WAKE IMPACT ANALYSIS

PHEZUKOMOYA WIND FARM, SOUTH AFRICA

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Date:	22/01/2018
Version:	Final version
Classification:	Confidential

DISTRIBUTION LIST

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Number of hard copies:	0
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EXECUTIVE SUMMARY

This report, requested by Innowind (Pty) Ltd, presents results of the wake impact analysis of the Phezukomoya wind farm project on the existing Noupoort wind farm, located 10 km northeast of Noupoort, in South Africa. A single wind farm configuration was considered for the planned Phezukomoya wind farm, comprising 55 Vestas V150 4 MW wind turbines with 150 m rotor diameter and 105 m hub height for a total installed capacity of 220 MW. The Noupoort wind farm, on the other hand comprises 35 Siemens SWT-2.3-108 2.3 MW wind turbines with108 m rotor diameter and 99.5 hub height.

The following wind measurements were supplied to 3E:

- 120 m Noupoort West mast: 29.5 months of data from a 120 m measurement mast installed at the site, and whose configuration complies with best practices,
- 120 m Noupoort East mast: 29.8 months of data from a 120 m measurement mast installed 5 km from the site, and whose configuration complies with best practices.

After data processing and analysis, the following devices and periods selected for being the most representative of the short-term wind regime at site:

- 120 m Noupoort West mast: 2 years period 24/09/2015- 23/09/2017
- 120 m Noupoort East mast: 2 years period 14/09/2015 to 13/09/2017

3E considers that these measurements may not adequately represent wind conditions at all wind turbine locations.

Short-term measurements were then correlated to long-term reference data to compensate for seasonal and annual wind variations. ERA-Interim S31.228 E25.308 data and the Linear regression method were selected.

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 location and hub height of each wind turbine.

Short-term measurements were then correlated to long-term reference data to compensate for seasonal and annual wind variations:

- 120 m Noupoort West mast: ERA-Interim S31.228 E25.308 data and the Linear regression method were selected.
- 120 m Noupoort East mast: ERA-Interim S31.228 E25.308 and the Linear regression method were selected.

It should be noted that the details of measured and long-term extrapolated wind speeds were removed from this report at request by the client due to the confidential nature of such information.

Wake impact of Phezukomoya wind farm on Noupoort wind farm is then calculated and as follows:

Configuration		V150, 4MW, @105m
Wake impact on Noupoort Wind Farm	**[%]**	**0.15**

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 curves

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DOCUMENT REVIEW HISTORY

Version #	Date	Author	Summary of changes
1	22/01/2018	Olgu Yildirimlar	Initial version

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.).
CFSR	CFSR (Climate Forecast System Reanalysis) is a reanalysis dataset produced by the National Centers for Environmental Prediction (NCEP). It covers a period from 1979 to the present with a resolution of 0.5°.
Corine Land Cover	The Corine Land Cover database is an inventory of land cover in 44 classes. It was initiated in 1985 by the European Union and has been taken over by the EEA. 3E associates roughness information to each class in order to create roughness maps that are used in the wind flow models.
Displacement height	Large areas of tall obstacles affect the wind shear, lifting the zero velocity theoretical height by a value called the displacement height.
DSM / DEM	As opposed to DTM (Digital Terrain Model), DSM / DEM (Digital Surface Model or Digital Elevation Model) includes objects on the ground surface like forests and buildings.
Era-Interim	ERA-Interim is a reanalysis dataset produced by the European Centre for Medium-Range Weather Forecast (ECMWF). It covers a period from 1979 to the present, with a resolution of 0.75°.
EU-DEM	The Digital Elevation Model over Europe from the GMES RDA project (EU-DEM) is a Digital Surface Model (DSM) representing the first surface as illuminated by the sensors. The EU-DEM dataset is a realisation of the Copernicus programme, managed by the European Commission, DG Enterprise and Industry.
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).
MeteoDyn WT	MeteoDyn WT is a CFD (Computed Fluid Dynamics) software package for predicting wind resource and power production from wind farms in complex terrains.
Normal distribution	In probability theory, the normal (or Gaussian) distribution is a bell-shaped continuous probability distribution function with two parameters: the mean and the standard deviation.

	Normal distributions are extremely important in statistics and are often used in the natural sciences for real-valued random variables whose distributions are not known. One reason for their popularity is the central limit theorem (CLT), which states that, under mild conditions, the mean of a large number of random variables independently drawn from the same distribution is distributed approximately normally, irrespective of the form of the original distribution.
Probability of exceedance	In probability theory and statistics, the probability of exceedance is a number (in the range 0 to 100%) that represents the probability that a random variable falls above (or exceeds) a certain value. It is calculated as one minus the cumulative distribution function (CDF), which describes the probability that a variable will be found at a value less than or equal to X.
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
SCADA	SCADA stands for Supervisory Control And Data Acquisition. It refers to the wind turbine monitoring and control systems. It provides the wind turbine operator with data like wind speed and direction measured on the nacelle, power production, rotational speed, pitch and yaw angles (operating point of the wind turbine), etc.
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.
SRTM	The Shuttle Radar Topography Mission (SRTM) is an international research effort spearheaded by the U.S. National Geospatial-Intelligence Agency (NGA) and the U.S. National Aeronautics and Space Administration (NASA) that obtained digital surface models on a near-global scale from 56° S to 60° N, to generate the most complete high-resolution digital topographic database of Earth. The resolution of the produced datasets is three arc-second.
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 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.

1 INTRODUCTION

Objectives

Innowind (Pty) Ltd has contracted 3E to assess the wake impact of the Phezukomoya wind farm project on the existing wind farm Noupoort operated by Mainstream.

3E is an independent consultancy and software provider company (completely independent of Innowind) providing solutions to improve renewable energy system performance, optimize energy consumption and facilitate grid and market interaction.

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.

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 configurations to be studied,
- Section 3 details the processing of wind measurements into a representative wind regime meant for energy production calculations,
- Section 4 details wind flow modelling,
- Section 5 details wake impact analysis,

2 SITE AND PROJECT DESCRIPTION

Site description

The site is located 5.6 km southwest of Noupoort, as indicated in Figure 1. The region is an arid land. The terrain is rather complex, with differences in elevation of about 70 metres between the highest and lowest locations within the project boundaries. The north area of the site shows the highest elevations (cf. ANNEX A).

An existing wind farm is located 6.6 km northeast of the site. It comprises 35 Siemens SWT-2.3-108 wind turbines with 99.5 m hub height.

Figure 1: Site location (Source: Google Earth)

Available wind measurements

The client has provided 3E with wind measurements from the following devices, whose locations are indicated in Figure 2:

- 120m mast, located at the site,
- 120m mast, located 4.9 km E of the site,

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 for the Phezukomoya wind farm, comprising 55 turbines for a total installed capacity of 220 MW. The configuration to be studied has been provided by the client and is detailed in Table 1. The wind farm layout is illustrated in Figure 2, whereas wind turbines coordinates are listed in ANNEX C.

