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Planning and design of wind farms

42000

Wind Energy in South Africa: A Case Study of an Onshore Wind Farm

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Table of contents

Introduction

In this case study a wind farm near the southernmost tip of South Africa, in the Western Cape province, is planned and designed. This is done by following the WAsP modelling workflow and hierarchy, for wind resource assessment (WRA) and wind farm layout/calculations, while taking into account the economical feasibility of the project. Furthermore, critical factors in the environmental impact assessment (EIA) are identified and mitigation measures suggested. The wind farm's impact is also viewed in a societal context. Finally the planning and design of the project, considering the nearby grid infrastructure, is discussed.

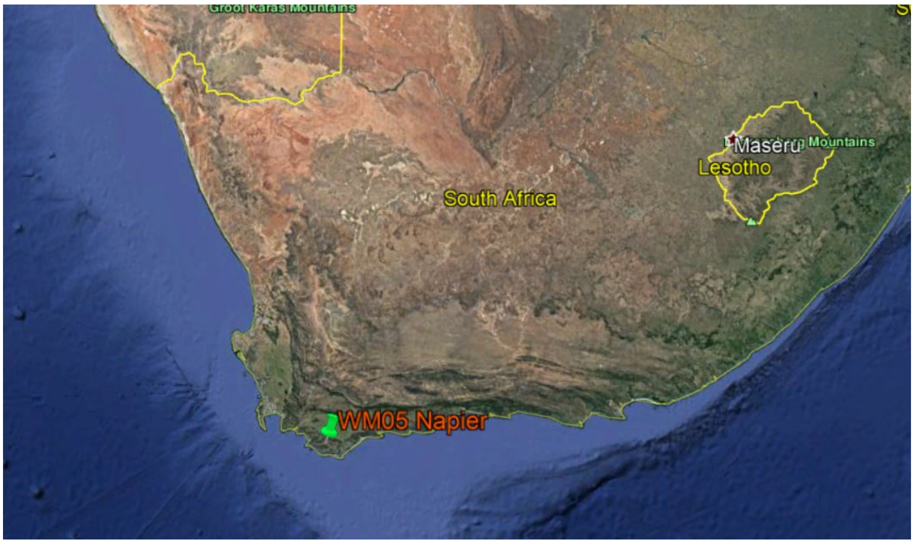


Figure 1: Site location. W05 met mast indicated by a green pin. Figure taken from Google Earth.

1 Wind Resource Assessment

1.1 Wind resource of S. Africa

South Africa's wind resources are affected by large-scale weather systems, that have seasonal variations as depicted in Figure 2. During summer the westerlies are well south of the continent, but in winter the circulating pressure systems move northward. Strong winds and gusts during winter are usually caused by cold fronts, moving over the southern part of the country, and ridging effect of high-pressure systems behind the fronts [34]. These synoptic scale weather systems, according to [6], are important indicators of strong wind conditions and variability in the wind resource at longer time scales (i.e. hours to days).

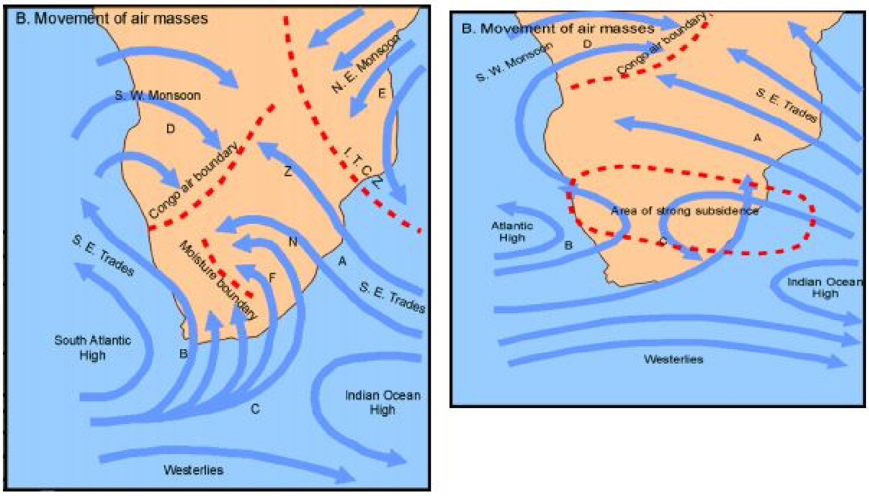


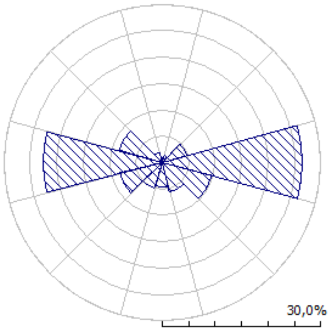
Figure 2: Summer (left) and winter (right) winds over South Africa taken from [34].

1.2 Measurements

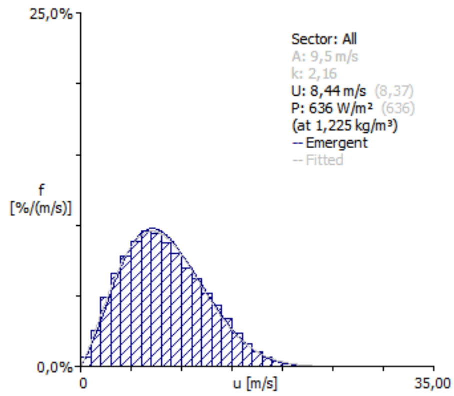
The measurement site WM05 is a part of a dense network of meteorological stations connected to the first phase of the Wind Atlas for South Africa (WASA1), a wind resource assessment project of the South African Wind Energy Programme (see e.g. [34][28][27]). Data from this site is largely available from the 1st of May 2010 to present time. The single 60 m mast is located 288 m a.s.l. at (E 380119, N 6169216) m in UTM 34. For photographic documentation of the mast design and surroundings, see [28]. No major obstacles are observed in the vicinity of the mast. The mast is instrumented with DTU developed anemometers (model P2546). It has five levels of anemometry, at 10 m, 20 m, 40 m, 60 m and 62 m height a.g.l., and wind direction is measured at 20 and 60 m (0.5 m/s threshold according to manufacturer). Measurements of the standard deviation of the 10 min mean wind speed are available at all heights. Other meteorological measurements include the temperature of air at 60 m, the gradient in temperature from 10 to 60 m, air pressure at 6 m and relative humidity at 60 m. See [27] for sensor specifications. Due to a few months gap in the data, from May 2014 to December 2014, the period from the 1st of May 2014 to the 1st of May 2015 is dropped from the measured time series. A total of 9 years of data (with 98.75% recovery rate at 62.5 m) is considered in this study, beginning on the 1st of May 2010 and ending on the 1st of May 2020.

1.3 Observed wind climate

Measurements (10 min averages) of wind speed at 62 m, and direction at 60 m are used in the resource assessment. The data is plotted in Figure 25 in Appendix A. Lower limit for the wind vane is set to 0.5 m/s (according to manufacturer, see [27]). The observed wind climate is plotted in Figure 3.



(a) Observed wind direction distribution (wind rose).

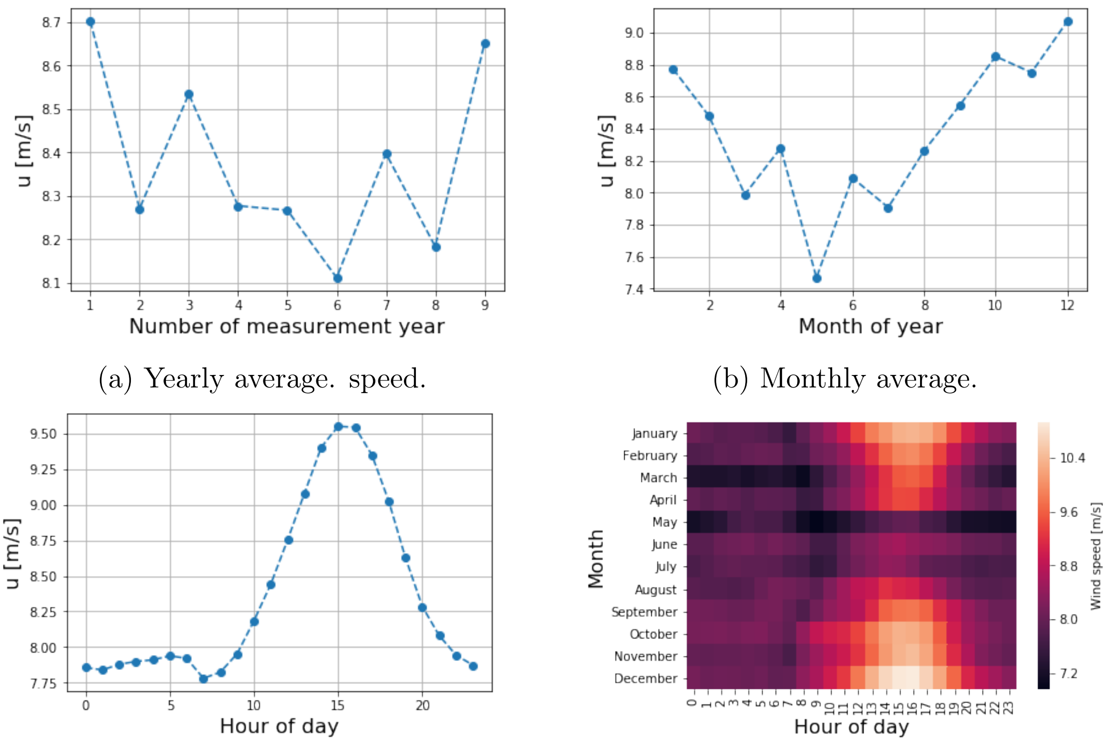


(b) Distribution of 10 min mean wind speed measurements, including an emergent (weighted sum of sector-wise) Weibull fit.

Figure 3: Distribution of wind speed and direction based on the measured time series at W05 (wind speed at 62 m height a.g.l. and wind direction measured at 60 m a.g.l.).

Eastern (bins centered at 60°,90° and 120°) and western (bins centered at 240°,270° and 300°) winds contribute to 80% of the total observed distribution. Sectors centered at 90° and 270° (due east and west) are clearly dominant in the wind rose, consisting of 26.5% and 22.6% of the distribution. Northern winds are almost non-existent and a only a small portion blows from the south. The dominant wind directions at the site are likely a result of the long-term geostrophic flow that is governed by seasonally varying large-scale pressure systems (see Figure 2). From Figure 25 it seems that Easterlies are more prominent during winter and Westerlies during summer, as expected. The topography of the area also seems to have some effects, with open land to the east and a small valley channeling the incoming westerly flow.

The emergent (sector-wise) average wind speed is 8.44 m/s and the mean power density is 636 W/m^2 (using 1.225 kg/m^3 for the air density). In Figure 4 the annual, monthly and hourly average of the 10 minute mean wind speed at the site (at 62 m a.g.l.) are presented, along with an annual speed cycle. Highest wind speeds at the mast are in the spring and summer during the early afternoon to early evening. The afternoon speed up might be connected to local low pressure formation over land during hot summer days, which sucks in air from the colder sea. The daily wind cycle is more uniform during winter months, when the average wind speed is lower. The windiest measurement year has an average annual wind speed of 8.7 m/s and the least windy year has an average of 8.1 m/s. The maximum inter-annual variability (with respect to the the long term observed mean wind speed of 8.37 m/s) is thus around 4%, and is likely governed by variations in the strength and position of large scale pressure systems from year to year.



(a) Yearly average. speed.

(b) Monthly average.

(c) Hourly average. .

(d) Observed annual speed cycle .

Figure 4: Annual, monthly and hourly averaged (observed) 10 min mean wind speeds at 62 m a.g.l., including an observed annual speed cycle for the W05 site.

The stability conditions at the site have been determined based on the Richardson number (see Appendix A), calculated from the meteorological measurements available at the mast. As seen from the distribution (Figure 27), the Richardson number is more often positive than negative at the measurement site. These weakly stable conditions result in relatively low turbulence intensity, and therefore less fatigue loads associated with turbulence.

