European Commission

Clean energy for EU islands: Pre-feasibility study for the repowering of Nasca Wind Farm, San Pietro Island, Italy

Clean energy for EU islands

Pre-feasibility study for the repowering of Nasca Wind Farm San Pietro Island, Italy

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Glossary

AEP	Annual Energy Production
AGL / ASL	Above Ground Level / Above Sea Level
BOP	BOP (Balance of Plant) refers to the civil and electrical infrastructure within the wind farm, including inter-array cables, junction boxes, foundations, and other components.
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 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 theoretical zero-velocity height by a value known as 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-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.
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
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).
NORMAL DISTRIBUTION	In probability theory, the standard (or Gaussian) distribution is a bell-shaped continuous probability distribution function with two parametres: 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 approximately normally distributed, regardless of the original distribution's form.
PROBABILITY OF EXCEEDANCE	In probability theory and statistics, the probability of exceedance is a number (in the range of 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
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 production from wind turbines and wind farms. WAsP was developed and distributed by the Danish Technical University (DTU) Wind Energy. It has become the industry-standard PC software for wind resource assessment in the wind power industry.
WEIBULL DISTRIBUTION	In probability theory and statistics, the Weibull distribution is a continuous probability distribution function with two parametres: 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	The difference in production is 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, and the wind speed distribution in each sector is approximated by a Weibull distribution defined by two parametres, A & k. A wind regime is defined by these parametres 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 airflow. 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

This report presents the results of the pre-feasibility assessment for the repowering of the Nasca Wind Farm, located on San Pietro Island, Sardinia, Italy. The actual wind farm consists of three 320 kW wind turbines, which have been out of use and in a state of disrepair for many years. A 999 kW operating PV plant is also installed in the same area. In 2012, the Regional Authority approved the repowering of the wind farm, with a new layout consisting of 2 x LTW70 installed at a hub height of 50 m and characterised by a tip height (total height) of 85 m. The project has never been realised.

To assess the repowering of the existing wind farm, this report considers a total of eight wind farm configurations. The wind farm project analysed in this report builds on the layout approved by the Regional Authority in 2012 and makes use, in all scenarios, of the same wind turbine positions. Two of the proposed layouts are characterised by wind turbines with lower tip heights with respect to the previously approved configurations. In contrast, the other six have higher tip heights but lower rotor diameters. All configurations are characterised by a total installed capacity of 2 MW and are listed as follows:

- Layout 1: 2x EWT DW61 1 MW wind turbine with 61 m rotor diameter and 46 m hub height,
- Layout 2: 2x EWT DW61 1 MW wind turbine with 61 m rotor diameter and 59 m hub height,
- Layout 3: 2x EWT DW61 1 MW wind turbine with 61 m rotor diameter and 69 m hub height,
- Layout 4: 2x EWT DW61 1 MW wind turbine with 61 m rotor diameter and 84 m hub height,
- Layout 5: 2x EWT DW58 1 MW wind turbine with 58 m rotor diameter and 46 m hub height,
- Layout 6: 2x EWT DW58 1 MW wind turbine with 58 m rotor diameter and 59 m hub height,
- Layout 7: 2x EWT DW58 1 MW wind turbine with 58 m rotor diameter and 69 m hub height,
- Layout 8: 2x EWT DW58 1 MW wind turbine with 58 m rotor diameter and 84 m hub height.

This preliminary stage study is based on a Virtual Met Mast (VMM) located at the site. The terrain at the site was modelled (in terms of elevation, roughness, and obstacles to 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. Concerning the wind regime on site, as a representative example, the expected Weibull mean wind speed at the location of wind turbine WT1 (cf. Figure 4, pink legend) at 59 m AGL is 6.6 m/s, with prevailing wind directions North North-West (NNW) and West North-West (WNW).

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

Energy production losses considered in this study are around 9.4 % for every configuration and breakdown as in Table 1. The resulting production from the different configurations is summarised in Table 2.

Table 1: Breakdown of energy production losses in the different scenarios.

Configuration		**DW61, 1 MW @ 46 m**	**DW61, 1 MW @ 59 m**	**DW61, 1 MW @ 69 m**	**DW61, 1 MW @ 84 m**	**DW58, 1 MW @ 46 m**	**DW58, 1 MW @ 59 m**	**DW58, 1 MW @ 69 m**	**DW58, 1 MW @ 84 m**
Scenario		**SC 1**	**SC 2**	**SC 3**	**SC 4**	**SC 5**	**SC 6**	**SC 7**	**SC 8**
Wake losses	**[%]**	**0.8**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Unavailability losses	**[%]**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**
Turbine		5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
BOP		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Grid		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Performance losses	**[%]**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Generic performance losses		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Suboptimal performance		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Hysteresis losses		0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1
Electrical losses	**[%]**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Environmental losses	**[%]**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Performance degradation not due to icing		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Performance degradation due to icing		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total losses (*)	**[%]**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**

Table 2: Summary of energy production in different scenarios.

Configuration		**2x DW61, 1 MW @ 46 m**	**2x DW61, 1 MW @ 59 m**	**2x DW61, 1 MW @ 69 m**	**2x DW61, 1 MW @ 84 m**	**2x DW58, 1 MW @ 46 m**	**2x DW58, 1 MW @ 59 m**	**2x DW58, 1 MW @ 69 m**	**2x DW58, 1 MW @ 84 m**
Scenario		**SC 1**	**SC 2**	**SC 3**	**SC 4**	**SC 5**	**SC 6**	**SC 7**	**SC 8**
Gross energy production	[MWh/y]	5,602	6,072	6,382	6,775	5,255	5,707	6,009	6,391
Total energy production losses	[%]	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
Net energy production (AEP)	[MWh/y]	5,064	5,489	5,770	6,125	4,752	5,161	5,433	5,779
Net full load equivalent hours	[h/y]	2,532	2,744	2,885	3,062	2,376	2,580	2,717	2,890

Nowadays, thanks to the PV plant in Nasca and several distributed rooftop PV plants, San Pietro Island has ~13.5% self-sufficiency in its electrical supply. The wind farm studied in this report has the potential to increase self-sufficiency to a value between 42.3% and 50.7%, depending on the scenario assessed (i.e., primarily based on the hub height of the new turbines).

The suitability of the existing distribution grid to host the new capacity from the wind farm has been preliminarily assessed by the Distribution System Operator (DSO) of San Pietro. The screening made it possible to verify that a 2 MW wind farm can be realised in Nasca without the need for significant improvements of the power grid. This is valid also in a condition of repowering to 1.6 MW (+0.6 MW) of the existing PV plant.

Concerning the transport of the turbine components to the site, it was assessed that - because of the peculiarities of the site itself - a beach landing would be unfeasible. A solution with transport via wheeled cargo on RORO ships to the port is more realistic. This transport strategy, however, would require the use of a blade lifter due to some sharp bends on the route to Nasca.

For further stages of project development, it is recommended that a 1-year met-mast acquisition be performed to define the wind conditions of the site, thereby supporting the selection of the exact wind turbine model and providing a bankable assessment of the expected yield. Additionally, the project's financial structure should be assessed to identify the best procurement solution, ensuring the highest possible impact on the Municipality of Carloforte and the entire community of San Pietro.

The Clean energy for EU islands secretariat would like to remind the reader that the results presented in this report are only valid if the power curves considered in the study are consistent with those of the turbine supply agreement. Additionally, it is worth noting that, for this report and at the current project development stage, no curtailment strategy is being applied (e.g., in relation to the grid, wind sector management, shadow flicker, and noise).

1. Introduction

1.1. Objectives

With the technical assistance of the CE4EUI secretariat to the Municipality of Carloforte on the Island of San Pietro (the Beneficiary), it was agreed to assess the long-term energy production of the Nasca Wind Farm project, as well as energy production exceeded with various probabilities. The results of the study are suited for a financial analysis of the project.

1.2. Methodology

This study is conducted in accordance with best industry practices [1][5] and managed in accordance with 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 regulation, the available wind measurements, the justified selection of suitable wind turbines and the wind farm configurations 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 details the calculation of energy production exceeded with various probabilities,
- Section 7 summarises the findings of the study and provides recommendations.

2. Site and Project Description

2.1. Site Description

2.1.1. Landscape

The Nasca site is located on the island of San Pietro, as indicated in Figure 1. The island's landscape is characterised by rocky cliffs, particularly along the coast. Small coves and beaches often break up these cliffs. The terrain is hilly, as illustrated in ANNEX A. Several roads ensure most dwellings on site can be accessed.

Three existing wind turbines, now abandoned, are located at the site. They consist of two-bladed wind generators from Ansaldo. The municipality has planned their removal, which might take place in the coming months.