Table 1: Wind farm configurations

Configuration		Phezukomoya wind farm: V150, 4 MW, @105m	Noupoort wind farm: SWT-2.3-108, 2.3 MW, @99.5m
Wind turbine manufacturer	[-]	Vestas	Siemens
Wind turbine type	[-]	V150	SWT-2.3-108
Number of wind turbines	[-]	55	35
Rated power per turbine	[MW]	4	2.3
Total rated power	[MW]	220.0	80.5
Rotor diameter	[m]	150	108
Hub height	[m]	105	99.5

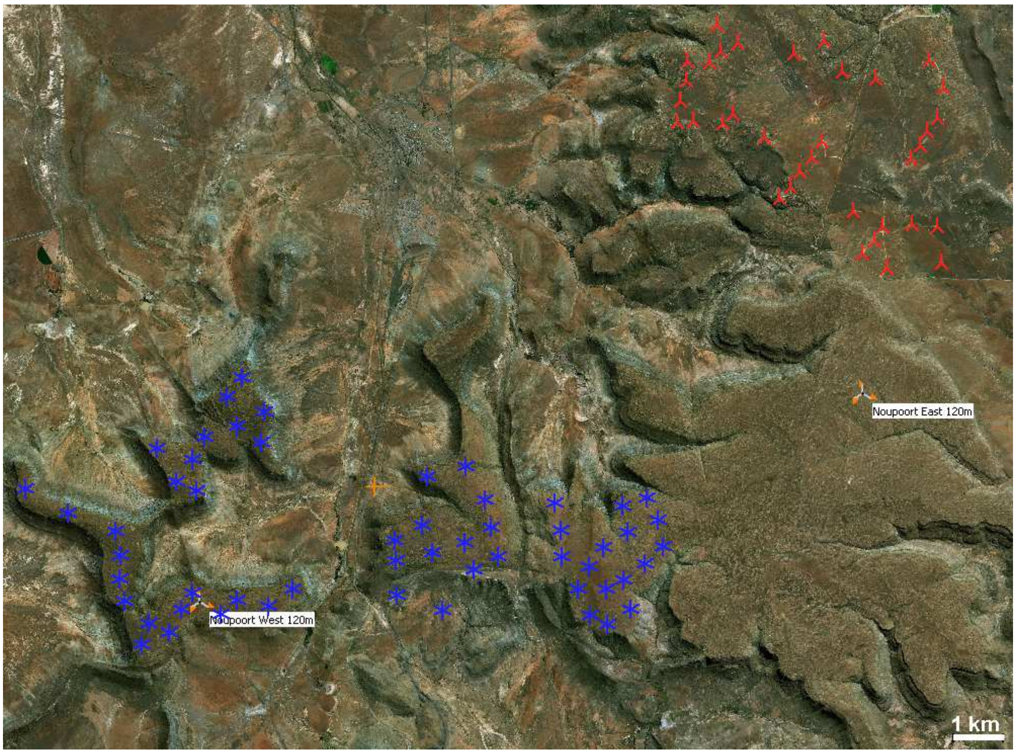


Figure 2: Aerial picture of the site with measurement device and wind turbines (Source: Bing, red items indicate Noupoort wind farm, blue items indicate Phezukomoya wind farm)

3 WIND DATA PROCESSING

3.1 SHORT-TERM WIND REGIME

3.1.1 120 m Noupoort West mast

The mast configuration complies with best practices. The period selected for the following steps of the study covers 2 complete years (24/09/2015 to 23/09/2017).

Configuration of measurement device

The mast was installed at the site by Wind Measurement International on 07/06/2015. It is a lattice mast, equipped with anemometers and wind vanes measuring the wind speed and direction at eight levels (from 39.68 m to 120 m AGL). The client provided 3E with an installation report [24], anemometers calibration certificates, 4 maintenance reports [25][26][27][28], and 10-minutes measurement data covering the period from 20/06/2015 to 05/12/2017 (29.5 months). The mast's coordinates and configuration details are provided in ANNEX B.

It should be noted that 3E assumes that any information provided by the client is correct.

The mast configuration complies with best practices [1] [2].

Data processing

Data are processed according to best practices [1] [2].

Anemometers calibration parameters have already been applied to the data provided to 3E. As a result, 3E assumes, but could not verify, that those parameters have been correctly applied.

The data are then cleaned. Most significant changes applied to the data are the following:

- The mast shading effect is corrected by alternatively using the measurements of both top anemometers depending on the wind direction (cf. ANNEX D),

After data processing, a period covering 29.5 months (20/06/2015 to 05/12/2017) is identified as being of sufficient quality for the purpose of this study.

Representativeness of the measurements for the site

The distance between the mast and the furthest wind turbine is of 9.5 km. Considering the terrain characteristics, the measurements may not be representative for the full extent of the site.

Limitation of the short-term period

In order to avoid the introduction of a seasonal bias in the next step of the study, the short-term period is limited to complete years (2 years in this case). For the selection of a single 2-year period within the whole short-term period of 29.5 months, the long-term expected production is calculated for each of the 5 rolling 2-year periods (with 1 month shift). As indicated in Table 2, the period between 24/09/2015 and 23/09/2017 is the most representative period for long-term extrapolation, and is thus selected for the next steps of the study.

Table 2: Long-term productions vs. mean, depending on the selected rolling period

Period	Difference vs. mean
24/06/2015- 23/06/2017	+ 0.1%
24/07/2015- 23/07/2017	+ 0.1%
24/08/2015- 23/08/2017	- 0.1%
24/09/2015- 23/09/2017	**0.0%**
24/10/2015- 23/10/2017	- 0.1%

Short-term wind regime

Details of measured short-term wind regime were removed from this report at request by the client due to the confidential nature of such information.

Table 3: Weibull parameters of the short-term wind regime

Wind measurement device	[-]	120m mast Noupoort West
Selected period	[-]	24/09/2015 – 23/09/2017
Height AGL	[m]	120
Arithmetic mean wind speed	[m/s]	
Weibull mean wind speed	[m/s]	
Weibull A	[m/s]	
Weibull k	[-]	
Prevailing wind directions	[-]	ESE, WNW
Wind directions with most energy content	[-]	ESE, WNW

3.1.2 120 m Noupoort East mast

The mast configuration complies with best practices. The period selected for the following steps of the study covers 2 complete years (14/09/2015 to 13/09/2017).

Configuration of measurement device

The mast was installed at the site by Wind Measurement International on 13/06/2015. It is a lattice mast, equipped with anemometers and wind vanes measuring the wind speed and direction at eight levels (from 39.68 m to 120 m AGL). The client provided 3E with an installation report [24], anemometers calibration certificates, 4 maintenance reports [25][26][27][28], and 10-minutes measurement data covering the period from 13/06/2015 to 05/12/2017 (29.8 months). The mast's coordinates and configuration details are provided in ANNEX B.

It should be noted that 3E assumes that any information provided by the client is correct.

The mast configuration complies with best practices [1] [2].

Data processing

Data are processed according to best practices [1] [2].