1.4 Topographical inputs

The topographical data was imported and edited using the WAsP Map Editor. An orography map (Figure 5) was imported from the web data base SRTM ver. 2, considering a height contour equidistance of 10 m.

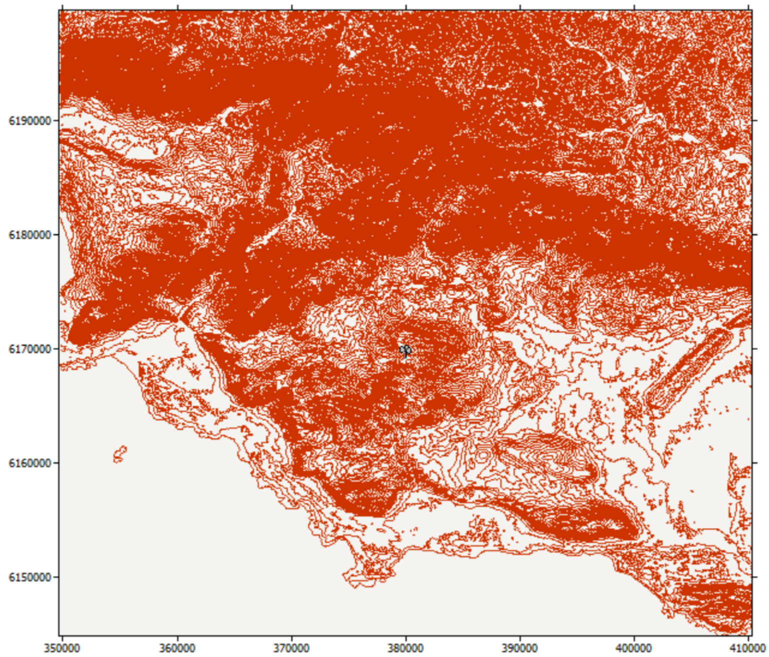


Figure 5: Orography map with extension of 60km generated from SRTM.

The roughness map was first imported from SRTM to provide sea and lake contours, and then edited based on satellite imagery from Google Earth. The land cover, typical of South Africa, is composed of farmlands, scrubland, forest and villages. The corresponding roughness lengths are given in the following table:

Table 1: Roughness values considered for the project.

Land cover	z_0 **(m)**
Farmland	0.05
Scrubland	0.2
Forest	1
Villages	0.5
Sea, lakes	0

An extension of 60 km in both the East-West and North-South directions was added in order to account for the effects of roughness changes according to IBL theory: 15km (100 times the hub height plus 50%) from any point located at 15km from the mast. This should enable the consideration of turbine sites at any location in a radius of 15km from the mast. The resulting land cover is depicted in Figure 6.

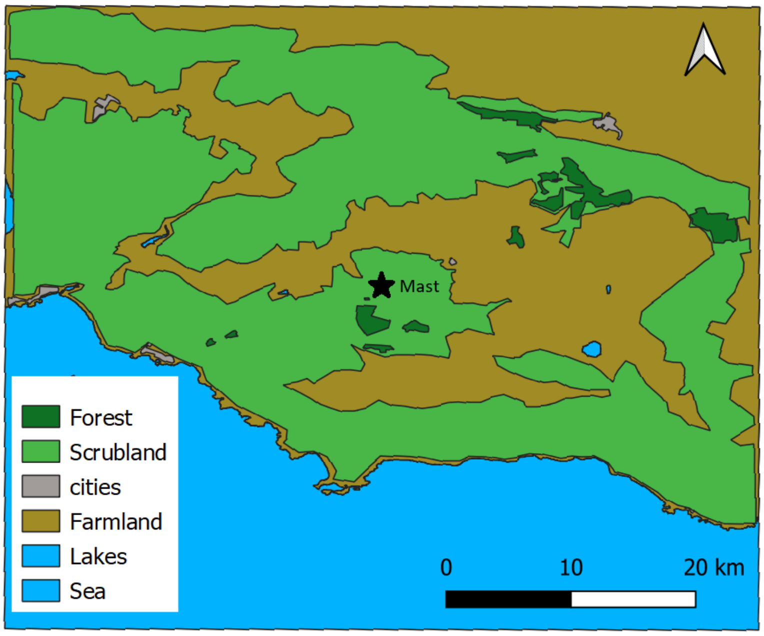


Figure 6: Land cover used for the project.

By fitting a log-law to the observed average wind profile (on a semi-log abscissa) for one measurement year, the roughness characteristics at the site can be estimated. The fitted wind profile, depicted by a straight line (see Appendix A), confirms that on average the logarithmic law is observed at the site. The corresponding roughness length is given by the intersection with the y-axis (0.13m). This value is slightly lower than the value considered for this area (0.2m). This is justified considering that the fit also integrates the effect of roughness changes further from the mast, where the roughness length is lower (0.05m). Overall, a roughness length of 0.2m for the scrubland is therefore a good approximation.

1.5 Generalized wind climate

Subsequently, using the information from the observed wind climate, the orography and the roughness, the generalized wind climate (GWC) is generated at the mast site. This process allows for the removal of both the effects of roughness and orography in order to calculate the mean wind speed at different heights for different roughness lengths. The heights were fixed to generate calculation at 80m, corresponding to the hub height of the planned wind turbines. Furthermore, the pressure, temperature and relative humidity were extracted from the measurements and applied to the GWC for the calculation of the air density (see values in Appendix A). The mean wind speeds calculated for the GWC are presented in the table below:

Table 2: Mean wind speeds for the GWC calculated from the measurements.

Height	**0m**	**0.03m**	**0.1m**	**0.4m**	**1.5m**
10m	8.24/s	5.96m/s	5.21m/s	4.10m/s	2.73m/s
25m	9.00m/s	7.05m/s	6.36m/s	5.35m/s	4.11m/s
50m	9.63m/s	8.03m/s	7.36m/s	6.40m/s	5.22m/s
80m	10.11m/s	8.83m/s	8.15m/s	7.19m/s	6.05m/s
200m	11.23m/s	10.96m/s	10.16m/s	9.12m/s	7.94m/s

For comparison, the GWC was also generated from the Global Wind Atlas (GWA). The results at 50m are presented below for both the measurements and GWA:

Table 3: Comparison of the mean wind speeds of the GWC at 50m calculated both from the GWA and from the measurements.

	0m	**0.03m**	**0.1m**	**0.4m**	**1.5m**
From measurements	9.63m/s	8.03m/s	7.36m/s	6.40m/s	5.22m/s
From GWA	8.91m/s	7.32m/s	6.71m/s	5.86m/s	4.82m/s

The mean wind speed calculated from the GWA is significantly lower than the one calculated from the measurements. This is likely due to the coarse resolution of the global weather model used for the GWA.

In Appendix A, the measured long term (average) wind profile is compared to the WAsP modelled profile at the site. The model seems to give a very good fit to the observed profile (see Figure 28).

1.6 Predicted wind climate

The predicted wind climate is calculated based on the GWC. The effects of orography and roughness are again considered, but this time to evaluate the climate at the potential wind farm locations. A map of the mean wind speed at 80m, generated from WAsP, is depicted in Figure 7.

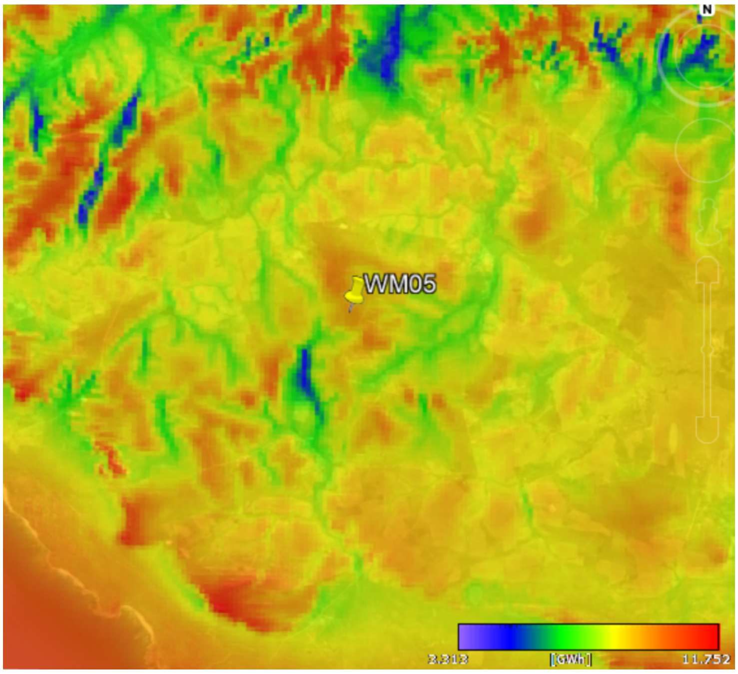


Figure 7: Mean wind speed at 80m corresponding to the predicted wind climate.

The wind resource matches the orography of the area, where very high wind speeds are predicted in the mountains at the north while relatively low wind speeds occur in the valleys. The hills at and near the mast locations are also characterized by relatively high wind speeds whereas the ridges near the sea at the South-West present even higher wind speeds. The low-lying and flat farmland (e.g. west of the site) has a moderate wind resource.

2 Wind Farm Calculations

2.1 Site selection

From the Predicted Wind Climate, several locations seem suitable for the project. Eight potential sites are depicted in Figure 8. The locations of the Agulhas National Park and Pearl Beach Reserve were also considered which discards the selection of sites 6, 4 and 3 (see EIA, section 4). Site 7 was finally chosen for its wind resource potential and its topographical characteristics (a large hill roughly 5km long and 3km wide). It is worth mentioning that this site borders a cliff at its South side, which could at first sight jeopardize the potential siting. However, it was verified that the RIX values for this site stay below 5 for the dominant East-West directions. On the other hand, it should be emphasized that the site is relatively far from the mast (12 km) and is close to the sea. WAsP, a microscale model, does not take the mesoscale flow effects into account, which might be relevant between the measurement site and the turbine site. This is assessed in subsection 2.6.

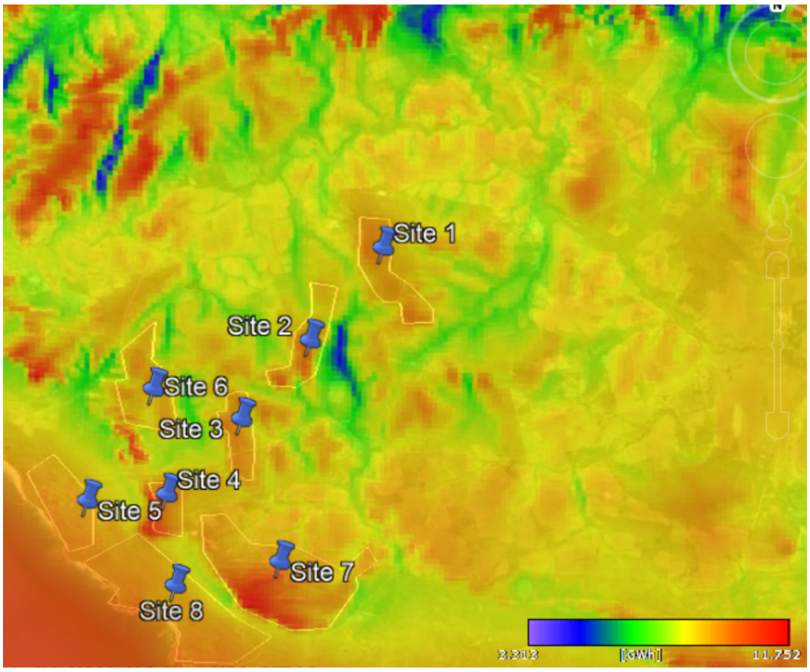


Figure 8: Possible sites in the studied area. The background map depicts the AEP for a V90 2MW wind turbine, at a hub height of 80m.

