mean	**4.87**	**92.3**	**5.07**	**92.3**

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