Anemometers calibration parameters have already been applied to the data provided to 3E. As a result, 3E assumes, but could not verify, that those parameters have been correctly applied.

The data are then cleaned. Most significant changes applied to the data are the following:

- The mast shading effect is corrected by alternatively using the measurements of both top anemometers depending on the wind direction (cf. ANNEX D),

After data processing, a period covering 28.9 months (13/06/2015 to 05/12/2017) is identified as being of sufficient quality for the purpose of this study.

Representativeness of the measurements for the site

The distance between the mast and the furthest wind turbine is of 6.9 km. Considering the terrain characteristics, the measurements may not be representative for the full extent of the site.

Limitation of the short-term period

In order to avoid the introduction of a seasonal bias in the next step of the study, the short-term period is limited to complete years (2 years in this case). For the selection of a single 2-year period within the whole short-term period of 29.8 months, the long-term expected production is calculated for each of the 5 rolling 2-year periods (with 1 month shift). As indicated in Table 2, the period between 14/09/2015 and 13/09/2017 is the most representative period for long-term extrapolation, and is thus selected for the next steps of the study.

Table 4: Long-term productions vs. mean, depending on the selected rolling period

Period	Difference vs. mean
14/06/2015- 13/06/2017	+ 0.2%
14/07/2015- 13/07/2017	+ 0.2%
14/08/2015- 13/08/2017	+ 0.3%
14/09/2015- 13/09/2017	**- 0.1%**
14/10/2015- 13/10/2017	- 0.6%

Short-term wind regime

Details of measured short-term wind regime were removed from this report at request by the client due to the confidential nature of such information.

Table 5: Weibull parameters of the short-term wind regime

Wind measurement device	[-]	120m mast Noupoort East
Selected period	[-]	14/09/2015 – 13/09/2017
Height AGL	[m]	120
Arithmetic mean wind speed	[m/s]	
Weibull mean wind speed	[m/s]	
Weibull A	[m/s]	
Weibull k	[-]	
Prevailing wind directions	[-]	WNW, ESE
Wind directions with most energy content	[-]	WNW, ESE

Compliance with the requirements of the RFP

This measuring campaign complies with the requirements of the RFP issued by the Department of Energy of the Republic of South Africa [3]:

- The length of the properly recorded wind data is sufficient (over 12 months).
- The top measurement height (120 m AGL) is above 2/3 of the intended hub height (105 m AGL).

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 the lowest uncertainty is selected.

3.2.1 Reference datasets

3E selects reference dataset from the following sources:

- MERRA-2 and post-processed ERA-Interim reanalysis data from WindPRO (4 closest grid points),
- Meteorological station data from WindPRO,
- Any long-term data provided by the client.

In cases these sources are considered insufficient, the following are also considered:

- Post-processed CFSR-E reanalysis data from WindPRO,
- Native ERA-Interim and CFSR data,
- NOAA meteorological station data and publicly available data from meteorological institutes.

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”. 3E considers a Pearson coefficient of 0.7 (all data or monthly averages) as a minimum prerequisite for a reference dataset to be considered for long-term extrapolation.

- **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. 3E considers data availability above 80 % as a minimum prerequisite for a reference dataset to be used for long-term extrapolation.
- **Consistency**: the reference dataset should not reveal any abrupt change or unrealistic trend. 3E applies a SNHT test [12] 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 [13][14] (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 6. Their long-term behaviours in terms of windiness are illustrated in Figure 3, whereas their geographical locations are indicated in ANNEX E.

Table 6: Selection of reference datasets

Type	Name	Time shift[1]	r (all data)	r (monthly averages)	Long-term period[2]	Concurrent period	Time resolution	Data availability	Trend test result[3]
MERRA	**MERRA2_ S31.000_E 025.000**	**-3h**	**0.712**	**0.793**	**1/12/2000-30/11/2017**	**2.45**	**1.00**	**100**	**OK**
MERRA	**MERRA2_ S31.500_E 025.000**	**-3h**	**0.708**	**0.870**	**1/12/2000-30/11/2017**	**2.45**	**1.00**	**100**	**OK**
MERRA	MERRA2_ S31.000_E 024.375	-3h	0.669	0.758	1/12/2000-30/11/2017	2.45	1.00	100	OK
MERRA	MERRA2_ S31.000_E 025.625	-3h	0.692	0.797	1/12/2000-30/11/2017	2.45	1.00	100	OK
ERA-Interim	**EmdERA_ S31.228_E 025.308**	**-3h**	**0.772**	**0.889**	**1/11/2001-31/10/2017**	**2.37**	**6.00**	**100**	**OK**
ERA-Interim	**EmdERA_ S31.228_E 024.605**	**-3h**	**0.775**	**0.878**	**1/11/2000-31/10/2017**	**2.37**	**6.00**	**100**	**OK**
ERA-Interim	EmdERA_ S30.526_E 025.308	-2h	0.708	0.835	1/11/2003-31/10/2017	2.37	6.00	100	OK
ERA-Interim	EmdERA_ S30.526_E 024.605	-2h	0.690	0.649	1/11/2003-31/10/2017	2.37	6.00	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

Type	Name	Time shift[1]	r (all data)	r (monthly averages)	Long-term period[2]	Concurrent period	Time resolution	Data availability	Trend test result[3]
Met. Station - METAR (Windpro)	Bloemfontein,_Bloemfontein_Airport_METAR_S29.100_E26.300	-3h	0.179	-0.039	1/11/2007-31/10/2017	2.37	1.00	88	Period too short to tell
Met. Station - METAR (Windpro)	Maseru_Moshoeshoe_METAR_S29.450_E27.550	-3h	0.143	-0.410	29/10/2009-29/10/2017	2.36	1.00	20	Not done
Met. Station - METAR (Windpro)	Port_Elizabeth,_Port_E_Apt_METAR_S33.990_E25.600	3h	0.033	-0.140	1/11/2003-31/10/2017	2.37	1.00	100	OK
Met. Station - METAR (Windpro)	East_London,_East_London_Airport_METAR_S33.030_E27.840	-3h	0.011	-0.293	31/10/2010-31/10/2017	2.37	1.00	63	Period too short to tell
Met. Station - SYNOP (Windpro)	SYNOP_68-633_S31.180_E24.950	-2h	0.535	-0.088	31/10/2014-31/10/2017	2.37	6.00	90	Period too short to tell
Met. Station - SYNOP (Windpro)	DEAAR(UA)_SYNOP_68-538_S30.650_E24.000	-2h	0.447	-0.005	1/11/2001-31/10/2017	2.37	3.00	97	OK
Met. Station - SYNOP (Windpro)	ALIWAL_NORTH_SYNOP_68-546_S30.800_E26.880	-2h	0.307	0.003	31/10/2014-31/10/2017	2.37	6.00	91	Period too short to tell