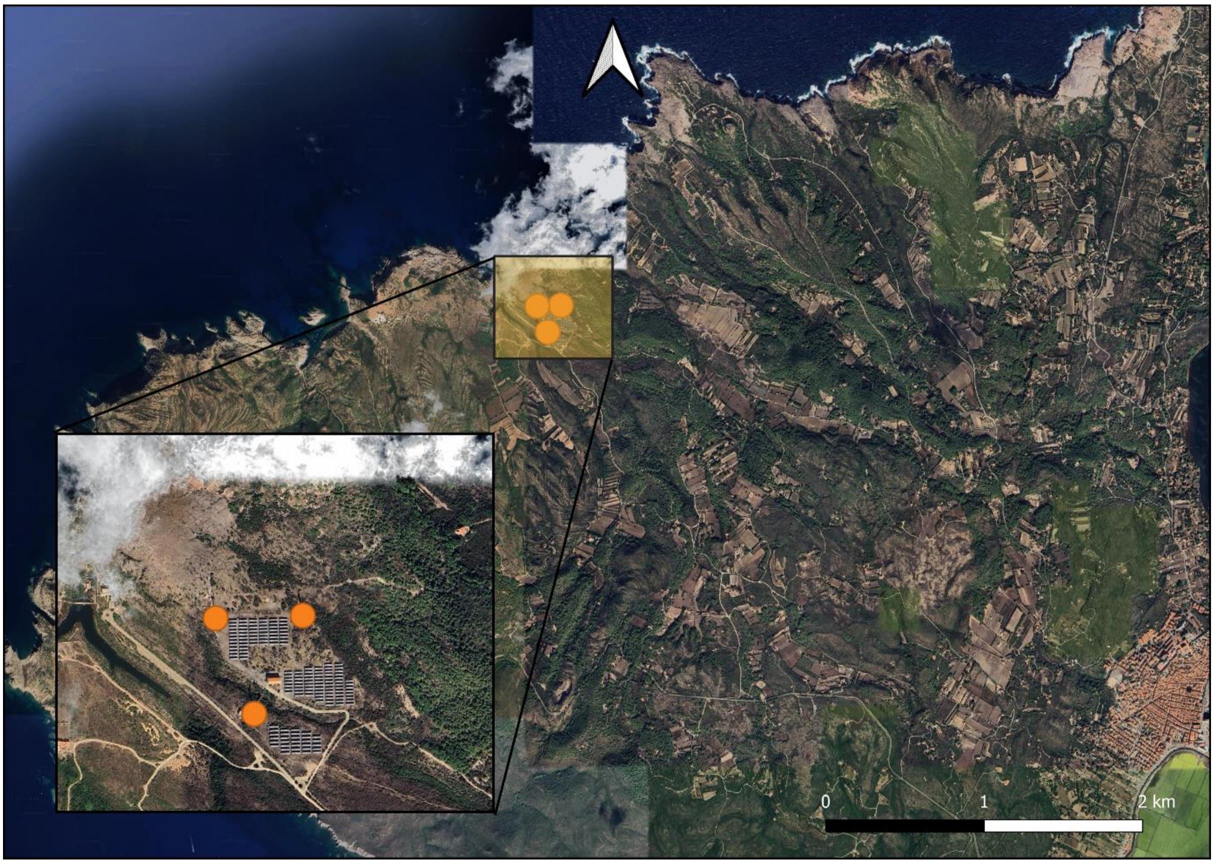

Figure 1: Site location (Source: Google Earth 2022). Orange circles indicate the position of the abandoned wind turbines.

2.1.2. Regulation

The island of San Pietro, due to its unique environmental and landscape richness, presents several spatial constraints. As inferred from the Carloforte Municipality WebGIS[1], the specific site of Nasca presents the following constraints:

- Site of Community Importance (SCI) ITB040027, for the protection of habitats and species (defined under the Habitats Directive).
- Special Protection Area (SPA) ITB043035 for the protection of birds (defined under the Birds Directive).
- Important Bird Area (IBA) "San Pietro and Sant'Antioco Islands".
- Part of the site is also within the 300 m buffer from the coastline, which – based on the Art. Article 42 of D.Lgs. 42/2004 makes it relevant in terms of landscape interest.

The SCI, SPA and IBA have been identified by the Sardinia region as unsuitable sites for the exploitation of wind energy, as stated in Resolution 40/11 del 7/8/2015. The process for identifying suitable and unsuitable sites is currently undergoing revision at the regional level, and new developments are expected in the coming months.

Notwithstanding the above constraints, it should be noted that the area already hosts a wind farm, currently in a state of abandonment and that a repowering intervention – never implemented – has already been approved in the past by the Regional Authority. Further details are provided in Section 2.2.2.

2.2. Project description

2.2.1. The Ansaldo wind farm and hybrid plant

In 1992, the Italian company Ansaldo built an experimental hybrid solar and wind plant at the project site in Nasca, with a total installed capacity of 1560 kW. The wind farm consisted of three MEDIT 320 wind turbines, each with a 320 kW capacity, two blades, and a 33 m rotor diameter, with a hub height of 26 m (total height: 42.5 m).

The solar and wind sections of the experimental plant, at the time, were very advanced and had different fortunes. The PV plant was fully repowered in 2012 and is currently successfully operating. The plant was constructed and is operated by the private company Carloforte Rinnovabili S.r.l., which pays an annual fee to the Municipality for the use of the public land on which it is installed. Despite some attempts to recover the wind farm, the wind turbines – which have reached their expected end-of-life - are instead currently in a state of disrepair, with the blades unsafe and at risk of falling.

[1] https://geoportalplus.nemea.cloud/carloforte.php

Figure 2: Detail of the Nasca hybrid power plant. Credits: Vanna Mocci.

Figure 3: Detail of the Nasca hybrid power plant. Credits: Vanna Mocci.

2.2.2. Previous activities for the wind farm repowering

The repowering of the Nasca Wind Farm has been discussed between the Municipality of Carloforte and the Sardinia Region over the past few years, with the involvement of Carloforte Rinnovabili S.r.l. and other private stakeholders.

A wind farm configuration which differs from the actual one was submitted to the Regional Authority. The plant consisted of 3x LTW70 Leitwind wind turbines with a 70 m rotor diameter, a 50 m hub height (total height of 85m), and an installed capacity of 2 MW each.

The project was approved in 2012 by the Regional Authority but is subject to considerable design modifications, specifically the reduction to two wind turbines and the relocation of one of the two turbines by approximately 60 m. These conditions were not considered favourable by the developer, and, in fact, the repowering project never came to fruition.

The configuration approved in 2010 is presented in Figure 4.

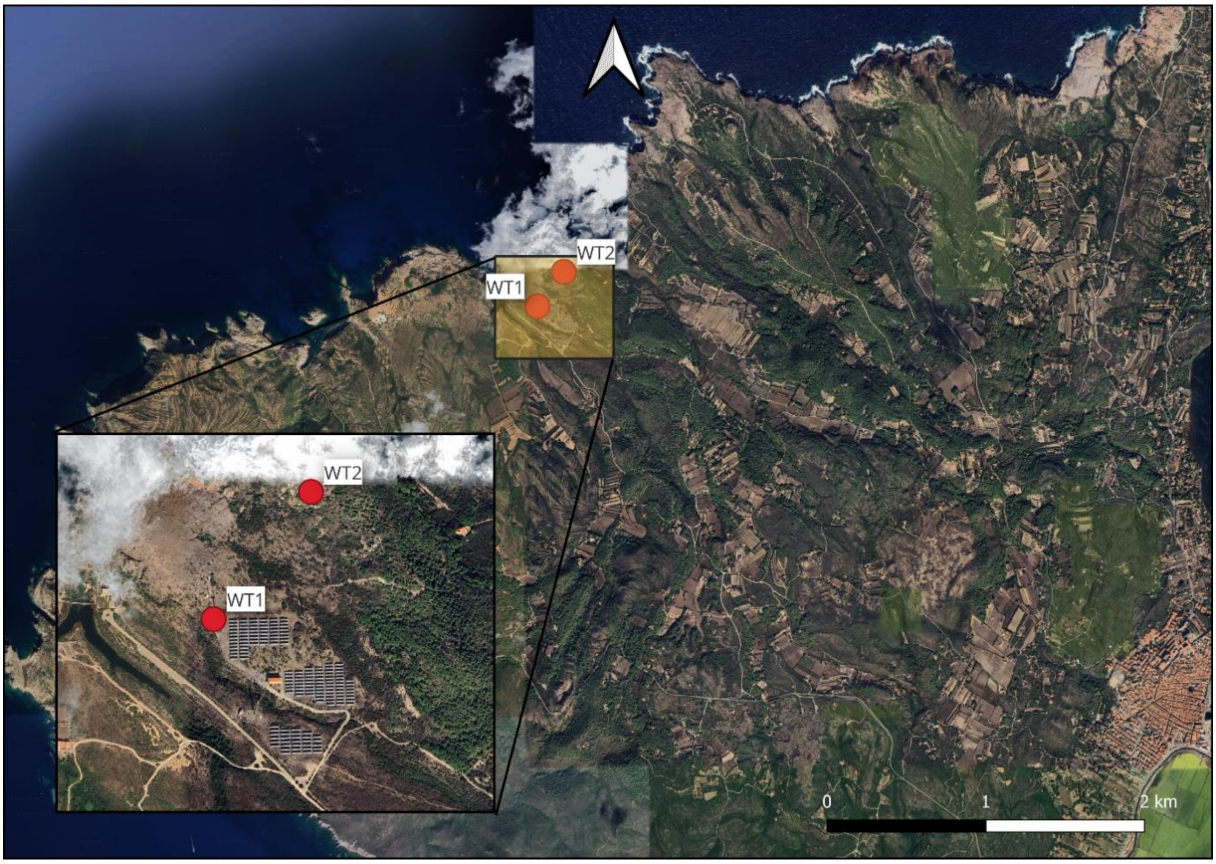

Figure 4: Aerial picture of the configuration approved by the Regional Authority in 2010 (Source: Google Earth, 2022)

2.2.3. Available wind measurements

No wind measurement campaign has been carried out on-site for the present project. Hence, this study utilises the wind statistics generated from a Virtual Met Mast (VMM) (see Annex D). This results in higher uncertainty values regarding the results, but the resulting trends can be considered reliable.