2.2 Wind turbine selection

The rated power of the chosen wind turbine reflects the value most commonly encountered in South Africa, in the range of 1.5 to 4MW [3]. The wind turbine has also been selected in order to stay within the ratio of 2/3 recommended, between the measurement height and the hub height. Two wind turbines were therefore considered for the calculations, both with a hub height of 80m: the Vestas V90 2MW class S and the Vestas V90 3MW class IA. The V90 2MW was finally chosen as it presents better characteristics regarding the loads, especially at high wind speeds. This is further discussed in the IEC verification section. The main characteristics of this wind turbine and its power curve are presented below:

Table 4: Main characteristics of the Vestas V90 2MW

Nominal power	2MW
Rotor diameter	90m
Hub height	80m
Cut-in speed	4m/s
Cut-out speed	25m/s
Rated speed	12m/s
IEC class	S

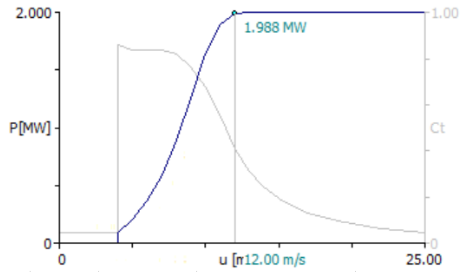
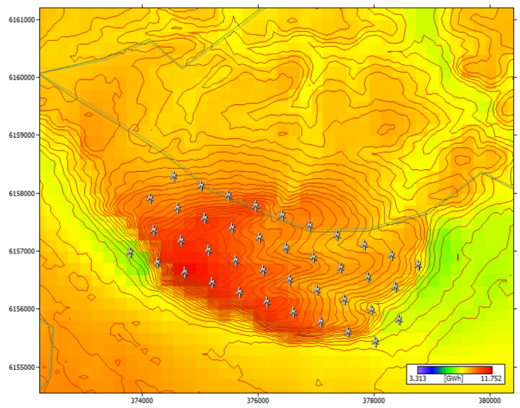


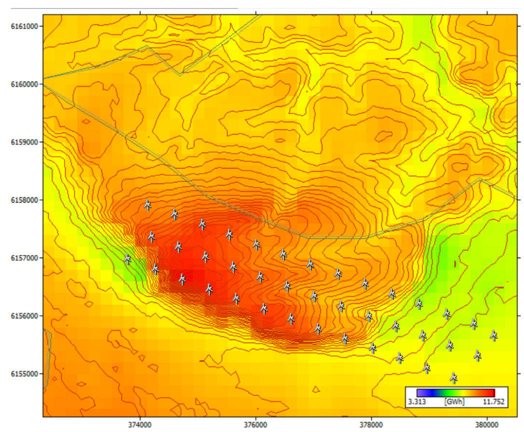
Figure 9: Power curve of the Vestas V90 2MW in WAsP.

2.3 Layouts

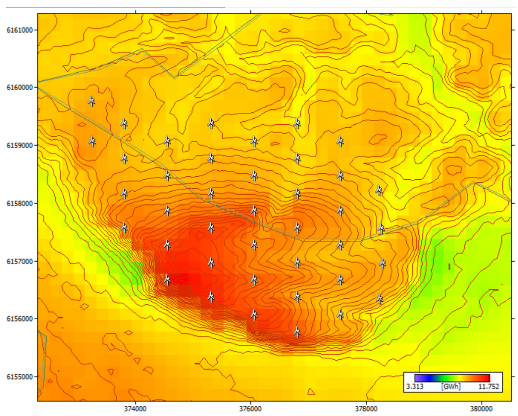
Four different layouts were studied, corresponding to different positions of the wind turbines. To enable the comparison, a fixed number of 40 wind turbines was used, with a constant installed power of 80MW. The layout was refined iteratively in order to optimize the AEP, limit the wake loses and ensure compliance with the IEC inclination criteria. Finally, all wind turbines were placed north of the cliff, both for aesthetic reasons and to avoid the possible upwind and downwind deceleration before and after passing the hill.



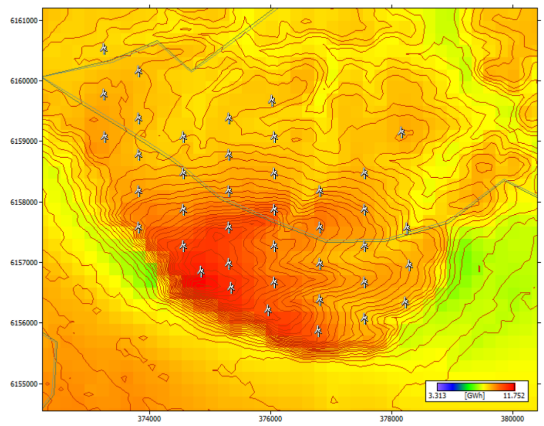
(a) Layout 1



(b) Layout 2



(c) Layout 3a



(d) Layout 3b

Figure 10: 4 main layouts 80MW realized for the project.

The final layout (3b) was retained for the wind farm. It is characterized by a distance of 600 m (6.7 diameters) between wind turbines in the South-North, cross-wind direction, and 750m (8.3 diameters) in the East-West, wind direction. This way, the losses are limited to 4.4% and the capacity factor reaches 52.1% (considering the net AEP, after subtraction of the wake loses). The results and main characteristics of the four layouts are summarized in the following table:

Table 5: Main results for of the 4 layouts studied

Layout	**Gross AEP (GWh)**	**Wake losses (WAsP)**	**Net AEP (GWh)**	**Capacity factor**
1	390.1	7.9%	359.4	51.3%
2	376.0	8.1%	345.6	49.3%
3a	389.1	4.4%	371.9	53.1%
3b	382.1	4.4%	365.0	52.1%

2.4 Energy yield of the wind farm

The net AEP of the wind farm, after subtraction of the wake loses, is evaluated at 365.0 GWh, corresponding to a capacity factor of 52.1%. However, in order to better assess the wind farm and generate energy estimates and revenue projections, various technical losses need to be taken into account. These are defined below and the values considered for the project are presented in Table 6.

The wind turbine availability accounts for faults, maintenance, delayed maintenance due to impeded access, lightning, and cable unwrapping [39]. The balance of plant availability corresponds to the availability of electrical infrastructure of the plant up to the point of connection to the grid. The grid availability takes into consideration the risk of grid outages and includes the delays for the wind farm to come back to full operation after these outages. The values considered for those three factors are typical values for wind farms.

The electrical losses are located between the low voltage terminals of each wind turbine and the point of connection to the grid. It corresponds to the overall efficiency of the electrical systems. Here a typical conservative value of 2% is considered. The turbine performance losses correspond to the difference to the power curve introduced by regulation of the turbine in response to variable wind speed. In order to avoid repeated start up and shut down of the turbines when the wind speed varies close to the cut-out wind speed, hysteresis is introduced in the control algorithm. A typical value for turbine performance losses is 1%. The final losses considered here are environmental losses which are not expected to be especially high at the site, due to the overall temperate climate at the site with a relatively warm winter. Environmental losses are therefore evaluated to be 1%.

Finally, losses due to curtailment are not considered as no sector management has been introduced in the design of the wind farm.

Table 6: Technical losses considered to assess the energy yield of the wind farm.

Turbine availability	97%
Balance of plant availability	99%
Grid availability	99%
Electrical losses	2%
Turbine performance losses	1%
Environmental losses	1%
Curtailment	0%

Overall, the losses reach 8.7% and subsequently the energy yield of the wind farm is estimated at 333.2 MWh, corresponding to a capacity factor of 47.5%, a relatively high value for an onshore wind farm.

2.5 Sensitivity analysis

The sensitivity of the AEP estimate to changes in the wind resource and wind farm layout is analysed, by systematically changing the WAsP modelling input values one at a time. Part of the results are presented in Table 7, see Appendix B for the full table. As can be seen, the model is by far most sensitive to changing the GWC from WM05 to GWA at the turbine site. The horizontal extrapolation is thus likely the most prominent uncertainty for the wind resource assessment at the turbine site. Other input parameters have less effect, with the wind speed measurements and the air density being the most sensitive climate parameters. It is interesting to note that increasing the elevation detail from 10 m to 5 m has negligible effects on the AEP, but by decreasing the detail from 10 to 20 m increases the AEP by 2-3%. The AEP is also more affected by doubling the background roughness, than halving it. Furthermore, by applying a counter-clockwise 15° offset to the measurements the AEP increases, but for a clockwise rotation the AEP decreases. The difference in AEP can be explained by the roughness rose, and sector wise roughness differences. As for the layout, it is interesting to see how the direction offset affects the net AEP. The effect on the net AEP is almost double then on the gross AEP when the offset is -15°, indicating increased wake losses.

Table 7: Sensitivity analysis of the wind resource and wind farm layout. For the full results, see table Table 17 in Appendix B

Input parameter	Change	ΔAEP (gross) [%]	ΔAEP (net) [%]
U calibration	1%	-1.21	-1.30
Anemometer height	-1%	-0.22	-0.23
Direction offset	+15° // -15°	0.72 // -0.63	0.87//-1.24
Air density	+2%	0.97	1.00
Background roughness	0.05 → 0.025 m	0.33	0.33
Background roughness	0.05 → 0.10 m	-0.82	-0.85
GWC	→ GWA	-12.18	-12.64
Elevation detail	10 → 20 m	2.4	2.6
Elevation detail	10 → 5 m	0.02	0.04
Hub height	+2 m	0.79	0.83
Posistion of the WF	10 m North	-0.07	-0.08

2.6 Uncertainty analysis

Various uncertainties are introduced in the calculation of the energy yield of the wind farm. The main uncertainty derives from assuming a constant GWC from the measurements mast to the site. This assumption is actually not completely realistic as the mesoscale flow is expected to be effected by the terrain along the coast. This effect can be seen on the GWC wind rose obtained from the Global Wind Atlas (GWA) at the turbine site (Figure 11). North-Western winds, that follow the coastline, are more dominant than winds from due west. This means that the bulk of the westerly flow is affected by higher roughness length (more incoming flow over land), resulting in a lower average wind speed at the site. Moreover, calculations using the GWC from the GWA yield mean wind speeds that are around 9% lower than those calculated via horizontal extrapolation from the measurements. An uncertainty of 9% for the horizontal extrapolation is therefore considered to account for this effect, but it should be noted that the GWA underestimates the wind resource in the area (as shown in subsection 1.5 at the mast site). It is hard to directly assess the meso-scale induced bias to the flow modelling, in order to correct for these effects, justifying a higher uncertainty estimate (using the simple measure described above).

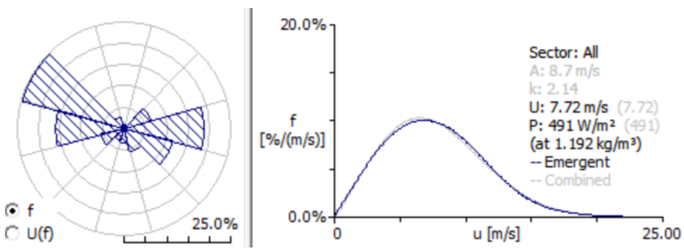


Figure 11: Wind rose and distribution for the turbine number 1 generated considering the GWC at the site.

Other uncertainties with respect to the wind speed arise from the inter-annual variability, the long-term climate correction and the measurements. As described in section 1, the inter-annual variability is around 4%. Given the large sample of data available from the mast site, long-term climate correction is taken as only as 1% to account for climate change effects. Finally, the uncertainty for the measurements is considered at 2%, which is a quite low value accounting for the relative high quality of the anemometers installed by DTU (see subsection 1.2 and [27]). Vertical extrapolation of the wind profile is not considered in the uncertainty calculations, as the extrapolation is only 20 m and the WAsP wind profile is fairly representative of the mast measurements. Uncertainty on the air density is also not taken into account, as measurements from the mast are used for the calculation. However, the proximity to the sea might affect the air density at the turbine site. The uncertainty is likely less than 2%, which (according to the sensitivity analysis) roughly has an 1% impact on the AEP (and is thus deemed negligible in our analysis).