Type	Name	Time shift[1]	r (all data)	r (monthly averages)	Long-term period[2]	Concurrent period	Time resolution	Data availability	Trend test result[3]
Met. Station - SYNOP (Windpro)	SYNOP_68-647_S31.920_E26.880	-3h	0.318	0.265	31/10/2000-31/10/2017	2.37	6.00	88	OK

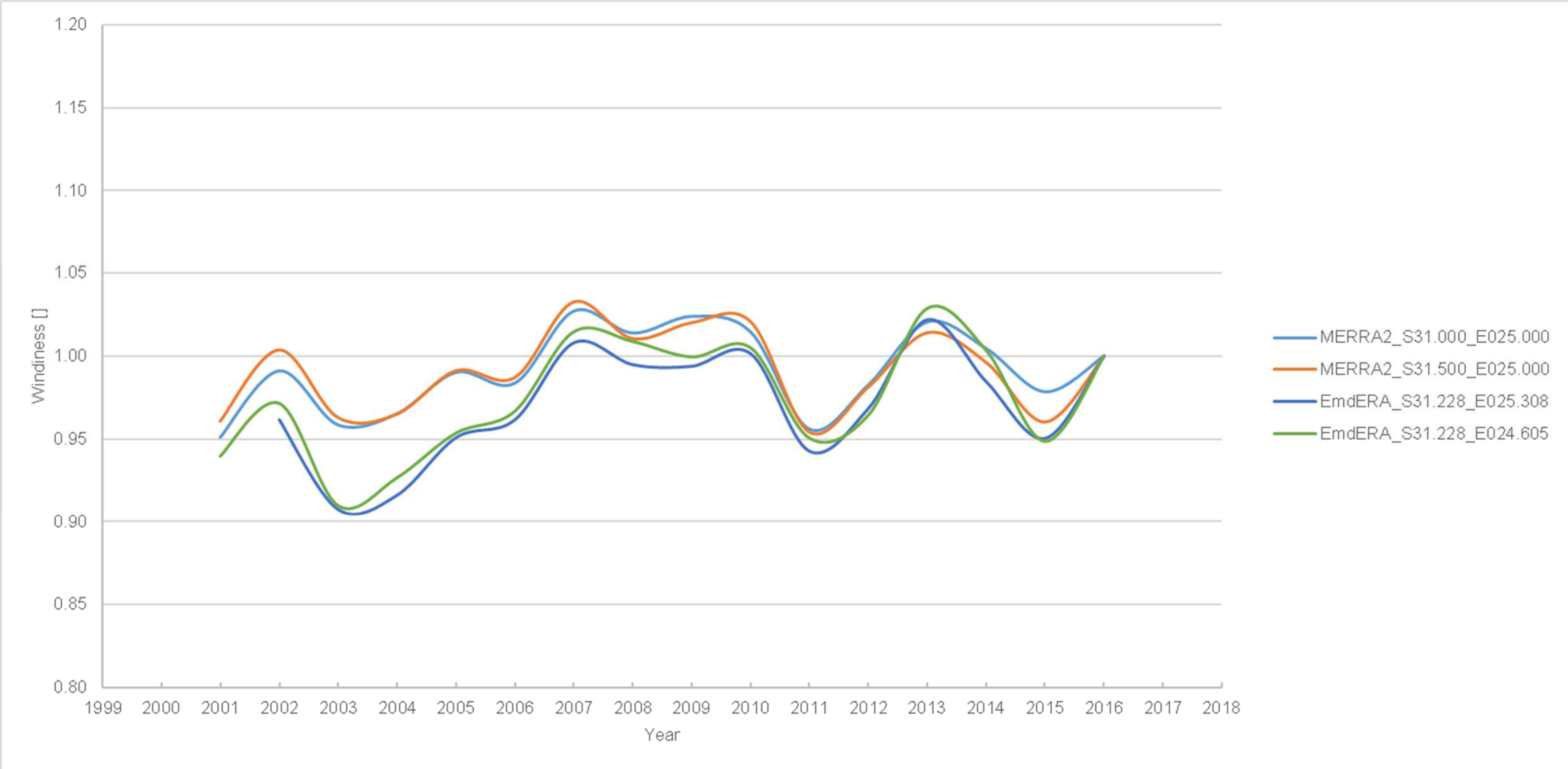


Figure 3: Annual windiness relative to last concurrent year

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. A comparative analysis of these methods is provided in ANNEX G.

3E only considers MCP methods if r (all data) exceeds a threshold of 0.7. For the Wind Index method, 3E considers that the same threshold applies, but this time using the monthly averaged r-value.

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

- For 120 m Noupoort West mast: The least uncertainty[4] is obtained from ERA-Interim S31.228 E25.308 data using the Linear regression MCP method, which is therefore the selected combination of reference data and extrapolation method. ANNEX F illustrates the agreement between the measurements and the reference dataset.

  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 17-year period 01/11/2001 – 31/10/2017. The Weibull parameters of this new time series are given in Table 7. The mean wind speed expected over the long-term is slightly lower than measured over the short-term ; the prevailing wind directions are ESE and WNW, which are exactly the same to what is observed over the short-term.

  It should be noted that details of long-term extrapolated wind regime were removed from this report at request by the client due to the confidential nature of such information

Table 7: Long-term extrapolation results

Wind measurement device	[-]	120m Noupoort West mast
Long-term period	[-]	01/11/2001 – 31/10/2017
Height AGL	[m]	120
Arithmetic mean wind speed	[m/s]	
Weibull mean wind speed	[m/s]	
Weibull A	[m/s]	
Weibull k	[-]	
Prevailing wind directions	[-]	ESE, WNW
Wind directions with most energy content	[-]	ESE, WNW

[4] Uncertainty figure results from a calculation based on many parameters and is calculated for every potential combination of reliable reference data and long-term extrapolation method.in order to identify the combination with the lowest uncertainty, which should then be used in the study.

- For 120 m Noupoort East mast: The least uncertainty[5] is obtained from ERA-Interim S31.228 E25.308 data using the Linear regression MCP method, which is therefore the selected combination of reference data and extrapolation method. ANNEX F illustrates the agreement between the measurements and the reference dataset.
  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 16-year period 01/11/2001 – 31/10/2017. The Weibull parameters of this new time series are given in Table 7. The mean wind speed expected over the long-term is slightly lower than measured over the short-term; the prevailing wind directions are WNW and ESE, which are exactly the same to what is observed over the short-term.
  It should be noted that details of long-term extrapolated wind regime were removed from this report at request by the client due to the confidential nature of such information

Table 8: Long-term extrapolation results

Wind measurement device	[-]	120m Noupoort East mast
Long-term period	[-]	01/11/2001 – 31/10/2017
Height AGL	[m]	120
Arithmetic mean wind speed	[m/s]	
Weibull mean wind speed	[m/s]	
Weibull A	[m/s]	
Weibull k	[-]	
Prevailing wind directions	[-]	WNW, ESE
Wind directions with most energy content	[-]	WNW, ESE

[5] Uncertainty figure results from a calculation based on many parameters and is calculated for every potential combination of reliable reference data and long-term extrapolation method.in order to identify the combination with the lowest uncertainty, which should then be used in the study.