2.2.4. Wind turbine selection

In the absence of on-site wind measurements to conduct detailed site compliance, the selection of suitable wind turbines is based on the classes defined in the relevant IEC norms [2], as well as on the Global Atlas of Siting Parametre (GASP) to provide for suitable wind statistics.

GASP indicates that the site has characteristics which make it suitable for:

- Wind turbines in Class IEC III for hub heights up to 50 m.
- Wind turbines between Class IEC II and IEC III for hub heights up to 100 m hub.

Therefore, it is chosen to analyse the productivity of both IEC II and IEC III wind turbines at different hub heights. The compliance of specific wind turbine models with the IEC requirements will need to be verified based on on-site wind data acquisitions at later project stages.

The Beneficiary indicated that the new project should have wind turbines with rotor diameters and hub heights comparable to those already authorised. For the scope of this work, 3E identified the EWT DW58 - 1 MW (Class IIA)[2] and the EWT DW61 - 1 MW (Class IIIA)[3] as possibly suitable to the site characteristics.

2.2.5. Wind farm configurations

In this report, **a configuration refers to the combination of a wind farm layout and a wind turbine type**, specifically a turbine model and hub height. Eight configurations are considered, comprising two turbines with a total installed capacity of 2 MW.

The configurations to be studied have been agreed between 3E and the Beneficiary and are detailed in Table 3. All configurations are based on two wind turbines located at the same locations, which were approved in 2012, as depicted in Figure 4. Therefore, the wind farm layouts are the same for all the scenarios considered, with the only difference consisting of the wind turbine model and hub height. Wind turbine coordinates are listed in ANNEX B.

.

[2] https://ewtdirectwind.com/products/dw58/

[3] https://ewtdirectwind.com/products/dw61/

Table 3: Wind farm configurations.

Configuration		DW61 1 MW @ 46 m	DW61 1 MW @ 59 m	DW61 1 MW @ 69 m	DW61 1 MW @ 84 m	DW58 1 MW @ 46 m	DW58 1 MW @ 59 m	DW58 1 MW @ 69 m	DW58 1 MW @ 84 m
Scenario		SC 1	SC 2	SC 3	SC 4	SC 5	SC 6	SC 7	SC 8
Wind turbine manufacturer	[-]	EWT	EWT	EWT	EWT	EWT	EWT	EWT	EWT
Wind turbine type	[-]	DW61	DW61	DW61	DW61	DW58	DW58	DW58	DW58
Number of wind turbines	[-]	2	2	2	2	2	2	2	2
Rated power per turbine	[MW]	1	1	1	1	1	1	1	1
Total rated power	[MW]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Rotor diameter	[m]	61	61	61	61	58	58	58	58
Hub height	[m]	46	59	69	84	46	59	69	84

Table 4: Comparison between the authorised power plant and the new wind farm scenarios studied in this report in terms of rotor diameter and tip height

Scenario	Wind turbine model	Rotor diameter [m]	Hub height [m]	Difference in rotor diameter [m]	Diff. in tip height (total height) [m]
Authorised	LTW70	70	50	/	/
SC1	DW61	61	46	-9	-9
SC2	DW61	61	59	-9	+5
SC3	DW61	61	69	-9	+15
SC4	DW61	61	84	-9	+30
SC5	DW58	58	46	-12	-10
SC6	DW58	58	59	-12	+3

Scenario	Wind turbine model	Rotor diameter [m]	Hub height [m]	Difference in rotor diameter [m]	Diff. in tip height (total height) [m]
SC7	DW58	58	69	-12	+13
SC8	DW58	58	84	-12	+28

A comparison between the authorised wind farm and the new proposed scenarios is presented in Table 4 in terms of the rotor diameter and tip height (i.e., the distance between the ground and the top of the blade when the blade is in a vertical position). All scenarios are characterised by a lower rotor diameter with respect to the wind farm authorised in 2012. A lower tip height also characterises scenarios SC1 and SC5, whereas SC2 and SC6 have slightly higher tip height. Scenarios SC3, SC4, SC7 and SC8 have instead significantly larger tip heights.

3. Wind Data Processing

3.1. Preliminary remarks

3.1.1. Wind Resource assessment – industry best practices

For each project, 3E selects the most suitable wind resource dataset, taking into account the site location, the availability of wind statistics in the vicinity, and the ability of these statistics to accurately predict electrical production and measured data in the surrounding area.

3.1.2. 3E's Virtual Met Mast

Since no such measurement campaign was conducted for this project, this study is based on 3E's Virtual Met Mast (see Annex D).

This database leverages more than 20 years of experience accumulated by 3E in the field of wind resource assessment. It combines three modelling stages: it starts from the reanalysis dataset ERA5, on which it applies a simplified version of the mesoscale model WRF using a deep-learning algorithm. Then, the resource is further refined geographically using WAsP as a microscale model. Finally, the time granularity is increased from 1 hour to 10 minutes using a statistical down-sampling methodology.

3.1.3. Validation, calibration and uncertainty

The model chain and results are continuously validated on measurement devices and operational farms worldwide, with more than 250 validation points. The analysis shows an improved standard deviation in the modelled wind speed and energy yield compared to datasets such as ERA5 and the Global Wind Atlas, which are typically used when measurement data is lacking.

3.2. Selected wind data

For this project, wind statistics were generated from the Virtual Met Mast time series located at the site location:

Table 5: VMM coordinates (UTM (north)-WGS84 Zone: 32)

	Longitude (X)	**Latitude (Y)**	**Altitude**
VMM	435,964.8	4,335,585.7	55

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 that describes elevation, roughness, and other relevant obstacles to wind flow that are not modelled as roughness (cf. Annex C).

The terrain model used in this study represents the current conditions, which are assumed to remain constant throughout the wind farm's lifetime.

4.1.1. Elevation

Elevation differences across the site can highly influence the wind regime. For this study, terrain elevation is modelled within a radius of 15 km (in line with WAsP recommendations [8]) based on EU-DEM 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 values are all equal to zero for this project, which allows WAsP to be used for wind flow simulations.

4.1.2. Roughness length

Roughness length is a key parametre 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 modelled using a land-use database. The Sentinel-2 Land Cover (2023) database is used, and roughness length values specific to each land use are applied according to 3E's methodology. The validity of the land use areas and the roughness lengths is checked by comparison to aerial imagery.

The aerial imagery from GeoData, dated 2022, is used for this purpose and is assumed to be representative of the site conditions at the time of writing this report.
The roughness model is adapted to ensure that the land use area shapes align with the aerial imagery.

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 might not properly consider 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 near a large obstacle (such as a forest, industrial area, or urban area), the wind is blocked and flows over the obstacle. In this case, a displacement height needs to be applied, as recommended by WAsP.

Applying a displacement height consists of 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, no obstacles meet this criterion; hence no displacement height is modelled.

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.

4.3. Wind regime at site

The long-term wind regime at a 59 m hub height is provided as an example of the location of the wind turbine WT1 in Scenario 2, as shown in Table 6 and Figure 5.

Table 6: Long-term wind regime at the site

Location	**[-]**	**WT1, Scenario 2**
Height AGL	[m]	59
Weibull mean wind speed	[m/s]	6.70
Weibull A	[m/s]	7.54
Weibull k	[-]	1.826
Prevailing wind directions	[-]	NNW
Wind directions with the most energy content	[-]	NNW