Uncertainties are also considered on the energy yield. Typical values are used here. All uncertainties and the combined overall uncertainty are presented in the following table:

<table>
<tr><th>Type</th><th colspan="2">Uncertainty</th></tr>
<tr><td>Wind measurements</td><td>2%</td><td rowspan="4">10.1% on wind speed</td></tr>
<tr><td>Long-term climate correction</td><td>1%</td></tr>
<tr><td>Inter-annual variability</td><td>4%</td></tr>
<tr><td>Horizontal extrapolation by flow model</td><td>9%</td></tr>
<tr><td>Turbine performance</td><td>6%</td><td rowspan="5">7.5% on AEP</td></tr>
<tr><td>Wake-loss modelling</td><td>3%</td></tr>
<tr><td>Turbine availability</td><td>3%</td></tr>
<tr><td>Balance of plant availability</td><td>1%</td></tr>
<tr><td>Grid availability</td><td>1%</td></tr>
<tr><td>Total uncertainty</td><td colspan="2">16.9%</td></tr>
</table>

Table 8: Uncertainty analysis of the wind resource and wind farm layout and its effect on the AEP

The resulting exceedance percentiles P_{50}, P_{75} and P_{90} are presented in Figure 12 and the corresponding energy yields are displayed in Table 9 along with the capacity factor. The difference between P50 and P90 is around 70 GWh, which is quite significant, but in both cases the capacity factor is relatively good (>35%).

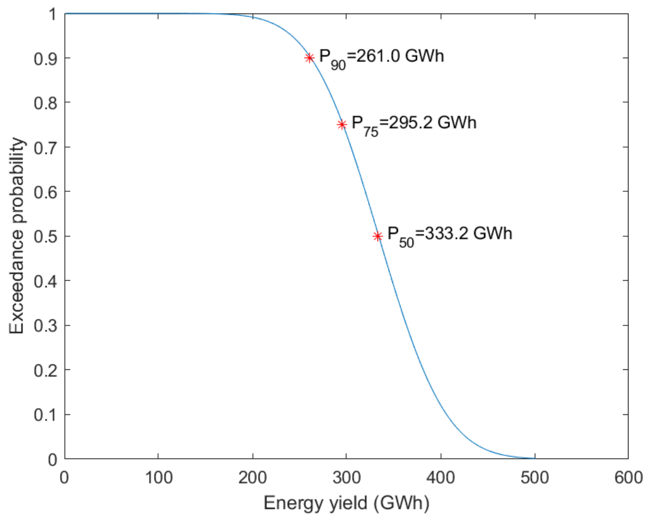


Figure 12: Energy yield prediction for different probabilities.

Table 9: Summary of energy yield and capacity factor prediction.

	Energy yield (GWh)	**Capacity factor**
P50	333.2	47.5%
P75	295.2	42.1%
P90	261.0	37.2%

To conclude, the chosen final layout (3b) has a good wind resource but the distance from mast and proximity to the sea (major roughness change) makes it hard to validate the results. The P_{50} energy yield is likely biased due to terrain induced meso-scale flow effects, which is difficult to correct for. WAsP is effectively outside its designed operational envelope, and further measurements at the site are needed.

2.7 IEC verifications

The IEC compliance was verified with the Wind Farm Assessment Tool (WAT). The class selection of the turbine was mainly based on three criteria: the extreme wind conditions, the amplitude of wind speed (average and distribution) and the turbulence intensity.

As seen in Appendix A, the site is mostly characterized by stable conditions. Those conditions which correspond to relatively low turbulence have been confirmed by using the measurements of the standard deviation of the wind speed at 62m as an input in the WAT model. Those measurements resulted in significantly lower turbulence intensity than the calculations made with WAsP engineering. However, the study of the wind speed evidenced relatively strong winds in site 7, where the layout was considered. Those conditions finally result in low requirements regarding the extreme winds, reasonable requirements with respect to turbulence intensity, and a need for a high class for wind speed criteria.

All IEC criteria were therefore assessed for the layout 3b for both Vestas V90 2MW class S and Vestas V90 3MW class IA. The wind turbine V90 3MW was discarded as it does not give satisfactory results for multiple critical criteria:

- Vave exceeded for 5 wind turbine sites;
- Wind speed pdf exceeded for all the wind turbine sites;
- Turbulence intensity exceeded for 2 wind turbine sites.

The need for a class S wind turbine was subsequently confirmed and the following parameters were considered for the Vestas 90 2MW:

Table 10: Chosen parameters for the wind turbine V90 2MW class S

50 years extreme wind	37.5 m/s
Average wind	11 m/s
Weibull k value	2.0
TI ref	0.18
TI slope parameter	3.0
max flow inclination	8.0
max shear parameter	0.2
min shear parameter	0.0

With those parameters, the wind conditions at the site comply with all the criteria of the IEC standard except the distribution of the wind speed for all the wind turbines. The results are displayed in Figure 13.

Turbine site	IEC...	V50 [m/s]	Vave [m/s]	Shear e...	Flow in...	Ieff	Imax	Speed...	Topog...
NapierProje...									
Turbine 1	S (...	30.27	8.45	0.156	0.77	OK	OK	pr...	OK
Turbine 2	S (...	30.25	8.61	0.160	0.32	OK	OK	pr...	OK
Turbine 3	S (...	32.05	9.63	0.140	7.85	OK	OK	pr...	OK
Turbine 4	S (...	30.34	8.81	0.154	1.00	OK	OK	pr...	OK
Turbine 5	S (...	32.71	10.02	0.136	7.62	OK	OK	pr...	OK
Turbine 6	S (...	30.38	8.68	0.163	4.50	OK	OK	pr...	OK
Turbine 7	S (...	29.48	8.47	0.165	5.27	OK	OK	pr...	OK
Turbine 8	S (...	34.38	10.33	0.123	6.21	OK	OK	pr...	OK
Turbine 9	S (...	31.52	8.98	0.158	3.56	OK	OK	pr...	OK
Turbine 10	S (...	35.59	10.78	0.111	5.63	OK	OK	pr...	OK

Figure 13: Checklist of the IEC criteria for layout 3b with wind turbine V90 2MW

Concerning the extreme wind, the highest 10 minutes average with a return period of 50 years is 35.6 m/s which is below the extreme wind criteria for a class III (V_{50} = 37.5m/s). For the turbulence criteria, one wind turbine doesn't comply with the category A (TI = 0.16) and the equivalent to category A+ is needed (TI = 0.18). The turbulence intensity rose and the curve of the effective turbulence intensity are displayed in Figure 14 for turbine 23, where it can be seen that the criteria from the IEC standard (grey curve) is respected by a good margin.

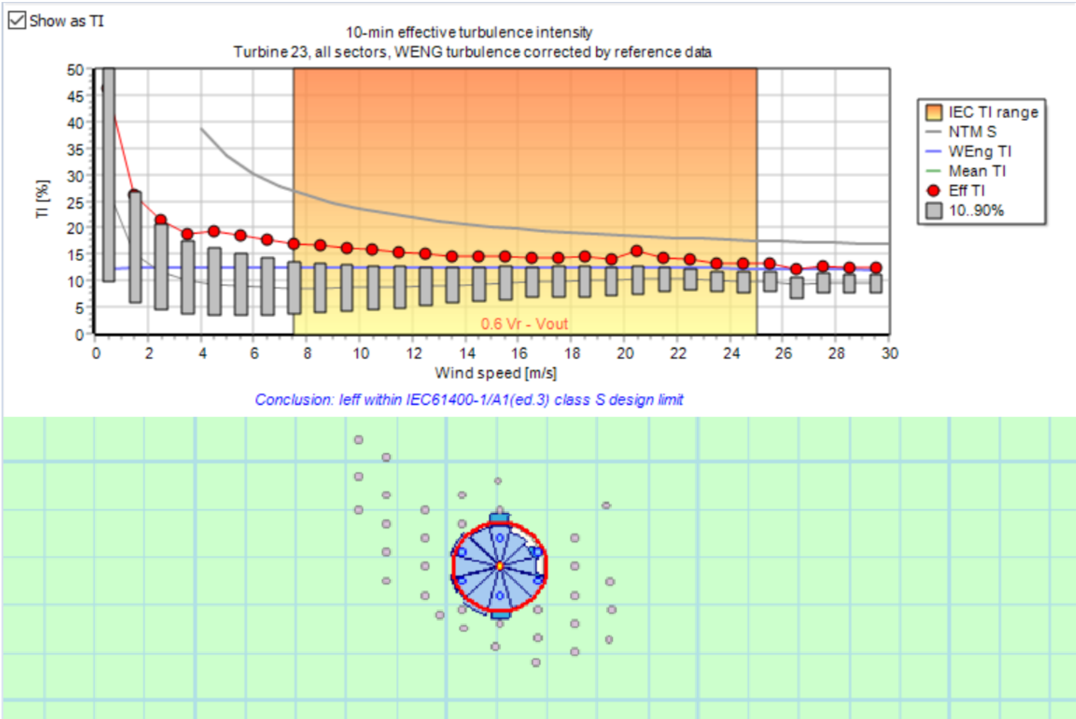


Figure 14: Effective turbulence intensity for a turbine in the middle of the wind farm and corresponding turbulence intensity wind rose.

It is worth mentioning that the criteria for the flow inclination angle (< 8deg) was not verified for layout 3a and a correction of 4 wind turbine positions, placed further from the cliff, was necessary to ensure compliance. Finally, the distribution of wind speed could not comply with the IEC standard as can be seen for turbine 23 in Figure 15. This can be remedied by further calculations realized by the manufacturer. Since there are significant margins for the extreme wind criteria and turbulence intensity (at least for the vast majority of wind turbine sites), it can be expected that further load calculations combining those attributes with the wind speed distributions would give positive results.

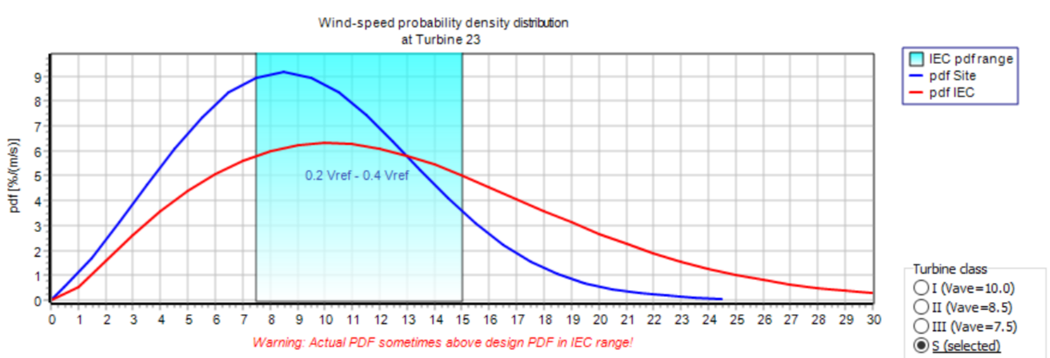


Figure 15: Wind speed probability density distribution of wind turbine 23 compared with IEC standard.

3 Economic and Financial Feasibility

3.1 Introduction to South Africa's Power Market

The South African energy matrix is made up of renewable, gas, coal, hydroelectric and nuclear. Electricity generation is primarily in the hands of state-owned company Eskom. Eskom owns 90% of the country's nominal generation capacity, while just 7,2% is held by Independent Power Produces (IPPs), which sell power to Eskom [17]. Moreover, Eskom is entirely responsible for the transmission and distribution (the latter together with local municipalities). South Africa is heavily reliant on its coal resources, which generated 39 GW of the country's installed capacity in 2019, representing roughly 74% of the total capacity. This places South Africa as 7th largest coal producer in the world. The installed capacity of renewable accounts just for 7%. Nevertheless, South Africa is planning to shift away from coal and is aiming to decommission 34 GW of coal-fired power capacity by 2050. It also aims to build at least 20 GW of renewable power generation capacity by 2030.[38]

3.2 Integrated Resource Plan regarding renewable energy

The Integrated Resource Plan (IRP) is an electricity plan developed by the Department of Energy of South Africa, with a forecast of the country's electricity demands and how this demand is to be met. It was first released in 2010, however it was approved recently by the Cabinet on October 2019.