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 [6]) based on SRTM data. Height contour lines are then generated with an elevation difference of 10 m between two successive lines.

It should be noted that SRTM is a digital surface model (DSM), which includes features such as forests and buildings.

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 [7].

Shapes of land use areas and roughness lengths are determined based on aerial imagery.

The aerial imagery from Google Earth and dated 2016 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, 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 area of obstacles (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, and are associated with a modification of roughness length [8].

In this study, no such large area of obstacles is present; hence no displacement height is applied.

4.2 WIND FLOW MODEL

WAsP is used to extrapolate the wind regime to the location and hub height of /each 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 /each wind turbine location.

For this project both masts were used as input to initiate the wind flow calculations. Considering the terrain characteristics, wind regime and inter-distances, it has been decided to use the Noupoort East mast for the turbines of the Noupoort wind farm and the Noupoort West mast for the most-western turbines of the Phezukomoya wind farm. For the turbines in between, both masts were used, weighted linearly with respect to their respective distance to the turbines. More specifically, the following turbines were studied that way: WTGs 31 to 36, 46, 48, 50 to 57, 60 to 61, 84 to 86.

WAsP is designed for ΔRIX values close to 0, where RIX[6] 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 [6], by computing ΔRIX between each wind turbine location and the location of the measurement device used for wind flow simulations.

The ΔRIX values varies at the wind turbine locations between -3.8 and 6.7. These values are above the allowed values for the use of WAsP. However, it should be noted that the purpose of this study is to estimate wake impact between wind farms. In this context, 3E's professional opinion is such that the wind speeds calculated by WAsP will be in the right order of magnitude leading to reliable wake results.

[6] Ruggedness index

5 WAKE IMPACT ANALYSIS

The additional wake losses due to the planned Phezukomoya wind farm on the existing Noupoort project was calculated by using the N.O. Jensen (EMD) : 2005 wake model implemented in WindPRO.

In order to account for the long-term representative losses, the long-term extrapolated meteorological data (cf. Section 3.2) was used to initiate the flow model.

Table 9: Wake impact on the Noupoort wind farm caused by the Phezukomoya project

Configuration		V150, 4MW, @105m
Additional wake impact on the Noupoort wind farm	**[%]**	**0.15**

6 CONCLUSIONS AND RECOMMENDATIONS

3E has calculated the additional wake impact caused by the Phezukomoya wind farm project on the existing Noupoort wind farm. The calculated loss representative for a 20 year period is provided in the following table:

Table 10: Wake impact on the Noupoort wind farm caused by the Phezukomoya project

Configuration		V150, 4MW, @105m
Additional wake impact on the Noupoort wind farm	**[%]**	**0.15**

Due to the large distance between the 2 wind farms and the frequency of the wind being rather limited from the sectors of south-south-west and west-south-west, the additional wake impact is quite small.

7 REFERENCES

[1] MEASNET. Evaluation of site-specific wind conditions. Version 1, Nov 2009.

[2] IEA (International Energy Agency). Recommended practices for wind turbine testing and evaluation. Wind speed measurement and use of cup anemometry. Second print 2003.

[3] GL-GH, position statement on the WINDCUBE/ZephIR remote sensing devices, 2012

[4] Ecofys, The Ecofys position on Lidar use, 2013

[5] Department of Energy South Africa, Request for qualification and proposals for new generation capacity under the IPP procurement programme, 03/02/2012.

[6] The WAsP team, "WAsP best practices and checklist", DTU, June 2013.

[7] Y. Cabooter, K. De Ridder, J.P. Van Ypersele, C. Tricot. Improved prediction of wind power in Belgium, Part 1. SPSD II, Belgian Science Policy, October 2006.

[8] GL Garrad Hassan: "Optimizing the parameterization of forests for WAsP wind speed calculations: A retrospective empirical study", EWEA 2012.

[9] WindPro user manual.

[10] Nils G. Mortensen, Ib Troen and Erik Lundtang Petersen. European Wind Atlas published for the Commission of the European Communities Directorate-General for Science, Research and Developpement, Brussels, Belgium by Risoe National Laboratory, Roskilde, Denmark, 1989, ISBN 87-550-1482-8.

[11] T. Burton, D. Sharpe, N. Jenkins, E. Boussanyi. Wind Energy Handbook.

[12] H. Alexandersson, A homogeneity test applied to precipitation data. J. Climatol, 1986

[13] H.B. Mann, Non-parametric tests against trend, Econometrica, 1945

[14] M.G. Kendall, Rank Correlation Methods, Charles Griffin, 1975

[15] Lloyd W. Wind Resource assessment using Measure-Correlate-Predict Techniques, Crest MSc thesis, 1995.

[16] A. Rogers, J. Rogers and J Manwell. Comparison of the performance of four measure-correlate-predict algorithms, Journal of Wind Energeering and Industrial Aerodynamics 93, 2005, pp. 243-264.

[17] A Comparison of Measure-Correlate-Predict Techniques for Wind Resource Assessment, Crest MSc thesis, 1996.

[18] J.C. Woods and S.J. Watson. A new matrix method of predicting long-term wind roses with MCP, J Wind Engineering and Industrial Aerodynamics 66, pp 85-94, 1997.

[19] C. Heipke, A. Koch, P. Lohmann. Analysis of SRTM DTM – Methodology and practical results. Institute for Photogrammetry and Geoinformation (IPI), University of Hannover.

[20] G. Mortensen, L. Landberg, I. Troen, E.L. Petersen. Wind Atlas Analysis and Application Program (WAsP). Risoe National Laboratory, Roskilde, Denmark, 1993 and updates.

[21] Bowen, A.J. and N.G. Mortensen (1996/2005). WAsP prediction errors due to site orography. Risø-R-995(EN). Risø National Laboratory, Roskilde. 65 pp.

[22] Bowen, A.J. and N.G. Mortensen (1996). Exploring the limits of WAsP: the Wind Atlas Analysis and Application Program. Proc. 1996 European Union Wind Energy Conference, Göteborg, 584-587.

[23] Eskom Holdings Soc Limited, Power purchase agreement – wind projects, Pursuant to the renewable energy independent power producer procurement programme, 03/08/2011.

[24] Noupoort West Installation Report rev2, Wind Measurement International, 03/07/2015.

[25] Maintenance Schedule & Report, Wind Measurement International, 30/04/2016.

[26] Maintenance Schedule & Report, Wind Measurement International, 06/12/2016.

[27] Maintenance Schedule & Report, Wind Measurement International, 25/09/2017.