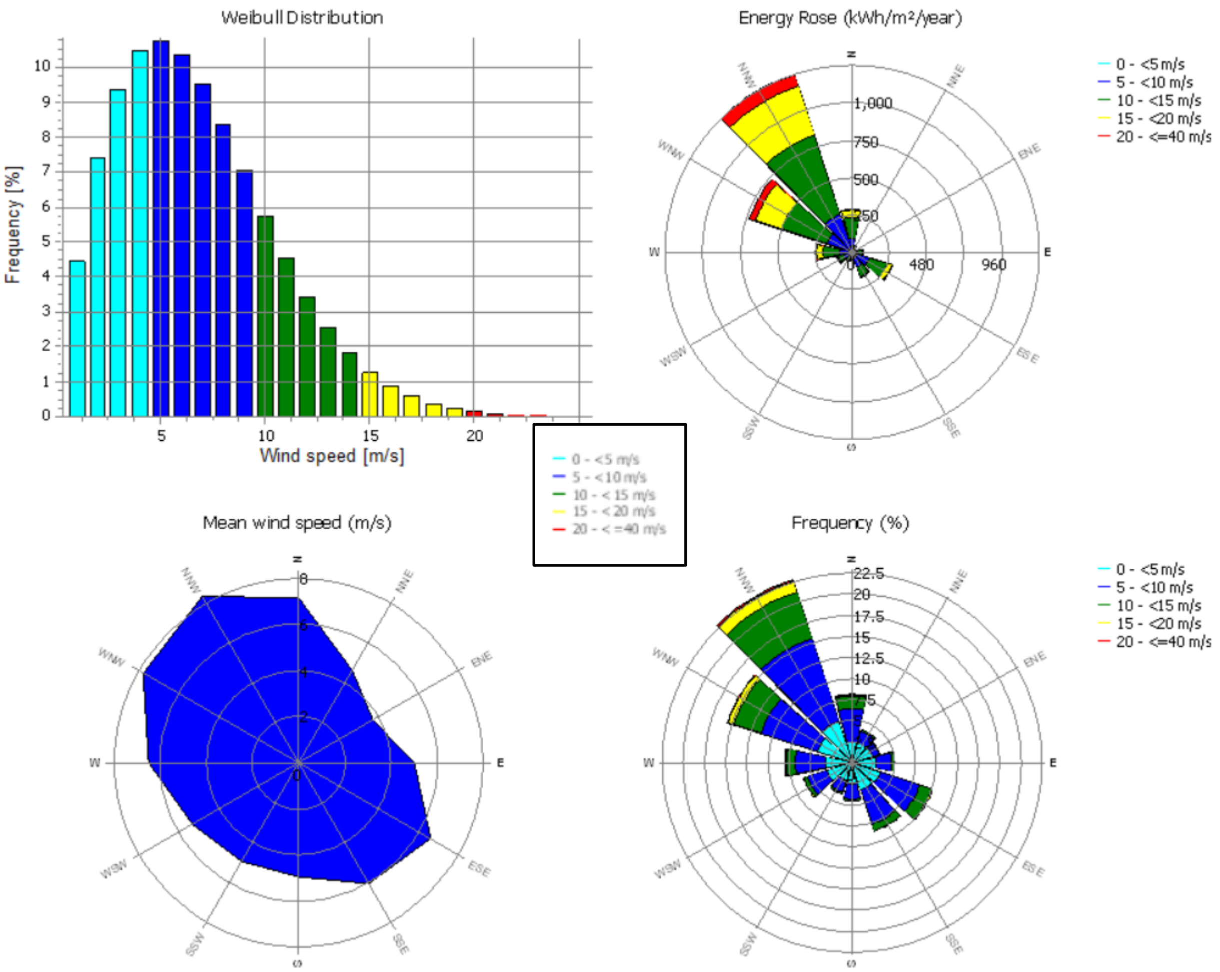

Figure 5: Long-term wind regime at the site.

5. Energy Production Losses

5.1. Gross energy production

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 E.

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 made using the new recommended WindPRO method, which is an adjusted version of the IEC 61400-12 method, improved to match turbine control [11].

For this project, air density at hub height ranges between 1.190 and 1.196 kg/m^3, depending on the wind turbine location and hub height. WindPRO calculates air density based on temperature and pressure measurements from the Virtual Met Mast (VMM). 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

5.2.1. General losses

In addition to the energy conversion losses considered in the power curve, other losses affect the electrical power that is expected to be delivered to the grid. The following losses are taken into account in this study and are summarised in Table 7 further below. Other losses may apply but are considered negligible in this study.

5.2.1.1. Turbine interaction losses

Turbine interaction losses are due to the mutual influence of the wind turbines, downstream as well as upstream. The kinetic energy extraction resulting in losses downstream of the turbines is calculated using the N.O. Jensen (PARK2): 2018 wake model. The induction zone leading to a blockage loss upstream of the turbines is estimated with the Forsting self-similarity model. Both models, as implemented in WindPRO, are used. The influence of existing wind farms is not taken into account in the calculations (cf. section 2.1) since it is supposed that the turbine studied in this project is a replacement of the existing one.

5.2.1.2. Unavailability losses

Unavailability losses are due to downtime of the wind turbines or balance of the 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 evaluated for this project as 5.0 % of the energy production. This is a conservative estimate based on availability guarantees, often being around 97 % in operation and maintenance (O&M) contracts on the mainland, plus some margin to consider for the increased difficulties related to San Pietro being a small island.
- 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. This value should be further investigated with the local Distribution System Operator (DSO) at later project stages.

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.

5.2.1.3. 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 (value between 0.0% and 0.1% depending on the configuration). The wind distribution at the site is such that this type of event is unlikely to occur frequently.
    - Suboptimal turbine performance due to limitations of the turbine system is considered to be 0.2% regardless of the site's complexity. 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 generic performance 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.

5.2.1.4. Electrical losses

Electrical losses occur in cables and transformers, ensuring the efficient transmission of electricity to the wind farm substation. 3E typically evaluates them as 1.5 % of the energy production for a wind farm of this size and layout. This value is based on the analysis of data from an extensive portfolio of operational wind farms.

5.2.1.5. 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 0.95 % for this study,
- Aerodynamic performance degradation of turbine blades due to icing is estimated at 0.2 % for this study,
- Potential turbine shutdowns due to icing conditions are estimated at 0 %. This loss is estimated based on the icing frequency calculated from reanalysis data [25]. The actual loss will highly depend on the icing detection method and the operational strategy applied to follow up on icing formation.
- At this stage, 3E does not consider any loss for potential turbine shutdowns due to lighting, hail or ice. If specific shutdown rules are enforced, their impact on production should be evaluated separately.

5.2.2. 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, bird or bat preservation, etc.). No curtailment losses are applicable.

5.2.3. Losses summary table

The energy production losses defined in the preceding sub-sections are summarised in Table 7.

Important note: some losses considered in this study are industry standard values that 3E estimates are 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 7: Expected energy production losses.

Configuration		DW61, 1 MW @ 46 m	DW61, 1 MW @ 59 m	DW61, 1 MW @ 69 m	DW61, 1 MW @ 84 m	DW58, 1 MW @ 46 m	DW58, 1 MW @ 59 m	DW58, 1 MW @ 69 m	DW58, 1 MW @ 84 m
Scenario		**SC 1**	**SC 2**	**SC 3**	**SC 4**	**SC 5**	**SC 6**	**SC 7**	**SC 8**
Wake losses	**[%]**	**0.8**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
Unavailability losses	**[%]**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**
Turbine		5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
BOP		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Grid		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Performance losses	**[%]**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Generic performance losses		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Site-specific losses		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Suboptimal performance		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Hysteresis losses		0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1
Electrical losses	**[%]**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Environmental losses	**[%]**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Performance degradation not due to icing		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Performance degradation due to icing		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total losses (*)	**[%]**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**

(*) The production losses in % are combined as: $\boldsymbol{Total = 100 - \frac{\prod_i (100 - Loss_i)}{100^{(N-1)}}}$

5.3. Net energy production

Energy production losses are 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 8. For each configuration, the following results are provided:

- 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 computed in Section 5.
- 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: the amount of time it would take for the wind farm to yield its annual production if it were able to produce at full load constantly.
- Net capacity factor: 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 8: Expected wind farm energy production figures.

Configuration		DW61, 1 MW @ 46 m	DW61, 1 MW @ 59 m	DW61, 1 MW @ 69 m	DW61, 1 MW @ 84 m	DW58, 1 MW @ 46 m	DW58, 1 MW @ 59 m	DW58, 1 MW @ 69 m	DW58, 1 MW @ 84 m
Scenario		**SC 1**	**SC 2**	**SC 3**	**SC 4**	**SC 5**	**SC 6**	**SC 7**	**SC 8**
Mean wind speed	[m/s]	6.36 - 6.87	6.7 - 7.18	6.93 - 7.38	7.22 - 7.63	6.36 - 6.87	6.7 - 7.18	6.93 - 7.38	7.22 - 7.63
Gross energy production	[MWh/y]	5,602	6,072	6,382	6,775	5,255	5,707	6,009	6,391
Wake losses	[%]	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7
Other losses	[%]	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Total energy production losses	[%]	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
Net energy production (AEP)	**[MWh/y]**	**5,064**	**5,489**	**5,770**	**6,125**	**4,752**	**5,161**	**5,433**	**5,779**
Net full load equivalent hours	[h/y]	2,532	2,744	2,885	3,062	2,376	2,580	2,717	2,890
Net capacity factor	[%]	28.9	31.3	32.9	34.9	27.1	29.4	31.0	33.0

6. Other considerations

This section provides some considerations on relevant topics not dealt with in the previous sections, namely the island electricity balance, requirements for grid connection and logistics.

6.1. Island energy balance

Based on the San Pietro Clean energy transition agenda [26], the overall electricity consumption of the island amounted to 16.445 GWh/year in 2019. The PV generation on the island, accounting for both the 999 kW PV plant in Nasca and 513 kW of distributed rooftop PV, was estimated at 2.216 GWh in 2019, leading to an electric self-sufficiency of ~13.5%.

The new wind farm in Nasca, based on the results presented in this report, is expected to produce between 4.752 GWh/year and 6.125 GWh/year based on the chosen configuration. Therefore, the intervention could lead to a self-sufficiency value of between 42.3% and 50.7%, substantially contributing to the decarbonisation of San Pietro. Other interventions of distributed PV generation and repowering of the Nasca PV plant could lead the island to a fully renewable power mix. Given that San Pietro is interconnected to the mainland, this target could be – at least in the first phase – achieved by examining the annual energy balance without necessarily installing storage facilities.

6.2. Requirements for grid connection

The Municipality of Carloforte and the Clean energy for EU islands secretariat have exchanged with the DSO operating on the island to assess the suitability of connecting additional renewable capacity at the Nasca location. The project site is indeed located in a rural and low-densely inhabited area and is connected via a single medium voltage (MV) line to the rest of the power grid.