By far the biggest portion of the new-build in IRP 2019 for the years to 2030 comprises wind and solar PV. The IRP anticipates an additional capacity of 14,400 MW of wind and 6,000 MW of Solar PV. [14]

3.3 Costs estimations

Due to the fact that firms in the wind energy sector don't provide information about their prices (unless they are contacted for a feasible real project), most of the prices in this section are estimations. Different sources have been taken into account in order to obtain somewhat realistic costs for the economical evaluation, yet some of them may not be completely accurate.

It is also important to note that, even though the project is situated in South Africa all costs will be displayed in euros and not in South African Rand (ZAR); at present rate, 1 Euro = 18.39 ZAR. The main reason for this is that most of the sources regarding costs of wind farms display them in euros. Nevertheless, it is important to remark the fact that the South African Rand is more volatile (see Table 11) than the euro [19]. This adds uncertainty for the possible investors, even if the economical indicators for the project are attractive. Therefore it would be more accurate for future stages, to calculate the cash flows using the ZAR currency with an assessment of inflation.

Table 11: Inflation rate for South African Rand from 2016-2020.

Year	South Africa Inflation Rate %
2016	6.59
2017	5.18
2018	4.50
2019	4.12
2020	4.12

3.3.1 CAPEX

The CAPEX (Capital Expenditure) are funds used to purchase goods or services that will be used to improve a company's performance in the future. The factors included in the CAPEX mainly come from the Development and the Implementation phase of a wind farm project, but costs from the Decommissioning phase should also be included. Although the costs incurred in the latter will probably take place in the last year of the project, they will be included in initial period of the cash flow for simplicity. The **total CAPEX** for the project was estimated to be 122,680,000 €.A more detailed description is presented below.

Development and project management: This includes wind resource and site assessment, preliminary design and engineering, permits needed to install the wind farm in the area, legal and contractual advisory and the environmental study as well. These cost were estimated to be approximately 7,160,000 €.

Wind turbines: This is the main contributing factor to the CAPEX for onshore wind farms. The total cost for installing commercial-scale will vary significantly depending on the number of turbines, cost of financing, when the purchase agreement was executed and location of the project among others. [40] The total cost for the acquisition, shipping and assembly for the 40 Vestas V-90 2.0 MW was estimated to be 84,800,000 €. The distribution of the wind turbine costs can be observed in Figure 16. The overall turbine cost consists of: acquisition cost (AC = 85%); shipping and assembling (SA = 5%); and electrical installation (EI = 10%).

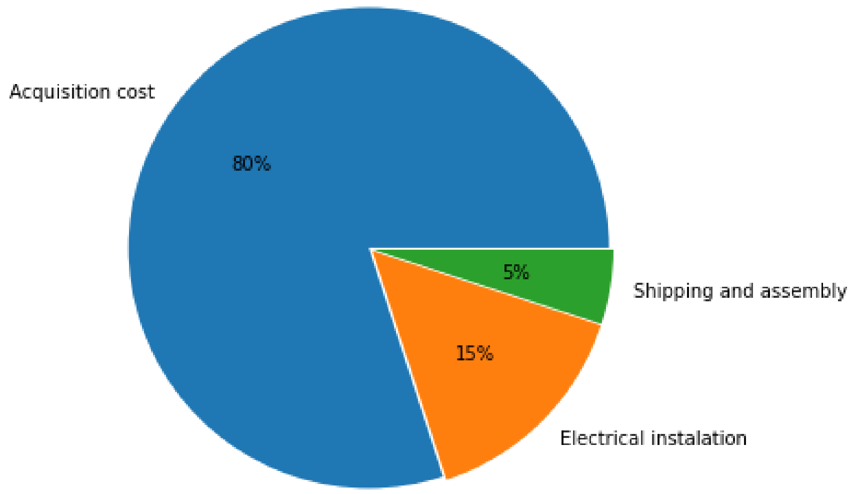


Figure 16: Distribution of wind turbine costs.

Grid connection: The costs of grid connection consist in cables, transformers, sub-station and the connection to the transmission network as well. These costs amount to a total of 19,350,000 €. [8]. (Note: The distance from site 7 to the PCC might require longer OHTL than normal. See further discussion in subsection 6.4).
Foundation: These costs are mainly the construction for the site preparation and the foundations of the towers. Foundation costs were estimated to be 6,570,000 €.
Decommissioning: The decommission costs have to be considered as a part of the CAPEX. As stated before, for simplicity these costs are considered at the beginning of the project, as they do not represent a significant amount of the total project cost. Total decommission cost estimated to be 4,800,000 €.

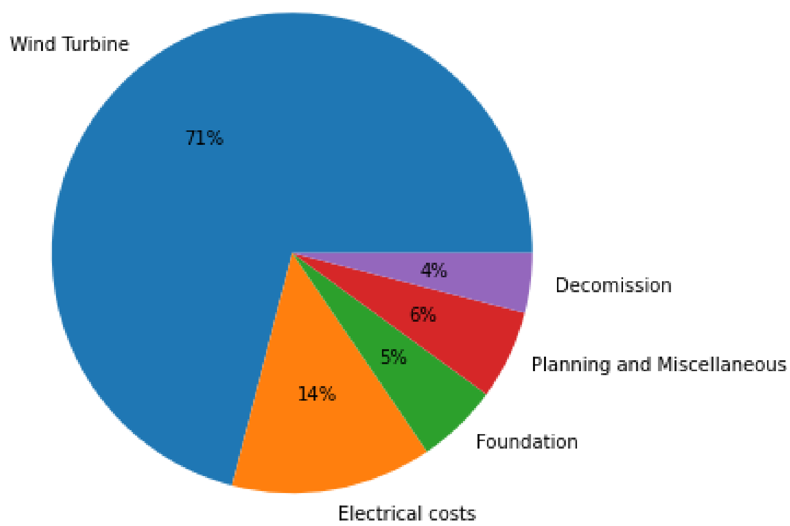


Figure 17: CAPEX costs distribution.

3.3.2 OPEX:

The OPEX (Operational Expenditure) consists in the operation and maintenance costs. For a 2.0 MW wind turbine the annual operation and maintenance costs are around 40,000 € per turbine. [4]

3.4 Discount rate for wind farm in South Africa

The discount rate is an estimation of the cost of the capital for a company to build certain projects. It is calculated as a weighted average of both the cost of equity and the cost of debt. Perceived country risk, alternative investment yields or inflation are several factors that can affect the discount rate among others. The discount rate for wind farm projects in different country's was provided. For an onshore wind farm in South Africa the discount rate is estimated in 7.4%.

3.5 Support mechanisms for Renewable energy in South Africa

Failure of the REFIT program

The National Energy Regulator of South Africa (NERSA) approved a Renewable Energy Feed-in Tariff (REFIT) policy in 2009. The tariffs were designed to cover generation costs plus a real return on equity of 17% percent. Moreover, it would be fully indexed for inflation [11]. Although the initial tariffs were generous, considerable uncertainty remained regarding the legality of FIT within South Africa's public procurement framework, and there were considerable delays in finalizing power purchase agreements (PPA) with Eskom.

Birth of REIPPPP program

In 2011, after receiving legal advice that FIT's were inconsistent with public finance and procurement laws, the Department of Energy announced that a competitive bidding process for renewable energy would be launched, known as the Renewable Energy Independent Power Producer Procurement Program (REIPPPP).

Renewable energy auctions

Renewable energy auctions are a type of support mechanism for renewable energy technologies. The growing use of auctions is mainly motivated by their ability to apply a competitive mechanism for price determination [20]. In most cases renewable energy auctions are opened by the government of a country. They will specify the capacity (kW) or the electricity generation (kWh) which is up for auction, as well as the generation technology and sometimes the generation location. Project developers can then submit a bid to the auction, outlining their project proposal and stating the price per unit of electricity at which they will be able to realise their project. The government then evaluates the different offers, ranking them based on their price and other criteria. The best candidates are then selected and the government signs a power purchasing agreement with the successful bidders. [13]

3.5.1 Electricity prices in South Africa

There is public information available about average tariffs (USD/MWh) and capacity (offered and awarded) from 2011-2015 for different energy sources [21]. In Figure 18 the evolution of the price for Wind and also Solar PV is plotted. In Table 12 a resume for the different Bid Windows (BW) just for Wind energy auction is displayed, in both USD and € (rate was 1 USD equal 0.83 €). For the evaluation metrics of this project, the price of energy was 49.6 €/MWh (the last Bid Window in 2015) was considered. However, a sensitivity analysis for it will be also presented.

Table 12: Summary of energy price for Bid Windows between 2011-2015.

	Average tariff ($/MWh)	**Average tariff (€/MWh)**
BW 1 (2011)	140	115.7
BW 2 (2012)	110	90.9
BW 3 (2013)	80	66.1
BW 4 (a) (2014)	50	41.3
BW 4 (b) (2015)	60	49.6

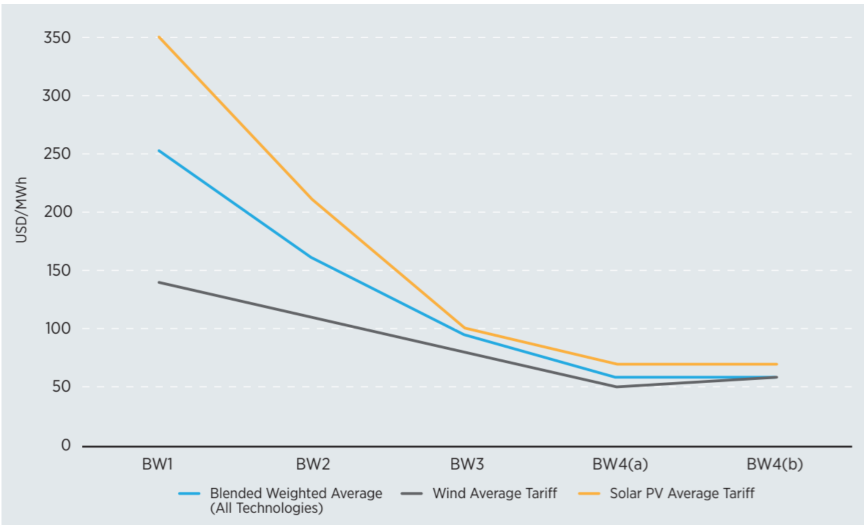


Figure 18: Electricity price for Wind energy (grey) and Solar PV (orange) for Bid Windows during 2011-2015.

3.6 Net Present Value (NPV) and Internal Return Rate (IRR)

Using the above described CAPEX and OPEX, and considering the P_{50} energy yield from Table 9 the annual cash-flow for the project can be computed. Then, considering the 7.4% discount rate the future cash-flows can be actualized and the Net Present Value of the project can be computed (actualized cash-flows minus investments). Further, the Internal Rate of Return (IRR) can be calculated as the rate that yields NPV equal to zero. In Figure 20 a sensitivity analysis plot for electricity price is displayed. The values are displayed as a table in Table 13. It can be seen that the Net Present Value for 0.049 €/kWh is 28.540 millions of euros, but if the electricity price is reduced to 0.04 €/kWh the project will not be profitable any more (NPV negative).

Table 13: NPV and IRR as function of electricity price.

Elec. price (€/kWh)	**NPV (mill €)**	**IRR (%)**
0.03	-33.9	3.20
0.04	-2.0	7.16
0.049	28.5	10.52
0.06	61.7	13.88

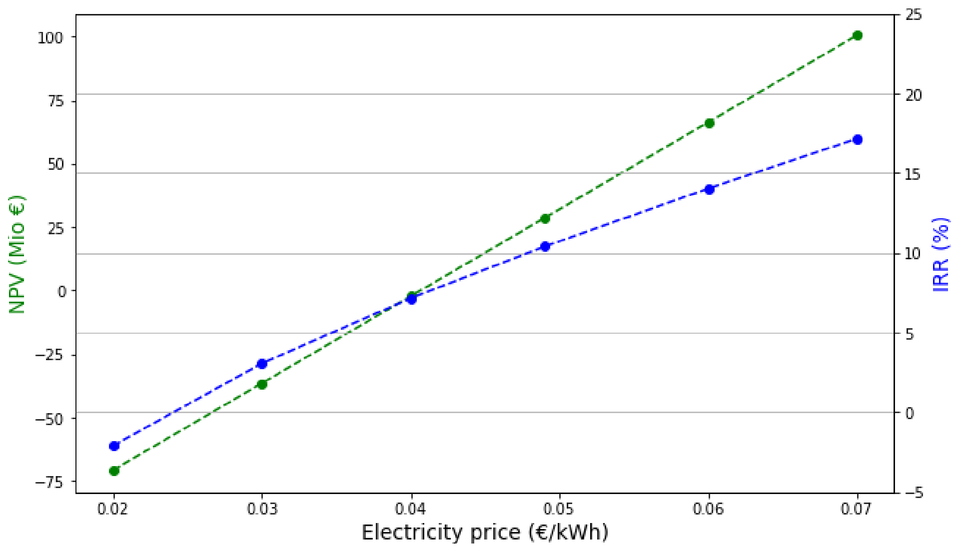


Figure 19: Net Present Value (NPV) and Internal Rate of Return (IRR) for different electricity prices, considering a 7.4% discount rate.