[28] Additional Works Report, Wind Measurement International, 12/10/2017

ANNEX A SITE DESCRIPTION ILLUSTRATIONS

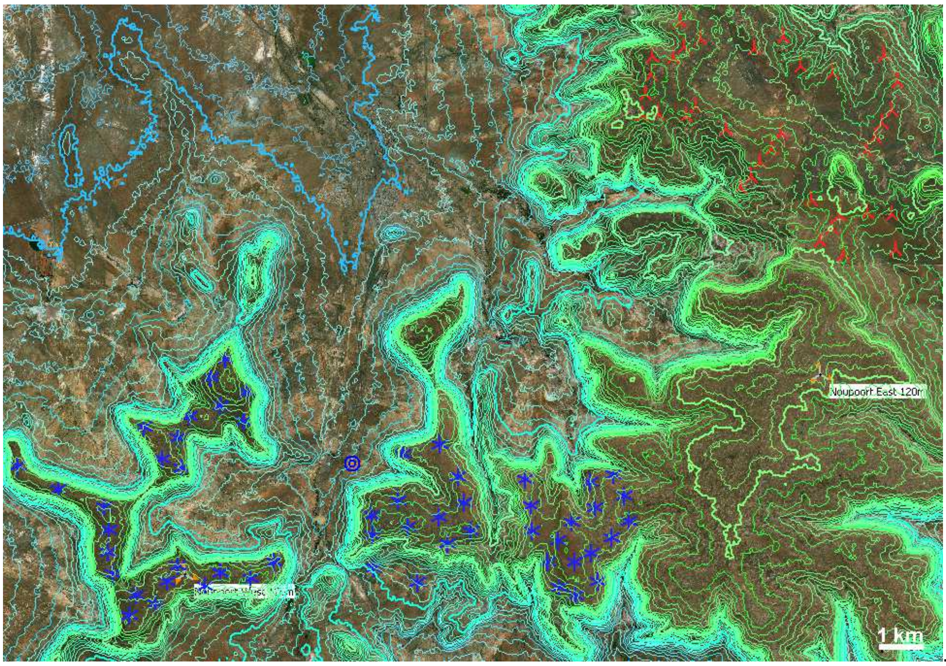


Figure 4: Site elevation (contour lines every 10 metres, and warmer colours denote higher elevations, red items indicate Noupoort wind farm, yellow items indicate Phezukomoya wind farm)

ANNEX B CONFIGURATION OF MEASUREMENT DEVICE

Table 11: Characteristics of measurement devices (coordinate system: WGS1984 - UTM Zone 35S)

Measurement device	Noupoort West Mast	Noupoort East Mast
Longitude (X)	300,815 m	314,139 m
Latitude (Y)	6,539,3807 m	6,543,577 m
Altitude	1,760 m	1,814 m
Measurement heights AGL	120 m, 119.68 m, 100 m, 99.68 m, 80 m, 79.68 m, 40 m, 39.68 m	120 m, 119.68 m, 100 m, 99.68 m, 80 m, 79.68 m, 40 m, 39.68 m
Date begin	20/06/2015	13/06/2015
Date end	05/12/2017	05/12/2017
Period length	29.5 months	29.8 months
Availability	98.6 %	99.3 %

Table 12: Instruments for the 120 m Noupoort West mast and calibration factors

Channel	Sensor	Slope	Offset	Height AGL	Orientation
C1	Thies Anemometer First Class	0.04589	0.2686	120 m	30 °
P1	NRG Anemometer	0.761	0.34	119.679 m	30 °
C2	Thies Anemometer First Class	0.04604	0.2480	100 m	30 °
P2	NRG Anemometer	0.763	0.30	99.679 m	30 °
*C3	Thies Anemometer First Class	0.04596	0.2641	80 m	30 °
C4	NRG Anemometer	0.759	0.35	79.679 m	30 °
C5	NRG Anemometer	0.759	0.36	40 m	30 °
C6	NRG Anemometer	0.762	0.32	39.679 m	30 °

Se1	NRG Windvane	-	-	118 m	30 °
Se2	NRG Windvane	-	-	98 m	30 °
Se3	NRG Windvane	-	-	78 m	30 °
Se4	NRG Temperature	-	-	97.5 m	30 °
Se5	NRG Temperature	-	-	37.5 m	30 °
Se6	NRG Pressure	-	-	20 m	30 °
Se7	NRG Humidity	-	-	20 m	30 °

*Thies Anemometer @80 m was replaced in October 2017.

Table 13: Instruments for the 120 m Noupoort East mast and calibration factors

Channel	Sensor	Slope	Offset	Height AGL	Orientation
C1	Thies Anemometer First Class	0.04617	0.2226	120 m	30 °
P1	NRG Anemometer	0.759	0.37	119.679 m	30 °
C2	Thies Anemometer First Class	0.04610	0.2286	100 m	30 °
P2	NRG Anemometer	0.760	0.34	99.679 m	30 °
C3	Thies Anemometer First Class	0.04610	0.2262	80 m	30 °
C4	NRG Anemometer	0.762	0.33	79.679 m	30 °
C5	NRG Anemometer	0.760	0.35	40 m	30 °
C6	NRG Anemometer	0.760	0.36	39.679 m	30 °
Se1	NRG Windvane	-	-	118 m	30 °
Se2	NRG Windvane	-	-	98 m	30 °

Se3	NRG Windvane	-	-	78 m	30 °
Se4	NRG Temperature	-	-	97.5 m	30 °
Se5	NRG Temperature	-	-	37.5 m	30 °
Se6	NRG Pressure	-	-	20 m	30 °
Se7	NRG Humidity	-	-	20 m	30 °

ANNEX C WIND TURBINES COORDINATES

Table 14: Wind turbines coordinates and altitudes of the Phezukomoya wind farm (coordinate system: WGS1984 - UTM Zone 35S)

Turbine	Longitude (X)	Latitude (Y)	Altitude
	[m]	[m]	[m]
WTG1	297,313	6,541,669	1,726.70
WTG2	298,171	6,541,181	1,731.00
WTG3	299,125	6,540,810	1,757.80
WTG4	299,238	6,540,324	1,758.30
WTG5	299,203	6,539,849	1,758.70
WTG6	299,315	6,539,399	1,750.00
WTG8	299,648	6,538,531	1,768.90
WTG9	299,793	6,538,956	1,754.70
WTG10	300,672	6,539,572	1,751.10
WTG12	301,235	6,539,138	1,743.00
WTG13	302,201	6,539,292	1,740.00
WTG14	302,695	6,539,652	1,722.30
WTG15	300,756	6,541,621	1,745.20
WTG16	300,356	6,541,808	1,750.00
WTG17	299,968	6,542,479	1,750.00
WTG18	300,671	6,542,254	1,740.00
WTG19	300,926	6,542,691	1,740.00
WTG20	301,575	6,542,917	1,754.30
WTG21	302,059	6,542,592	1,740.00
WTG22	302,121	6,543,207	1,759.20
WTG23	301,355	6,543,519	1,769.30
WTG24	301,663	6,543,903	1,770.00
WTG25	305,694	6,539,214	1,620.00
WTG26	304,775	6,539,530	1,608.70
WTG27	304,771	6,540,212	1,731.80
WTG28	304,751	6,540,613	1,734.90
WTG29	305,292	6,540,925	1,727.20
WTG30	305,499	6,540,372	1,738.30
WTG31	306,155	6,540,574	1,733.50