The repowering of the Nasca PV plant presents a concrete possibility for enhancing renewable self-production on San Pietro. Therefore, the suitability of the existing grid must also be evaluated in regard to further possible expansions of the PV plant itself. Therefore, the Clean energy for EU islands secretariat and the Municipality of Carloforte have requested the DSO a preliminary screening of the grid connection options for two different future scenarios:

- **Scenario A**:
  - **+ 2 MW wind farm:** installation of a 2 MW wind farm (i.e., the wind farm studied in this report).
  - **+0.6 MW PV:** Repowering of the existing PV plant up to 1.6 MW.

- **Scenario B**:
  - **+ 2 MW wind farm:** installation of a 2 MW wind farm (i.e., the wind farm studied in this report).
  - **+1.8 MW PV:** Repowering of the existing PV plant up to 2.8 MW.

As a result of the preliminary screening, the DSO assessed that **Scenario A could be implemented without significant grid interventions**, therefore with short timing and reduced costs. Scenario B, characterised by a higher PV capacity with respect to Scenario A

(+1.2 MW), would instead require significant interventions on the existing grid and, therefore, considerable expenses for the grid connection.

6.3. Logistics

Due to San Pietro's peculiarities, the project execution may require the implementation of non-conventional transportation for overloaded (nacelle/drivetrain and hub) and oversized (turbine blades and tower sections) equipment.

A high cliff characterises the northern coast of the island, so a beach landing is not supposed to be a practicable solution. Due to the characteristics of the port and the limited size of the project, all components should be transported on the island by means of wheeled cargo and RORO ships. Adequate ships for transporting turbine blades and tower sections should be considered.

A preliminary route to the site was identified in Figure 6. The characteristics of the road, with several sharp bends and a passage through a forest, will require the use of a blade lifter to minimise the required civil works and the environmental impact on the surrounding area.

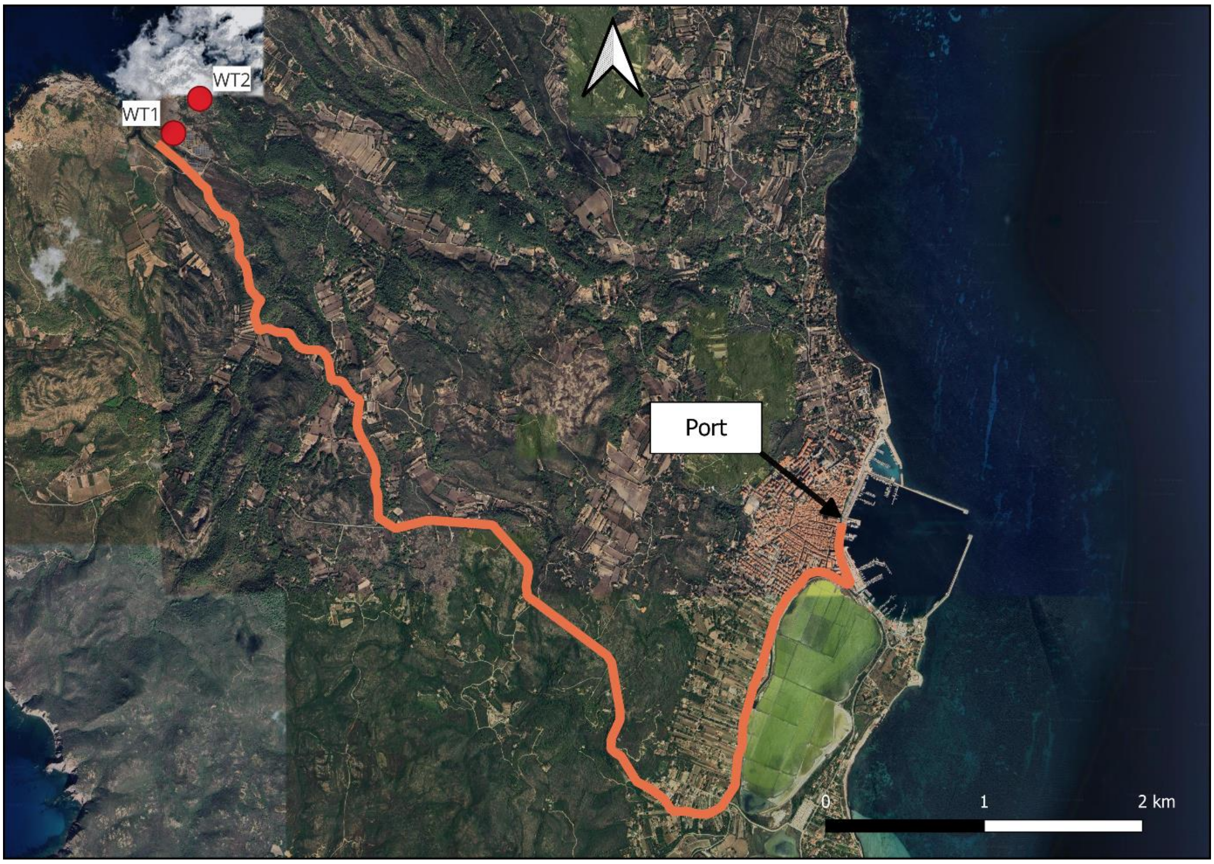

Figure 6: Road from the port to the site

7. Conclusion

3E has calculated the expected energy production and the associated uncertainties for the eight proposed configurations of the San Pietro wind farm project. The main production anticipated results for a 20-year period are summarised in Table 9.

The two wind turbines have similar yields, with the DW61 benefiting from a slightly larger rotor diameter compared to the DW58. As expected, the yield increases with increasing hub height because of the increase in wind speed with height.

The difference between the 46 m hub height and the 59 m hub height is significant, in the order of 500 MWh/year for both wind turbine models. The profitability of further increases in hub height, leading to the increased tip heights presented in Table 4, needs to be assessed in relation to the required increase in investment costs, as well as the additional authorisations from the Regional Authority.

Important notes:

- It should be noted that 3E assumes that any information communicated by the client is correct.
- Results of AEP calculations are specific to the curtailment strategies considered in this study. Any change to these curtailment strategies will require the recalculation of AEP.
- Several energy production losses considered in this study are industry standard values that 3E estimates are 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: Key results from the LTYA study.

Configuration		DW61, 1 MW @ 46 m	DW61, 1 MW @ 59 m	DW61, 1 MW @ 69 m	DW61, 1 MW @ 84 m	DW58, 1 MW @ 46 m	DW58, 1 MW @ 59 m	DW58, 1 MW @ 69 m	DW58, 1 MW @ 84 m
Scenario		**SC 1**	**SC 2**	**SC 3**	**SC 4**	**SC 5**	**SC 6**	**SC 7**	**SC 8**
Mean wind speed	[m/s]	6.36 - 6.87	6.7 - 7.18	6.93 - 7.38	7.22 - 7.63	6.36 - 6.87	6.7 - 7.18	6.93 - 7.38	7.22 - 7.63
Gross energy production	[MWh/y]	5,602	6,072	6,382	6,775	5,255	5,707	6,009	6,391
Wake losses	[%]	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7
Other losses	[%]	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Total energy production losses	[%]	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
Net energy production (AEP)	**[MWh/y]**	**5,064**	**5,489**	**5,770**	**6,125**	**4,752**	**5,161**	**5,433**	**5,779**
Net full load equivalent hours	[h/y]	2,532	2,744	2,885	3,062	2,376	2,580	2,717	2,890
Net capacity factor	[%]	28.9	31.3	32.9	34.9	27.1	29.4	31.0	33.0

8. Next steps and recommendations

This work is a preliminary stage study and can be used by the Beneficiary to compare the different options available. It can also be used to agree with relevant stakeholders on the most suitable configuration in terms of rotor size and turbine height.

For further stages of the project development, it is advised that the following activities are performed:

- **1-year met-mast acquisition for defining the wind conditions of the site**. This step is fundamental for assessing the compliance of different wind turbine models with local site conditions and providing a bankable assessment of the expected yield. A tubular met mast of approx. A 60 m height could provide relevant information in terms of wind speed, direction, and turbulence for wind turbines with hub heights up to 90 m. It is recommended that the measurement campaign be developed in line with the prescriptions from the standard IEC61400-50 [27]. Such a campaign could have a cost of around ~75 kEUR, to be further evaluated with potential service providers.
- **Definition of the financial structure of the project**. Once the preferred configuration is identified, the Beneficiary can request a detailed quotation for the supply, transport and installation of the preferred wind turbine model. Once the profitability of the investment is verified, the procurement solution (e.g., Public-Private Partnership) will have to be discussed with the relevant stakeholders. A preliminary CAPEX estimation for the project amounts to 3,000 kEUR, assuming a hub height of ~70 m and including the costs of civil works, transportation, and installation.

If required by the Regional Authority, an environmental impact assessment could also be needed. It is worth noting that the locations for the wind turbines discussed in this project have already been approved by the Regional Authority in the past, as the project was intended as a repowering of the existing and abandoned wind farm. Therefore, the main discussion with the authorisation authority could rather be around the rotor diameter and tip height of the different proposed solutions.