In Figure 20 the net present value is plotted as a function of the discount rate, assuming electricity price of 0.049 €/kWh. According to this plot, the project will have negative NPV if the discount rate is higher than 10.5%.

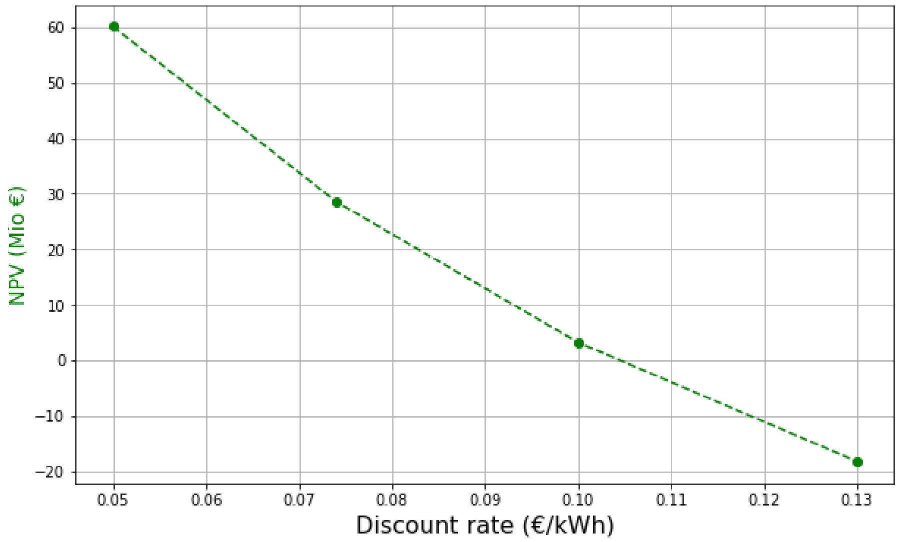


Figure 20: Net Present Value (NPV) for different electricity sale price, considering different discount rates and energy price 0.049 €/kWh.

3.7 Additional economic key figures

Simple payback time One simpler but not less important indicator of a project is the payback time. Knowing the Net Present Value (NPV) is of course necessary, however it does not provide information about the expected time to repay the initial investment.

For this project, considering the P50, the electricity price 0.049 €/kWh and discount rate 0.74 % the simple payback time is 8.4 years, meaning that after this time the initial investment plus the decommission costs are returned.

Simple Cost of energy The cost of energy can be described as the constant price per unit of energy that means the investment is just repaid. The formula used for calculation of CoE is:

$$\mathrm{Simple\,CoE} = \frac{\mathrm{I_0} * \mathrm{repayment\,fraction} + \mathrm{C_{O\&M}}}{\mathrm{AEP}} \tag{1}$$

Considering the repayment fraction as 0.1 (meaning the project would take 10 years to pay the investment back) the cost of energy for this project has a value of 4.162 €c/kWh. In case of a FIT scheme, this value could be compare with the tariff to give a first glance of the economic viability.

4 Environmental Impact Assessment

4.1 Overview and Identification of Critical Environmental issues

All minor and major constructions must conduct an Environmental Impact Assessment before disturbing the possibly delicate environment. Due to page and time constraints, a proper environmental investigation can not be performed for this site, but some of the environmental issues that were identified are presented in Table 14.

Figure 21: The natural parks are within the green areas and possible wind farm locations within the white boundaries, with the yellow pin marking the mast.

4.2 Analysis of Critical EIA Issues

The most critical issues identified in the previous section will be further examined here, and possible mitigation measures discussed in the following one.

4.2.1 Protected Areas

To the southwest and southeast of the mast at the Napier site lie two protected areas, Agulhas National Park and Pearly Beach Nature Reserve, which can be seen in Figure 21. The wind resource assessment lead to a few promising sites, which were later discovered to clash with the parks' borders and thus could not be utilized. After discarding the compromised sites, site 7 offered the best wind resources according to the research done in subsection 2.3 as well as the biggest area suitable for wind turbine placement. The site unfortunately sits right in between the two parts of Agulhas park, and would definitely have some impact on park visitors both via noise and visuals (see Figure 41 and Appendix D). To the west of site is the nature

Table 14: Issues identified during the EIA process. Production, Construction, Operation and Decommission have been abbreviated as P, O, C and D

Project Phase	Issues
P, C, D	**Emission of harmful gases:** Although wind turbines emit very little CO2 during their lifetimes, and the CO2 emitted during production and construction is usually "payed back" within six months [18]. During construction and decommissioning, other harmful gases like carbon monoxide might be emitted by vehicles.
C, O, D	**Noise and dust pollution:** The South African standard SANS10400 dictates the following allotted windows of time for construction: • Before 6 am and after 6 pm any day of the week. • Before 6 am or after 5 pm on a Saturday. • On Sundays or public holidays. Another regulation to look to is the Western Cape Noise Control Regulation. As the site is in a rather rural location it is unlikely to bother any residential areas.
C, D	**Water pollution:** No noticeble rivers or lakes were identified near site 7. Within the Agulhas National Park there are however some wetlands. This should be taken into account and the National Water Act would have to be consulted in the process.
C, O, D	**Disturbance of land/vegetation:** Heavy machinery operated during construction and decommission can lead to destruction of vegetation. See further discussion in subsubsection 4.2.2.
C, O, D	**Disturbance of wildlife:** See subsubsection 4.2.3 for further discussion.
C	**Archaeological impact assessment:** An important concern of an EIA is the possible existence of archaeological materials on site, and thus this must be thoroughly researched.
C, O, D	**Visual pollution:** Although there are no existing laws concerning visual pollution, this factor weighs heavily in the public's eyes and 125 m of steel and fiberglass sticks out in the natural environment.

reserve, which is less likely to be affected (see Figure 39 in Appendix D) but further research would be needed to confirm it. The chosen are for the wind farm has even been declared as a zone viable for expansion of the parks borders, along with a very large part of the southern peninsula (Figure 42 in Appendix D). Interestingly, very close to this site is the Buffeljags abalone farm (red pin in Figure 21), which was been permitted to utilize two Vestas wind turbines for its own production [16].

4.2.2 Indigenous vegetation

The terrestrial vegetation is arguably the most significant component of the biota of the Agulas plain (AP) [23] (see Appendix D for a description of the AP). Its protection is considered vital for the conservation of fynbos in South Africa, which supports much biodiversity. More than 1750 plant species have been recorded from the AP (some being unique to the peninsula) [23]. The proposed turbine site is situated on a Sandstone hill-top covered in Sandstone fynbos vegetation. See Appendix D for a rough map of the vegetation distribution in the AP and a geologic map of the area. A more detailed survey of the existing flora and fauna at the site should be conducted prior to the construction, to prevent habitat destruction of wildlife that resides in fynbos vegetation (mainly rodents and small carnivores [23]).

4.2.3 Birds and bats

A primary concern in terms of the avifauna is the collision of birds and bats with turbines and power lines. The avifauna near the AP is diverse with 230 bird species recorded, including the endangered Cape Vulture and Black harrier [23]. Large flocks of migrating birds are not associated with the area.

Cape Vultures are known to regularly use the air-space within 50 km around their roosts and breeding colonies. Increased flight activity and risk behaviour are along ridge tops, cliffs, steep slopes and wind corridors. These areas are likely to be of high sensitivity [30]. See Figure 32 in Appendix D for the distribution of Cape vultures in South Africa. An isolated breeding population is found nearly 80 km East of the proposed wind farm site.

The Black harrier has a small global population and low genetic diversity, and requires special protection from all human impacts [32]. Several pairs are known to nest in the Overberg region (see Figure 33 in Appendix D). Displaying, migrating and breeding harriers often fly at blade heights and are thus subjected to collision with turbines. Breeding birds can especially be (negatively) affected by disturbance associated with the construction, operation and maintenance of the farm [32].

Local and cumulative regional effects of wind farms on bats in South Africa are not well known. This is due to lack of knowledge about movement patterns and population of most bat species in South Africa [1]. This makes it difficult to directly assess and predict impacts [2]. Bat carcasses have been found near turbine sites [10], including in the western cape region [2]. For recommended site screening measures see Appendix D.

4.3 Neighbours

In order to assess the impact a wind energy farm would have on its neighbours, visual and noise assessments can be conducted. Some of the most important neighbours would be the village of Wolvengat (north of the site), park visitors and any nearby agricultural farms. Due to page constraints, most of the visuals conducted can be found in the Appendix D, where some notable points of view are visualized, as well as one view of the turbines at night time, where their aviation lights are turned on. Figure 22 gives an idea of what the wind farm would look like in real life. No software was used to simulate noise around the farm, but as previously stated the area is rural.

Figure 22: A visualization of the windturbines in layout 3b, south of the location

4.4 Mitigation of Impact

Although obtaining a license for a wind farm on site 7 might be hard due to the close proximity of protected areas, it is not impossible. Thorough research on the impact on birds, vegetation and other wildlife, as well as water usage and archaeological findings should be conducted in the planning phase of the project. When issues arise, the developers should first try and find a solution to the problem, then try to minimize the damage, and finally, compensate for any damage done. Only if the farm has minimal impact should it be constructed at that site.

For example, in order to prevent unnecessary destruction of rare fynbos vegetation specific turbine placements in areas of high vegetational density could be reconsidered with regards to that. If this is not possible, the fynbos cover should be carefully removed and replanted near the site.

As for the avifauna, a detailed screening of the site (see Appendix D) is needed to prevent negative impact. The following mitigational measures are largely based on [30] and [32]. Turbines near the cliff edge should be reconsidered, and preferably moved away from the edge, as the edge is highly sensitive to risky flying behaviour of the Cape Vulture. Free rotation of blades under cut-in wind speeds should also be avoided. The visibility of turbines should be increased by painting one blade red or black, this however leads to increased visual pollution. Turbines should be curtailed at specific times of the breeding season or during migration of the Black harrier. Reduce the attractiveness of the habitat to harriers, effectively by destroying habitat for its prey. This is hard to recommend as any fynbos vegetational cover should be conserved at the site. Power-lines from the wind farm should be planned with known nesting places (of Cape Vulture and Black harrier) and bat colonies in mind.

As a mitigation measure for possible damage to nature, part of the wind farm's profits could be spent on funding research and conservative measures for the Agulhas National Park, effectively paying back and restoring any destruction of vegetation and negative impacts on wildlife that the wind farm might lead to. The construction of turbines does not mean that the land under them cannot become a part of the national park, and the site could even become a small museum for park visitors that want to learn about renewable energy.

4.5 Discussion of Pros and Cons

Despite ample wind resources, there are some disadvantages to the chosen site. To start with, the the site is far away from the high voltage grid (further discussed in subsection 6.4), it's proximity to nature reserves is bound to create a lengthy environmental impact assessment and the view of the turbines might annoy some of the park guests, as is feared with a national park in Scotland where a similar project is being planned [29].

However, South Africa is in dire need of renewable energy [41], and the carbon footprint a wind energy farm leaves on nature is inevitably going to be much smaller than the one of a coal plant with the same capacity [26]. By mitigating most of the wind farm's negative effects, one could argue that in the long term the wind farm aids in conserving nature, as it adds to the small but growing fleet of renewable energy farms South Africa has to offer, decreasing the usage of fossil fuels in the continent. The point of a nature reserve is after all to protect nature, and one way of doing that would be to use cleaner energy.