Turbine	Longitude (X)	Latitude (Y)	Altitude
WTG32	306,814	6,540,307	1,740.00
WTG33	306,667	6,540,883	1,730.00
WTG34	306,550	6,541,430	1,725.50
WTG35	305,394	6,541,913	1,710.00
WTG36	306,166	6,542,104	1,720.00
WTG46	307,954	6,541,374	1,780.00
WTG48	308,082	6,540,820	1,772.90
WTG49	308,106	6,540,304	1,778.10
WTG50	308,929	6,540,485	1,775.80
WTG51	308,649	6,540,090	1,783.50
WTG52	308,429	6,539,656	1,764.70
WTG53	308,662	6,539,115	1,756.70
WTG54	308,993	6,539,642	1,781.60
WTG55	309,335	6,539,825	1,773.90
WTG56	309,773	6,540,148	1,777.30
WTG57	310,139	6,540,501	1,773.30
WTG58	310,025	6,541,026	1,780.00
WTG59	309,817	6,541,483	1,768.20
WTG60	309,321	6,541,317	1,759.30
WTG61	309,430	6,540,783	1,762.60
WTG65	301,560	6,539,422	1,740.00
WTG66	300,456	6,539,248	1,760.00
WTG67	300,201	6,538,775	1,760.00
WTG84	306,330	6,540,024	1,740.00
WTG85	309,008	6,538,929	1,754.90
WTG86	309,478	6,539,233	1,770.00

Table 15: Wind turbines coordinates and altitudes of the Noupoort wind farm (coordinate system: WGS1984 - UTM Zone 35S)

Turbine	Longitude (X)	Latitude (Y)	Altitude
	[m]	[m]	[m]
WTG1	315,739	6,546,188	1,760
WTG2	315,648	6,546,932	1,778

Turbine	Longitude (X)	Latitude (Y)	Altitude
WTG3	315,139	6,546,967	1,790
WTG4	314,626	6,546,092	1,790
WTG5	314,147	6,546,386	1,795
WTG6	314,380	6,546,644	1,800
WTG8	314,552	6,546,923	1,799
WTG9	313,962	6,547,232	1,794
WTG10	315,120	6,548,300	1,760
WTG12	312,472	6,547,490	1,760
WTG13	312,704	6,547,718	1,764
WTG14	312,891	6,548,022	1,781
WTG15	313,116	6,548,315	1,790
WTG16	313,337	6,548,645	1,775
WTG17	312,164	6,548,723	1,780
WTG18	311,327	6,549,010	1,790
WTG19	311,540	6,549,196	1,780
WTG20	310,747	6,549,038	1,797
WTG21	310,420	6,549,036	1,798
WTG22	310,487	6,549,449	1,790
WTG23	310,612	6,549,867	1,788
WTG24	310,631	6,550,242	1,785
WTG25	311,061	6,550,226	1,778
WTG26	311,302	6,550,444	1,778
WTG27	311,631	6,550,608	1,779
WTG28	311,205	6,550,972	1,780
WTG29	312,761	6,550,419	1,762
WTG30	313,360	6,550,649	1,740
WTG31	313,731	6,550,050	1,740
WTG32	314,413	6,549,898	1,740
WTG33	315,301	6,548,558	1,751
WTG34	315,449	6,548,838	1,753
WTG35	315,641	6,549,105	1,750
WTG36	315,762	6,549,713	1,741
WTG37	315,494	6,550,265	1,728

ANNEX D MAST EFFECT CORRECTION

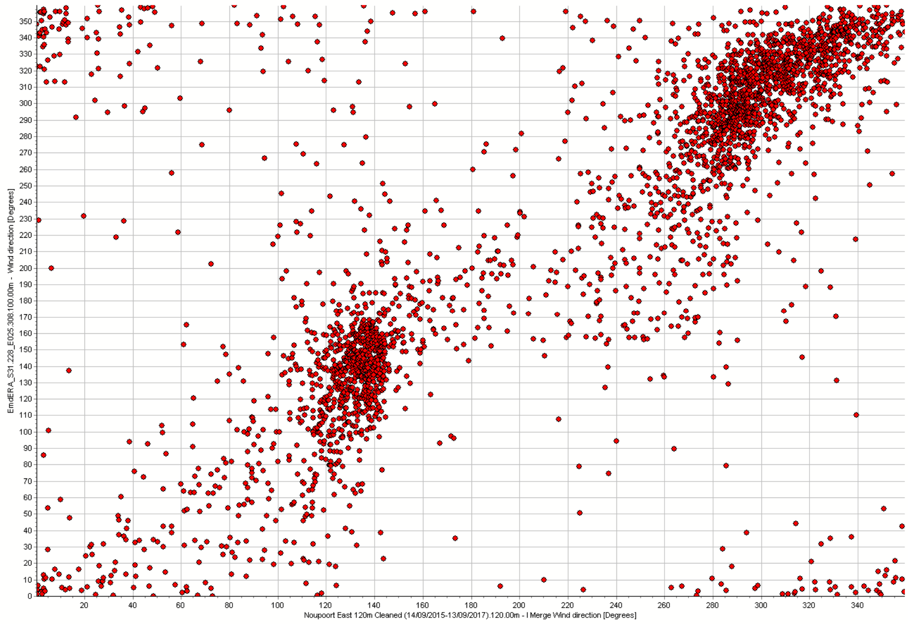
Table 16: Mast effect correction

Height	Primary anemometer	Secondary anemometer	Wind directions where secondary anemometer is used
120 m	C1	P1	154 ° - 167 °

ANNEX E LONG-TERM REFERENCE DATASETS

Figure 5: Location of the considered long-term reference datasets with respect to the site