References

[1] Assessorato Difesa dell'ambiente, Regione Siciliana, Determinazione n. 20249-948 del 28 Agosto 2012

[2] IEC 61400-1, Wind energy generation systems – Part 1: Design requirements, February 2019

[3] EMD International, GASP – The first Global Atlas of Siting Parametres and wind turbine Design Classes, Available at: https://www.emd-international.com/single-news/emd/gasp-the-first-global-atlas-of-siting-parametres-and-wind-turbine-design-classes/

[4] MEASNET. Evaluation of site-specific wind conditions. Version 2, April 2016.

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

[6] IEC 61400-12-1, Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines, March 2017

[7] The CDS Climate Copernicus, https://cds.climate.copernicus.eu

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

[9] 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.

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

[11] WindPro user manual.

[12] 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 Development, Brussels, Belgium by Risoe National Laboratory, Roskilde, Denmark, 1989, ISBN 87-550-1482-8.

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

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

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

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

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

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

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

[20] 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.

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

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

[23] 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.

[24] 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

[25] A. Albers (2013), "Assessment of Production Losses Due Due to Rotor Blade Icing"

[26] Comune di Carloforte, Agenda di transizione per l'energia pulita, Isola di San Pietro, 2019. Available at : https://clean-energy-islands.ec.europa.eu/system/files/2023-08/agenda-di-transizione-isola-di-san-pietro-2023.pdf

[27] IEC 61400-50, Wind energy generation systems – Part 50: Wind measurement

ANNEX A SITE DESCRIPTION ILLUSTRATIONS

Figure 7: Site environment with PV plant and abandoned wind farm

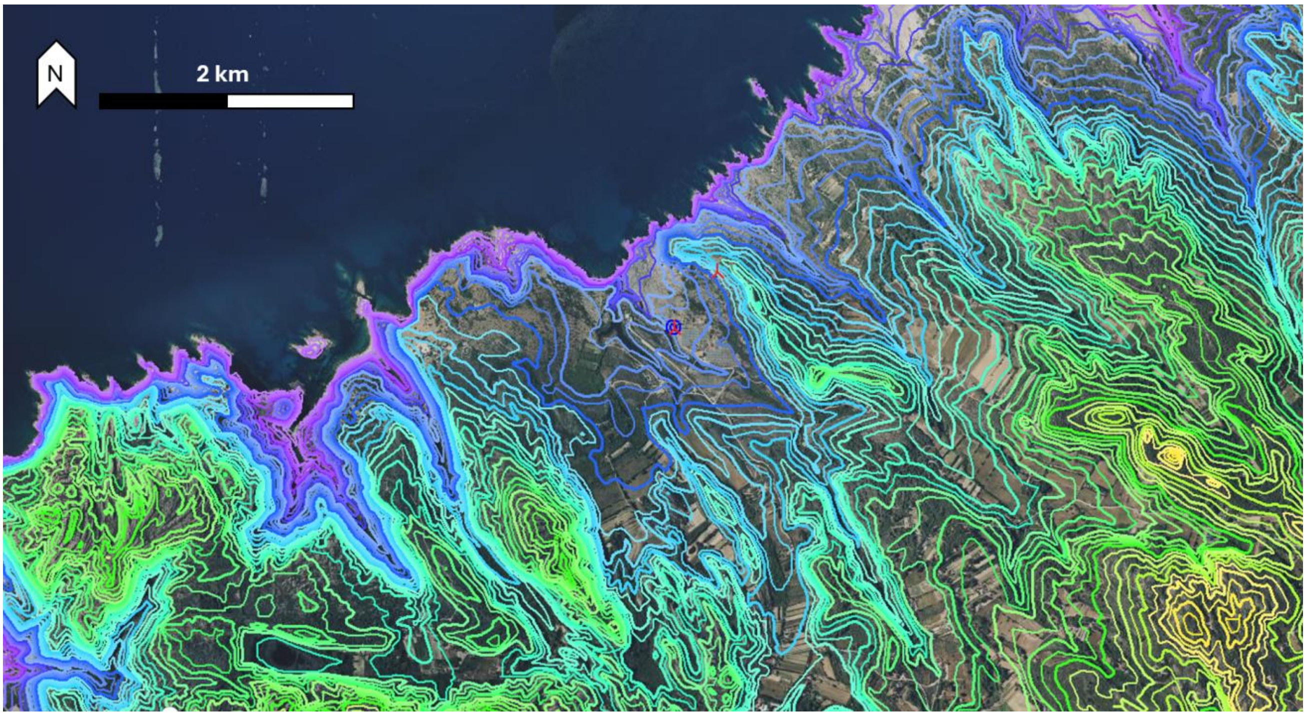

Figure 8: Site elevation (contour lines every 5 metres, and warmer colours denote higher elevations)

ANNEX B WIND TURBINE COORDINATES

Table 10: Wind turbine coordinates (UTM (north)-WGS84 Zone: 32)

Turbine	Longitude (X)	Latitude (Y)	Altitude
WT1	435,970	4,335,583	55
WT2	436,137	4,335,798	78

ANNEX C 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 Generalised Wind Climate or Wind Atlas. This Generalised Wind Climate is the hypothetical wind climate for an ideal, featureless and completely flat terrain with 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 account for the effects of terrain features.

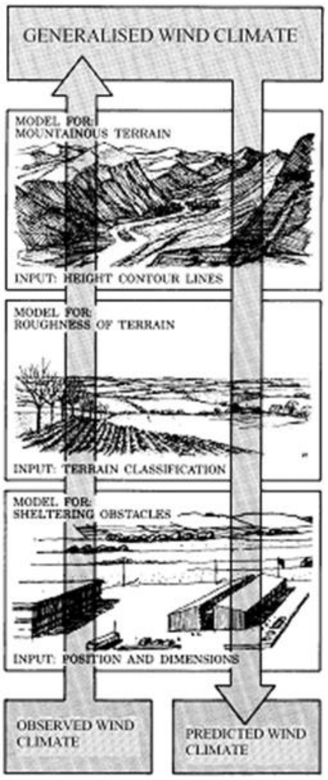

Figure 9: Wind Atlas methodology (Source: wasp.dk)

ANNEX D 3E's Virtual Met Mast (VMM)

Introduction

In 2022, 3E introduced its micro-scale wind resource model - the Virtual Met Mast (VMM). The model uses detailed orography and land cover data combined with meso- and micro-scale wind flow models at sub-hourly resolutions.
The resulting VMM has the following features:

- Temporal resolution of up to 10 minutes, comparable with most measuring masts;
- Spatial resolution of 30 metres;
- Availability anywhere on land, for onshore and offshore sites;
- At any height between 10 m and 300 m above ground level;
- Includes most parameters relevant to wind resource analysis, such as wind speed, direction, temperature, atmospheric pressure, relative humidity, air density and Monin-Obukov length (MOL).

The model undergoes continuous validation at numerous sites worldwide. As of August 2023, the model has a mean absolute error of 9.5% in hourly wind speed predictions.

This appendix presents the characteristics of the model and its validation, focusing on validation in the Belgian domain, and is based in part on academic publications produced by 3E [7][8][9].

Model chain

Like many wind data services, Virtual Met Mast is based on the WRF model (Weather Research & Forecasting model) [1].
Firstly, ERA5 reanalysis data are used to generate a mesoscale wind climate on a 3x3 km grid with hourly resolution by combining an adapted version of the Weather Research & Forecasting (or WRF) model and a Deep Learning model to optimise the computation process over long periods.
To achieve a spatial and temporal resolution capable of capturing the local effects of topography at a specific location and height, three models are successively applied to these mesoscale results over the entire computational domain:

- Spatial resolution is increased to 30 m by correcting for topographical effects using the WAsP flow model. Very high-resolution topographic data (10 m for land cover, 30 m for elevation) are used in this process best to capture the heterogeneity in the site's surroundings.
- The spectral domain of the WRF model is corrected using the principles of the Spectral Correction Method (SCM), which corrects the smoothing effect of WRF mesoscale simulations at hourly time resolution.
- The spectral domain of the WRF model is extended by including sub-hourly turbulence effects with a micro-scale spectral Atmospheric Boundary Layer (ABL) model to achieve an output resolution of 10 minutes [5].

Figure 10. An overview of the different modelling steps in the 3E micro-scale model provides a graphical overview of the final modelling approach. The following sections present each model and its corrections.