5 Wind Energy and Societal Context

5.1 South Africa's Power Crisis

South Africa's state-owned utility company Eskom is responsible for generation, transmission and distribution in South Africa. In 2019 their annual report cited a nominal capacity of 44172MW [15] and yet, at the end of that year the South African power grid lacked around 5000MW of generation, causing extensive black-outs due to load shedding in the country. In addition to this Eskom has amassed a large amount debt over the years [41], hindering their ability to meet the market's demand.

5.2 Unemployment in the Overstrand area

The wind farm location is in the municipality of Overstrand, district of Overberg within the Western Cape. Currently, the unemployment rate in Overstrand is at 15.6% and rising. With a population of around 102.000 people, it is the second largest municipal area of Overberg [37].

For offshore wind, the Global Wind Energy Council estimates as many as 17.3 jobs created per MW of wind installed, over a 25 year lifetime [24]. The National Renewable Energy Laboratory in the United states estimates that for a 100MW windfarm, some 60-80 construction site jobs will be created, along with 5-7 O&M jobs [35]. Numbers for onshore wind might be a bit lower, an increase in wind energy production in the surrounding would be a huge boost to Overstrand's economy.

5.3 Major Stakeholders

The stakeholders of the wind farm is everyone that either gains or loses something by its installation. Some of the major stakeholders identified include:

- Owner of the wind farm
- Eskom
- Planning and development team of wind farm
- Landowners
- Investors
- S. Africa, Western Cape, Overberg and Overstrand governments
- Local contractors and work force
- The nature reserves

The wind farm owners, investors and P&D team, will most likely profit from the process in due time, given that everything works out. The risks being that somewhere along the planning and designing phase, the project might get a no-go or that once constructed, the wind farm's yield is lower than anticipated. The local work force will also gain from such a project, as is stated in subsection 5.2 above.

The landowners could sell their land under the turbines or choose to lease it for a certain sum. They could even demand some percentage of the profits from the wind farm. A downside for the landowners could be a decrease in popularity, if the local community is set against the farm. Without any mitigation, there are only a downsides for the nature reserves, they stand to lose some of their attraction, and perhaps visitors, due to the turbines' proximity to the parks. Eskom and the government are working towards a goal of greater sustainability [15] and thus a wind farm would count as a win in their books.

5.4 Social acceptance measures

By involving the local community early on in the planning and design of the wind farm, a more positive perceptive will be gained. A push to more renewable energy will certainly be of interest for the younger generation, which is likely to be ashamed of their nations coal dependency. Interaction with young adults in the vicinity of the wind farm would help to increase its social acceptance. This can be done by including a special youth representative to the planning committee. Another clever way to invoke local commitment is to conduct a design contest for the logo of the wind farm. Further more a strong connection with the education system can maintain a good connection to the local community (benefit sharing). It is also important to reduce the visual impact and affect on wildlife to gain more public acceptance. The ownership of the wind farm can also be a strong influencing factor as community wind farms owned by local community stakeholders (e.g., farmers, landowners, individuals, municipality) often enjoy more trust than commercial developers [25].

6 Wind Farm Design and Planning

6.1 Relevant Legislation

In the last twenty or so years South Africa has been changing and updating their legislation for the country's struggling power grid, trying to incorporate some more renewable energy into the energy mix and driving IPP's to invest in renewables [33]. Some of the legislation relevant for the developing and constructing a wind farm has been compiled into the following list:

- **The South African Grid Code** Contains regulations for for appropriate voltage and frequency levels, allowed deviations form them, to name a minuscule amount of things.
- **National Energy Act 34 of 2008.** This act talks for increased use of renewables for energy prxoduction.
- **Electricity Regulation Act 4 of 2006.** Allows the minister of Energy to help IPP's to increase the supply of electricity and sets up a national regulatory framework for the supply industry.
- **National Energy Regulator Act 40 of 2004.** Dictates that a single regulator is supposed to regulate electricity, piped gas and petroleum industries.
- **Electricity Act 41 of 1987.** The act provides for the continued existence of the Electricity Control Regulator and for control of the generation and supply of electricity.
- **National Environmental Management Act 107 of 1998.** Principles on decision making for matter that affect the environment.
- **EIA Regulations (2014).** Dictates what activities require an EIA

- **Electricity Regulation Amendment Act 28 of 2007.** Makes the National Energy Regulator the head of the national electricity regulatory framework and provides for licenses connected to generation and transmission, for example.
- **Renewable Energy development Zones (REDZ) and Power Corridors.** Identifies zones for renewable energy development (like grid expansion) and streamlines all regulatory processes.
- **The Aviation Act, 1962.** The turbines must abide by aviation regulations. Fore example the farm must be 35 Km from an aerodrome, arranged in linear, clustered or grid-like configurations, painted bright white and have some lighting.
- **The South African Grid Code.**
- **The Grid Connection Code for Renewable Power Plants.**
- **The White Paper on Energy Policy for the Republic of South Africa.**
- **The White Paper on Renewable Energy.**
- **The Integrated Energy Plan.**
- **Reneable Energy Independent Power Producer Procurement Programme (REIPPPP)**
- **Sustainable Energy Strategy for the Western Cape**
- **Western Cape Land Administration Act 6 of 1998.** Regulates land and its usage.
- **Western Cape Planning and Development Act 7 of 1999.** Regulates planning and development within the province.
- **Western Cape Nature Conservation Laws Amendment Act No. 3 of 2000.**
- **Cape Nature and Environmental Conservation Ordinance No. 19 of 1974.**
- **Western Cape Noise Control Regulations 2013.**

6.2 Procedure for Permitting

During the process, some of the more critical permits necessary are:

- Environmental Authorisation (EA)
- South African Civil Aviation Authority Approval
- Section 53: Surface Land Use Approval
- Land Rezoning Approval
- Consent in terms of the Subdivision of Land Act
- Consent in terms of the Electronic Communications Act
- Water Use Licence

Once these permits have been procured, the windfarm would be entered into REIPPPP's bidding program, given that all the permits are actually obtainable and that the bidding window is open. Once the wind farm is in the run, REIPPPP has a two-step process of elimination and it scores each bidder for how well they meet their qualifications. For the first stage, it is determined if the bid is a "Compliant Bid", that is, a bid that both meets the general requirements and prescribed thresholds. For the second stage, all bids are compared based on price (weighted at 70%) and economic development criteria (weighted at 30%). The most qualified projects win the bid [12].

6.3 Wind Farm Electrical Equipment

The following electrical elements will be needed to ensure the wind farm's functionality:

- Wind turbine generators
- 20kV cables for the internal farm grid
- A 20kV/400kV step-up transformer
- Switchgear
- 400kV cables for transmission
- Metering devices

The low voltage (LV) of the wind turbine is usually stepped up to a medium voltage (MV) level within the nacelle and the wind turbines are then interconnected via underground MV cables, either with a radial or ring feeder. Each turbine is equipped with switchgear, so that individual turbines can be shut off for maintenance. The MV cables are then gathered together into the on-site substation, and there the voltage is stepped up to high voltage (HV) for transmission. Figure 23 shows a possible design for the MV cables. Within the substation, both on the MV and HV side, there is more switchgear, used to either switch off one of the MV lines and thus a part of the farm, or the whole windfarm [5]. With fixed speed turbines, there is

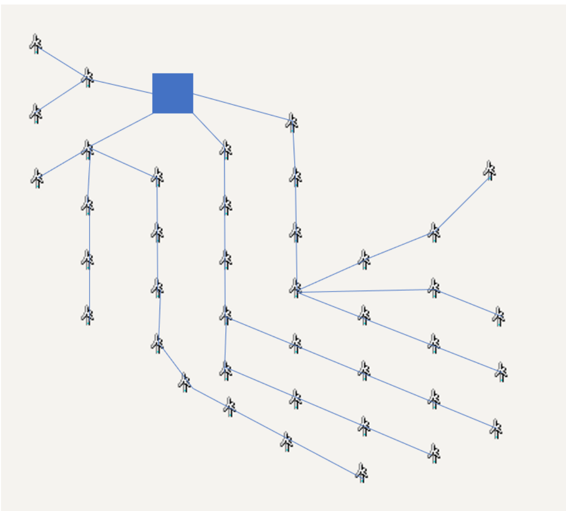


Figure 23: A possible design for a radial cable layout for the windfarm, with the blue square representing the windfarm's substation (3b layout of wind turbines)

usually also a capacitor bank to compensate for the reactive power consumed by the induction generator, but as the Vestas V90-2 MW wind turbine is a variable speed type, those won't be necessary for this wind farm. Metering devices would also have to be installed, in order to closely monitor the production so that protective and preventative action can be taken, as quickly as possible [5]. The cost estimation for the wind farm along with its electrical equipment can be found in section 3.

6.4 Grid Connection

The Western Cape transmission system is generally very well suited for high amounts of wind generation integration [9].The nearest existing point of common coupling (PCC) Eskom has to offer, at he moment, is unfortunately rather far away from the chosen site (Bacchus substation). Thankfully, Eskom has published their plans for 2021-2029 and they include the addition of a new 400 kV substation called Asteria, positioned between the towns of Hermanus and Caledon [31]. The location of Asteria can be seen in the top left corner of Figure 24.

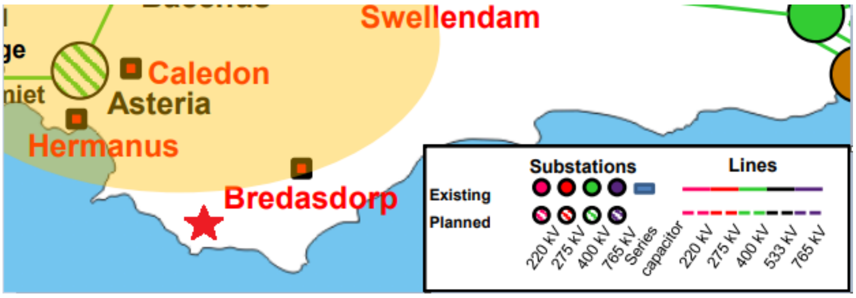


Figure 24: Planned substation of Asteria, windfarm location marked with a red star

The exact position of Asteria is not discussed in the plans, but by estimating a location the distance by road from Wolvengat (wind farm) to Bot River (possible substation) is around 120 km. Despite the considerable distance, adding a HV transmission line to this area could actually be quite logical considering the ample wind resources and the fact that the South African government has named Overberg a fast track area for large scale wind and solar production [7]. An image of the zones can be seen in Appendix D. Thus, despite a 100 km 400 kV overhead line being too large for just this one wind farm, other projects would most definitely benefit from it and might even consider co-funding it.

Another possibility would be for Eskom to finance this important addition to the country's infrastructure, as it would further encourage developers to invest in wind farms or solar energy farms in this area. This could also lead to another development in South Africa's grid, as connecting to the Proteus substation (upper right corner of Figure 24) in the east through the town of Bredasdorp would effectively strengthen the security of supply by closing the circle of HV overhead transmission lines. Of course the wind farm and its operations must adhere to the *South African Grid Code* and the *Grid Connection Code for Renewable Power Plants*.

7 Conclusions

Despite the intriguing possibility of ample wind resources at site 7, there are still many things to consider before launching into the process of developing a wind farm there. For one the horizontal extrapolation by WAsP at the site is not accurate enough due to the distance from the mast and the proximity to the sea. Thus a measurement campaign at the site would be needed. In addition to this, due to the high wind average measured the turbines would need to be of IEC class S.

For the economic analysis, it is remarkable that the project has good economical indicators (without any support or subsidy) and considering the P_{50} (conservative) energy yield. Nevertheless, it is worth mentioning that the feasibility of the project is quite sensitive to the electricity tariff, as the NPV is positive (roughly 28 mill. €) when considering the price of the 49.6 €/MWh (from BW 4b), but it becomes (slightly) negative when the tariff is reduced to 40 €/MWh (which is almost the price for BW 4a in the same year). Finally, the volatility of the South African Rand is also a drawback that was not taken into account in this analysis. As a conclusion, it would make sense to consider a full economic analysis (tax regimes and interest rate) for this project.