ANNEX F AGREEMENT OF THE SELECTED REFERENCE DATA WITH THE MEASURED DATA



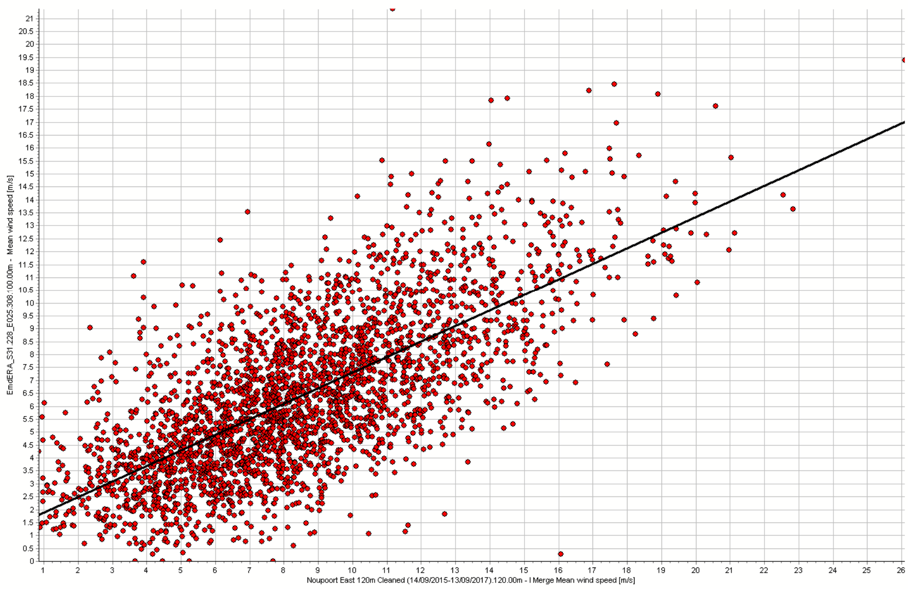
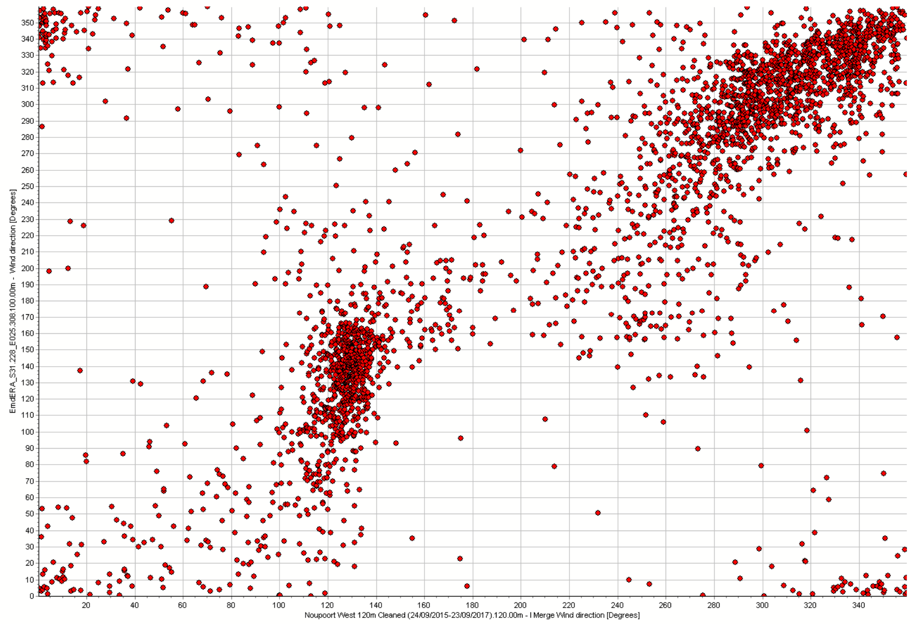


Figure 6: Comparison of the measured (X) and reference (Y) wind directions (top) and speeds (bottom) – Noupoort East Mast



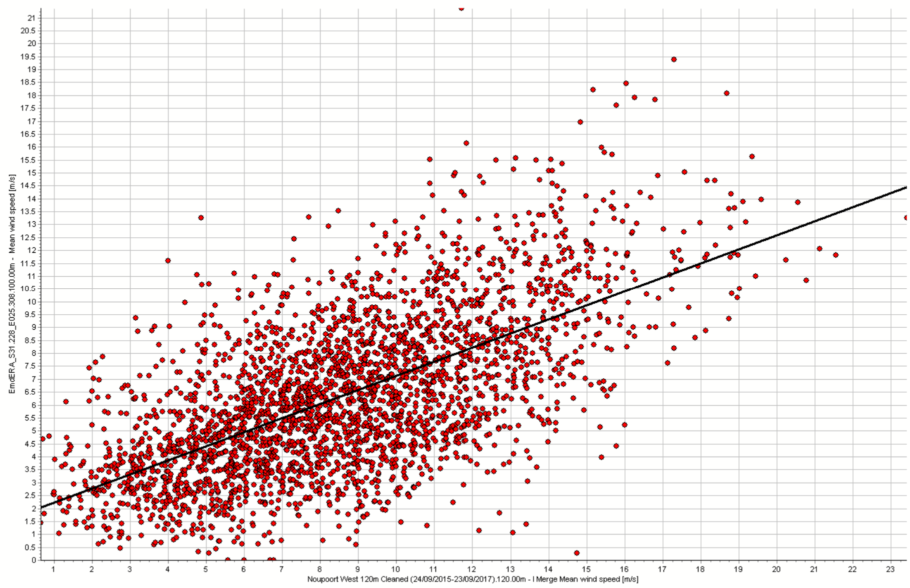


Figure 7: Comparison of the measured (X) and reference (Y) wind directions (top) and speeds (bottom) – Noupoort West Mast

ANNEX G 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 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 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.

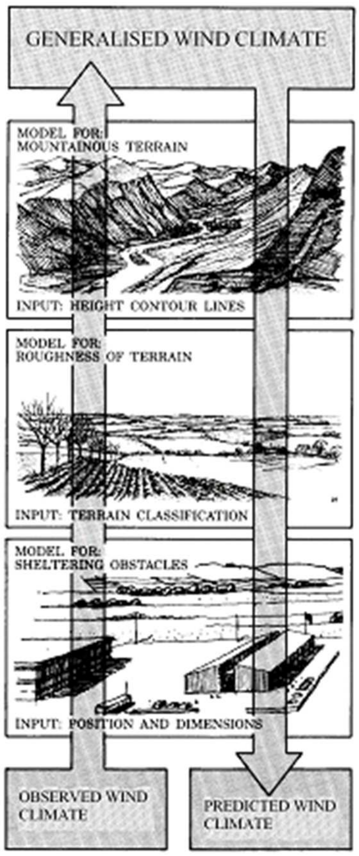


Figure 8: Wind Atlas methodology (Source: wasp.dk)

ANNEX I POWER & THRUST CURVES

Table 17: Power & thrust curves (PC & TC), air density = 1.225 kg/m³

Wind speed	V150		Wind speed	V150	
	PC	TC		PC	TC
[m/s]	[kW]	[-]	[m/s]	[kW]	[-]
3	78	0.998	13	4,000	0.212
3.5	172	0.919	13.5	4,000	0.188
4	287	0.860	14	4,000	0.168
4.5	426	0.847	14.5	4,000	0.151
5	601	0.838	15	4,000	0.137
5.5	814	0.832	15.5	4,000	0.124
6	1,069	0.823	16	4,000	0.113
6.5	1,367	0.817	16.5	4,000	0.103
7	1,717	0.805	17	4,000	0.094
7.5	2,110	0.792	17.5	4,000	0.087
8	2,546	0.778	18	4,000	0.081
8.5	3,002	0.742	18.5	4,000	0.075
9	3,427	0.679	19	4,000	0.069
9.5	3,751	0.602	19.5	4,000	0.064
10	3,922	0.516	20	4,000	0.060
10.5	3,977	0.435	20.5	4,000	0.056
11	3,999	0.369	21	4,000	0.052
11.5	4,000	0.316	21.5	4,000	0.049
12	4,000	0.274	22	4,000	0.046
12.5	4,000	0.240	22.5	4,000	0.043

QUALITY INFORMATION

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