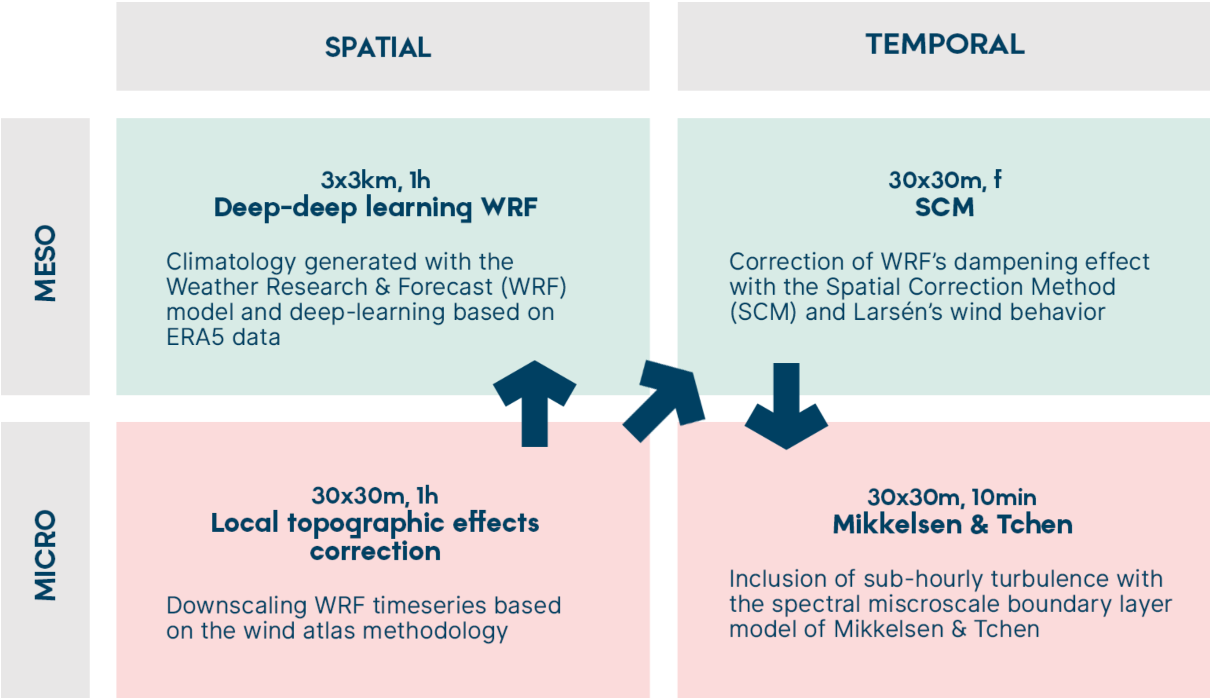

Figure 10. Overview of the different modelling steps in the 3E micro-scale model

The DL-WRF model of 3E

3E's large-scale wind model is based on the Weather Research & Forecasting (WRF) climate model, a state-of-the-art mesoscale numerical weather prediction system for atmospheric research and operational forecasting applications, widely used in the wind energy community.

3E operates its own version of the WRF model, which is based on research conducted as part of the development of the New European Wind Atlas (NEWA), and incorporates a Deep Learning (DL) component to reduce computational times [3][4].

The output of the DL-WRF model is a mesoscale atlas comprising a series of surface and atmospheric boundary layer meteorological variables with a spatial resolution of 3 kilometres and an hourly resolution for any desired historical period from 1989 onwards.

Given this spatial resolution in kilometres, the results of the DL-WRF mesoscale model are not representative of local characteristics resulting from micro-scale variations in orography and surface roughness. However, taking these effects into account is crucial for accurately determining the local wind climate at a site.

The resolution of the results is therefore increased using the micro-scale model developed by 3E on the basis of Jackson & Hunt's (1975) wind flux model for flux corrections and an adapted version of Troen & Petersen's (1989) wind atlas methodology for the final time series, using very high-resolution elevation and roughness maps derived from Sentinel satellites [2][3].

WRF spectral corrections

The WRF model has two main shortcomings with respect to spectral or temporal properties relevant to wind turbine performance modelling, namely:

- The smoothing effect that occurs in the mesoscale range of the spectrum, i.e. at frequencies between day^{-1} and h^{-1}, resulting in an underestimation of available energy.
- Higher-frequency fluctuations in the micro-scale range of the spectrum, i.e. frequencies above h^{-1}, which are not integrated into the hourly result. However, modelling 10-minute volatility is essential for modelling wind turbine performance.

3E's full-scale wind model resolves both limitations by correcting and extending the spectral domain of the WRF model, as shown in Figure 11.

3E corrects the dampening effect of WRF's mesoscale simulations directly in the frequency domain, following the principles of the Spectral Correction Method (or SCM) [4] and based on Larsén's observed wind behaviour in the mesoscale spectrum of 10^{-6} to 10^{-3} Hz [5].

The spectral correction consists of two steps. First, a regression of WRF's observed spectrum is performed in the frequency range from 8.10^{-6} to 3.10^{-5} Hz, for which it is assumed that WRF simulations are correctly capturing the spectral energy, together with a log-linear regression of Larsén's observed wind behaviour in the range of 10^{-6} to 10^{-3} Hz. Second, the simulated WRF spectral energy is scaled pro rata both regressions for the frequencies above 2.10^{-5} Hz or approximately 1.7 d^{-1}.

3E corrects the absence of higher-frequency fluctuations by extending the spectral domain of the WRF model before converting it to the time domain with a fast Fourier transformation.

3E includes sub-hourly turbulence effects by using the spectral microscale boundary-layer model of Mikkelsen & Tchen and superimposing the model to the corrected mesoscale model to create a single full-scale boundary-layer spectral model. Starting from the hourly WRF simulations, the spectral microscale model ranges from (2 h)$^{-1}$ to (2 s)$^{-1}$ to arrive at a time series with an output frequency of 1 Hz. After a fast Fourier transform, the high-resolution time series are grouped into 10-minute periods, for which realistic mean and standard deviation wind speed values can be obtained that resemble the typical output of a meteorological mast from a wind resource measurement campaign.

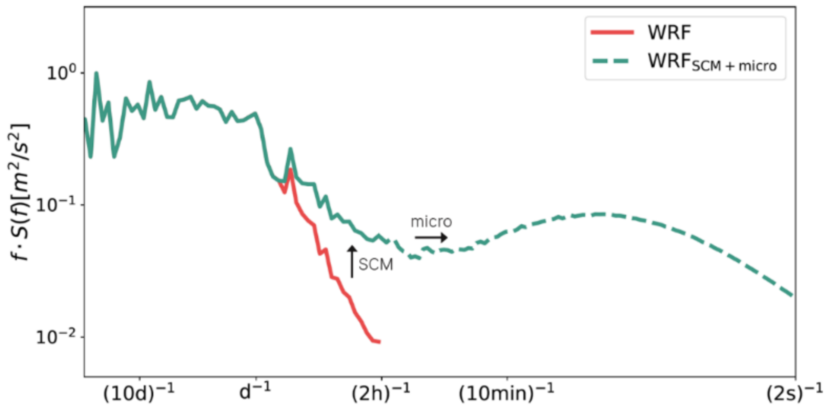

Figure 11. The spectrum of the WRF model and the resulting spectra of the two-step spectral corrections.

Validation of the Virtual Met Mast

As for most validations of physical or numerical models, our permanent internal validation model consists of three distinct steps:

- Obtaining measurement data, i.e. wind measurements of high-quality anemometers, used as a reference for the validation of the modelled wind data.
- Performing data validation, i.e. setting validation rules & constraints to ensure the quality of the reference measurement data.
- Defining and calculating the validation metrics, i.e. the key indicators used to validate the data accuracy and fit-for-purpose.

Each step is discussed separately below.

Reference measurement data

Consistent measurement data from 253 sites has been obtained and included in our internal permanent validation framework.

The sensor heights are between 59 and 115m above ground, with the bulk at around 80m. The validation period considered for each mast was a contiguous period of at least a full year, spanning from 1996 to 2022.

In most cases, the period was approximately two years (Min: 200 days, max: 21 years). The modelled time series were masked to the measurements (filtering out the missing data) to get a matching time series.
To facilitate comparison with ERA5, the validation was conducted at an hourly resolution. An hourly average of the measurement time series was performed to allow the comparison. The modelled wind speed and direction data was linearly interpolated to the measurement's height. This interpolation was done in velocity-component form (U and V) and then transformed back to magnitude and angle form (WS and WD).

The breakdown of the 253 sites per continent is detailed in the following table.

Table 11: Number of site per continent

	Europe	**Africa**	**Asia**	**America**	**Offshore**
Sites	84	41	13	4	4

Data Validation

Different quality checks and site selection rules are applied to the obtained data sets of wind measurements. The following validations are applied to the data time series with hourly resolution:

- From all datasets, only the sites were used with at least 1 year of measurement data, with 90% availability and a height of 60 metres or more.

- A min/max quality check: The minimum and maximum wind speed values are calculated and should be plausible, i.e., between 0 and 60 m/s.

Apart from these quality checks and parsing, no additional process is applied to the measurement data.

Validation Metrics

For the location of each validation site, 3E's Virtual Met Mast (VMM) data is requested through our operational API at hourly resolution for the validation period of the reference data source. Also, ERA5 data are requested to compare the validation metrics.
Successively, the following two metrics are calculated for both 3E's VMM as well as the ERA5 data for each site based on the measurement:

- The Mean Percentage Error on the mean wind speed (MPE)
- The Mean Absolute Percentage Error on the mean wind speed (MAPE)

In the following section, we will discuss the obtained validation metrics in detail.

Global Accuracy

The mean absolute percentage error (MAPE) of 3E's Virtual Met Mast is 7.2% for hourly data considering all 253 reference sites.

This MAPE represents the average of the absolute percentage errors of each entry in a dataset to calculate how accurate the forecasted quantities were in comparison with the actual quantities. Since a MAPE below 10% is generally considered as 'highly accurate forecasting '6, while a MAPE between 10-20% is considered 'good forecasting', 3E's VMM can be considered as 'highly accurate.'

As a reference, for the same 253 sites, the ERA5 data has an average MAPE of only 12.8% for hourly data. Given the significantly lower average MAPE, 3E's VMM is more accurate and more certain than ERA5 wind data.

Local Accuracy

The mean absolute percentage error (MAPE) of 3E's Virtual Met Mast is 12.5 % for hourly data considering all 15 reference sites in Southeast Asia. In general, it has been observed that the Virtual Met Mast underestimates the wind speeds in the continent, as the mean percentage error (MPE) is -6.4%. These values were used to calibrate the wind speed values obtained from the VMM generated for the current project.

References

[1] Skamarock, W.C. et al. (2008), “Description of the Advanced Research WRF Version 3”, Tech. Rep. NCAR/TN-475+STR, National Centre for Atmospheric Research.

[2] Jackson, P.S. & J.C.R. Hunt (1975), “Turbulent wind flow over a low hill”, Quarterly Journal of the Royal Meteorological Society 101, 929–955.

[3] Troen, I. & E.L. Petersen (1989), “European wind atlas”. Published for the Commission of the European Communities, Directorate-General for Science, Research, and Development, Belgium by Risoe National Laboratory, Denmark.

[4] Bastine D. et al. (2018), “Extreme Winds in the New European Wind Atlas”, J. of Physics: Conf. Series, 1102 and Skamarock W.C. (2004), “Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra”, Monthly weather review 132 3019–32.

[5] Larsén X.G., C.Vincent & S.E.Larsen (2013), “Spectral structure of mesoscale winds over the water”, Quarterly J. of the Royal Meteorological Society 139, 685–700.

[6] Lewis, C.D. (1982) International and Business Forecasting Methods.

[7] Schillebeeckx D. & G. Leroy (2022), “Generating long-term sub-hourly wind speed timeseries by coupling mesoscale models with full-scale spectra”, Journal of Physics: Conference Series 2151 012003.

[8] Witha B. et al. (2019), “WRF model sensitivity studies and specifications for the NEWA mesoscale wind atlas production runs”, Deliverable 4.3 of FP7-ENERGY.2013.10.1.2.

[9] Witha B. et al. (2019), “The NEWA Mesoscale Wind Atlas: production and ensemble runs”, Wind Europe Conference, Bilbao.

ANNEX E POWER & THRUST CURVES

Table 12: Power curves (PC), air density = 1.225 kg/m^3

Wind speed	**DW61, 1MW**	**DW58, 1MW**
	PC	**PC**
[m/s]	[kW]	[kW]
3	12	11
3.5	25	23
4	41	37
4.5	62	56
5	92	83
5.5	133	120
6	181	163
6.5	231	208
7	289	261
7.5	356	322
8	432	390
8.5	518	468
9	597	542
9.5	668	612
10	732	678
10.5	796	742
11	853	805
11.5	905	863
12	941	912
12.5	973	947
13	992	976
13.5	998	993
14	1000	998
14.5	1000	1000
15	1000	1000
15.5	1000	1000
16	1000	1000
16.5	1000	1000
17	1000	1000
17.5	1000	1000
18	1000	1000
18.5	1000	1000
19	1000	1000
19.5	1000	1000
20	1000	1000
20.5	1000	1000
21	1000	1000
21.5	1000	1000
22	1000	1000
22.5	1000	1000
23	1000	1000
23.5	1000	1000
24	1000	1000
24.5	1000	1000
25	1000	1000

Table 13: Thrust curves (TC), air density = 1.225 kg/m³

Wind speed	**DW61, 1MW**	**DW58, 1MW**
	Ct	Ct
[m/s]	[kW]	[kW]
3	0.844	0.856
4	0.842	0.850
5	0.840	0.848
6	0.837	0.846
7	0.833	0.843
8	0.830	0.840
9	0.785	0.804
10	0.707	0.731
11	0.596	0.630
12	0.509	0.540
13	0.383	0.430
14	0.297	0.330
15	0.237	0.263
16	0.194	0.214
17	0.162	0.178
18	0.136	0.150
19	0.116	0.127
20	0.100	0.110
21	0.088	0.095
22	0.077	0.084
23	0.068	0.074
24	0.061	0.066
25	0.054	0.059

ANNEX F DETAILED PRODUCTION PER TURBINE

This section details the production per turbine for all the configurations.

Table 14: Detailed production per turbine Scenario 1

Configuration	Scenario 1	Total	WT1	WT2
Gross energy production	**[MWh/y]**	**5,602**	**2,614**	**2,988**
Wake losses	[%]	0.8	0.6	0.9
Curtailment losses	[%]	0.0	0.0	0.0
Other losses	[%]	8.9	8.9	8.9
Total energy production losses	[%]	9.6	9.5	9.7
Net energy production (AEP)	**[MWh/y]**	**5,064**	**2,367**	**2,698**
Net full load equivalent hours	[h/y]	2,532	2,367	2,698
Net capacity factor	[%]	28.9	27.0	30.8

Table 15: Detailed production per turbine Scenario 2

Configuration	Scenario 2	Total	WT1	WT2
Gross energy production	**[MWh/y]**	**6,072**	**2,862**	**3,209**
Wake losses	[%]	0.8	0.6	0.9
Curtailment losses	[%]	0.0	0.0	0.0
Other losses	[%]	8.9	8.9	8.9
Total energy production losses	[%]	9.6	9.5	9.7
Net energy production (AEP)	**[MWh/y]**	**5,489**	**2,591**	**2,898**
Net full load equivalent hours	[h/y]	2,744	2,591	2,898
Net capacity factor	[%]	31.3	29.6	33.1

Table 16: Detailed production per turbine Scenario 3

Configuration	Scenario 3	Total	WT1	WT2
Gross energy production	**[MWh/y]**	**6,382**	**3,028**	**3,355**
Wake losses	[%]	0.8	0.6	0.8
Curtailment losses	[%]	0.0	0.0	0.0
Other losses	[%]	8.9	8.9	8.9
Total energy production losses	[%]	9.6	9.5	9.7
Net energy production (AEP)	**[MWh/y]**	**5,770**	**2,740**	**3,030**
Net full load equivalent hours	[h/y]	2,885	2,740	3,030
Net capacity factor	[%]	32.9	31.3	34.6

Table 17: Detailed production per turbine Scenario 4

Configuration	Scenario 4	Total	WT1	WT2
Gross energy production	**[MWh/y]**	**6,775**	**3,241**	**3,534**
Wake losses	[%]	0.7	0.7	0.8
Curtailment losses	[%]	0.0	0.0	0.0
Other losses	[%]	8.9	8.9	8.9
Total energy production losses	[%]	9.6	9.5	9.7
Net energy production (AEP)	**[MWh/y]**	**6,125**	**2,933**	**3,192**
Net full load equivalent hours	[h/y]	3,062	2,933	3,192
Net capacity factor	[%]	34.9	33.5	36.4

Table 18: Detailed production per turbine Scenario 5

Configuration	Scenario 5	Total	WT1	WT2
Gross energy production	**[MWh/y]**	**5,255**	**2,447**	**2,808**
Wake losses	[%]	0.7	0.6	0.9
Curtailment losses	[%]	0.0	0.0	0.0
Other losses	[%]	8.9	8.9	8.9
Total energy production losses	[%]	9.6	9.4	9.7
Net energy production (AEP)	**[MWh/y]**	**4,752**	**2,216**	**2,536**
Net full load equivalent hours	[h/y]	2,376	2,216	2,536
Net capacity factor	[%]	27.1	25.3	28.9

Table 19: Detailed production per turbine Scenario 6

Configuration	Scenario 6	Total	WT1	WT2
Gross energy production	**[MWh/y]**	**5,707**	**2,685**	**3,022**
Wake losses	[%]	0.7	0.6	0.8
Curtailment losses	[%]	0.0	0.0	0.0
Other losses	[%]	8.9	8.9	8.9
Total energy production losses	[%]	9.6	9.5	9.7
Net energy production (AEP)	**[MWh/y]**	**5,161**	**2,431**	**2,730**
Net full load equivalent hours	[h/y]	2,580	2,431	2,730
Net capacity factor	[%]	29.4	27.7	31.1

Table 20: Detailed production per turbine Scenario 7

Configuration	Layout 7	Total	WT1	WT2
Gross energy production	**[MWh/y]**	**6,009**	**2,845**	**3,163**
Wake losses	[%]	0.7	0.6	0.8
Curtailment losses	[%]	0.0	0.0	0.0
Other losses	[%]	8.9	8.9	8.9
Total energy production losses	[%]	9.6	9.5	9.7
Net energy production (AEP)	**[MWh/y]**	**5,433**	**2,576**	**2,858**
Net full load equivalent hours	[h/y]	2,717	2,576	2,858
Net capacity factor	[%]	31.0	29.4	32.6

Table 21: Detailed production per turbine Scenario 8

Configuration	Layout 8	Total	WT1	WT2
Gross energy production	**[MWh/y]**	**6,391**	**3,052**	**3,339**
Wake losses	[%]	0.7	0.6	0.8
Curtailment losses	[%]	0.0	0.0	0.0
Other losses	[%]	8.9	8.9	8.9
Total energy production losses	[%]	9.6	9.5	9.6
Net energy production (AEP)	**[MWh/y]**	**5,779**	**2,763**	**3,017**
Net full load equivalent hours	[h/y]	2,890	2,763	3,017
Net capacity factor	[%]	33.0	31.5	34.4