Furthermore, the extreme proximity to Agulhas national park and Pearly Beach nature reserve is bound to cause a lengthy EIA and permitting process, as different stakeholders battle out their priorities. The site has even been declared a possible area for a park extension and of course, Overberg has been identified a renewable energy development zone. Grid connection will need to be extensive but it might encourage further development in the area and have greater benefits in the long term. Considering the fact that South Africa is in dire need of additional renewable energy generation some compromises will need to be made.

Contributions

The group split the work amongst themselves as is depicted in Table 15. Authors in the table marked with a star (*) were the chapters main authors.

Table 15: The group's contribution table.

	Contributors		
Chapter 1: WRA	Gonzalo*	Gísli*	
Chapter 2: WFC	Boris*	Gonzalo*	Gísli
Chapter 3: E&F	Gonzalo*		
Chapter 4: EIA	Bergrós*	Boris*	
Chapter 5: SC	Bergrós*	Gísli*	
Chapter 6: P&D	Bergrós*		

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Appendices

A WRA

A.1 Observed Wind Climate

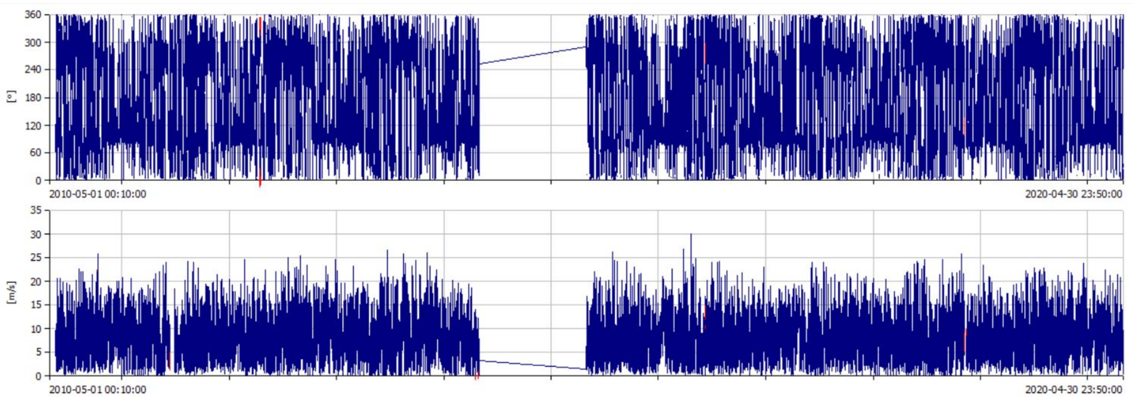

Figure 25: The observed time series of wind speed and direction at WM05 (62 m. a.g.l) used for the wind resource assessment.

A.2 Log-law fit to measurements

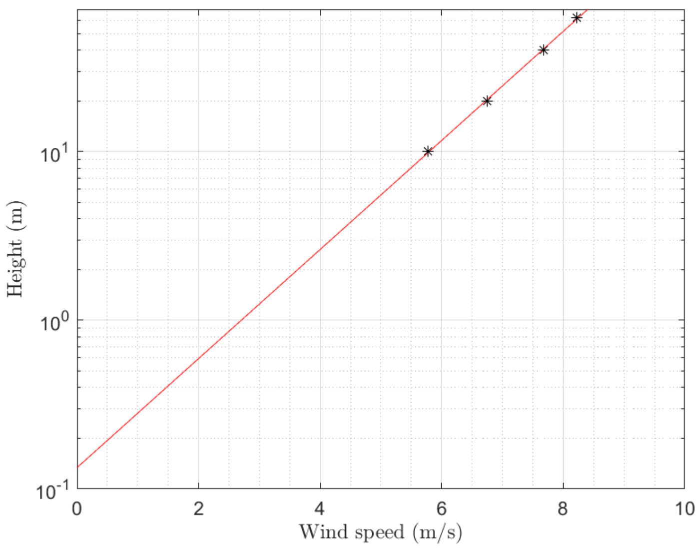

Figure 26: Fit to the wind profile at the mast site (for one measurement year).

A.3 Meteorological measurements

Mean temperature	15.29°C
Altitude temperature (a.s.l.)	347m
Mean pressure	98,376Pa
Altitude pressure (a.s.l)	293m
Mean relative humidity	77.9%

Table 16: GWC parameters from measurements

A.4 Stability Analysis

The stability conditions at the site have been determined based on the Richardson number which represents the ratio between the thermally and mechanically driven turbulence (see e.g. [22]). It also makes it possible to classify the stability conditions by comparing the temperature gradient with the dry adiabatic lapse rate. It is expressed as follows:

$$\mathrm{Ri} = \frac{\mathrm{g}}{\mathrm{T}} \frac{\mathrm{dT/dz} + \Gamma_{\mathrm{d}}}{(\mathrm{dU/dz})^2} \tag{2}$$

where g is the standard gravity, T the temperature measured at 10 m, dT/dz the temperature gradient between 10 m and 60 m, dU/dz the mean wind speed gradient between 10 m and 60 m and Γ_{d} the dry adiabatic lapse rate. The resulting distribution is presented in Figure 27.

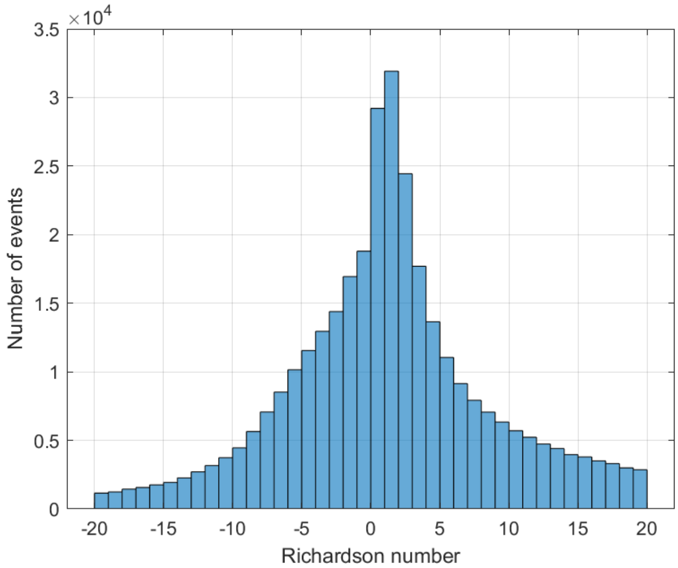

Figure 27: Richardson number distribution at the mast site.

As seen from the distribution, the Richardson number is mostly positive at the measurement site, which corresponds to stable conditions. The weakly stable conditions result in relatively low turbulence intensity, and therefore less fatigue loads associated with turbulence.

In Figure 28, the measured long term (average) wind profile is compared to the WAsP modelled profile at the site (from the generalized wind climate). Anemometers at 40 og 60 m a.g.l. are not used to represent the measured profile due to gaps in the data. As can be seen, the model fits the measurements quite well. This indicates that the roughness map is realistic for the nearby terrain, and that the default RMS and offset values of heat flux over land in WAsP (100 W/m^2 and -40 W/m^2) is representative for the site (near-neutral to weakly stable).

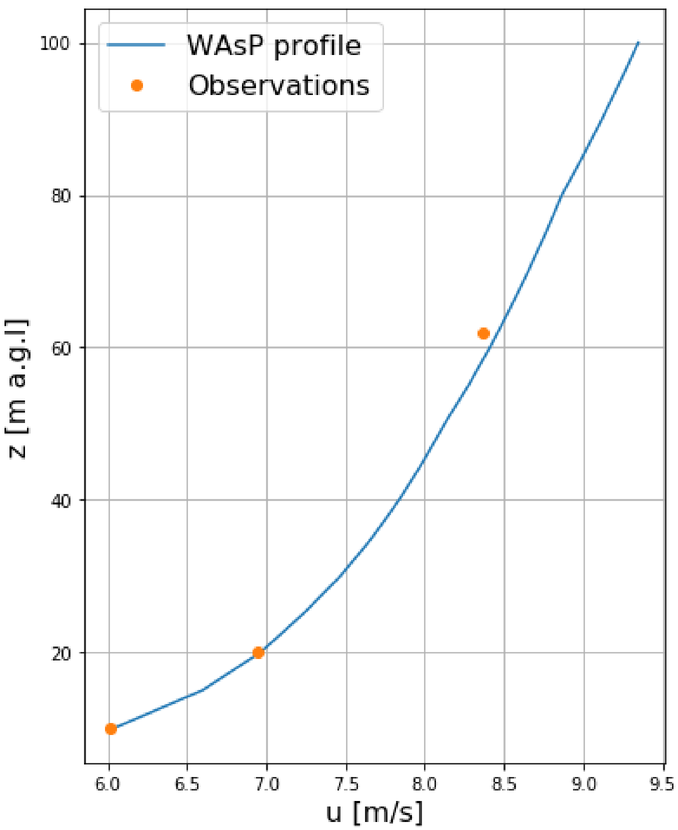

Figure 28: WAsP modeled wind profile (10 min mean) at the measurement site, along with the averaged measured wind speeds at 10, 20 and 62 m a.g.l.

B Sensitivity analysis details

In Table 17 the full results from the WAsP model sensitivity analysis are presented.

Input parameter	Change	ΔAEP (gross) [%]	ΔAEP (net) [%]
U calibration	1%	-1.21	-1.30
Anemometer height	-1%	-0.22	-0.23
Direction offset	+15° // -15°	0.72 // -0.63	0.87//-1.24
Air density	+2%	0.97	1.00
Neutral stability	→ 0 W/m^2	-2.31	-2.32
Background roughness	0.05 → 0.025 m	0.33	0.33
Background roughness	0.05 → 0.10 m	-0.82	-0.85
Heat flux	+20 W/m^2	0.17	0.16
Position of the mast	20 m North	0.09	0.09
Pressure	+1%	0.49	0.50
GWC	→ GWA	-12.18	-12.64
Elevation detail	10 → 20 m	2.4	2.6
Elevation detail	10 → 5 m	0.02	0.04
Geostrophic shear model	→ off	-0.48	-0.50
Hub height	+2 m	0.79	0.83
Posistion of the WF	10 m North	-0.07	-0.08
Atlas height	h→100m	0.32	0.38

Table 17: Sensitivity analysis of the wind resource and wind farm layout

C Cash-flow for project lifetime

Elec. Price>	€/MWh	€/MWh	€/MWh	€/MWh	€/MWh	€/MWh
	20	30	40	49.6	60	70
	AEP (GWh)	DISC RATE (%)	CAPEX	OPEX		
	333.2	0.074	122682569.4	1600000		
year	CASH FLOW	CASH FLOW	CASH FLOW	CASH FLOW	CASH FLOW	CASH FLOW
1	-€ 122,682,569.45	-€ 122,682,569.45	-€ 122,682,569.45	-€ 122,682,569.45	-€ 122,682,569.45	-€ 122,682,569.45
2	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
3	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
4	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
5	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
6	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
7	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
8	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
9	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
10	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
11	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
12	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
13	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
14	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
15	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
16	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
17	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
18	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
19	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
20	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
21	€ 5,064,000.00	€ 8,396,000.00	€ 11,728,000.00	€ 14,926,720.00	€ 18,392,000.00	€ 21,724,000.00
NPV	-€ 65,793,945.90	-€ 33,924,369.58	-€ 2,054,793.26	€ 28,540,000.00	€ 61,684,359.37	€ 93,553,935.69
IRR	-1.76%	3.20%	7.16%	10.52%	13.88%	16.93%

Figure 29: NPV and IRR for different electricity price.

D EIA

Agulhas Plain (AP) is situated on the southwest Cape coast stretching from Gansbaai (34º 35’ S, 19º 21’ E) in the west to Struisbaai (34º 49’ S, 20º 03’ E) in the east. The area is around 72 km in length and extends between 7 and 25 km inland up to the Bredasdorp mountains [23].

D.1 Vegetation and Geology

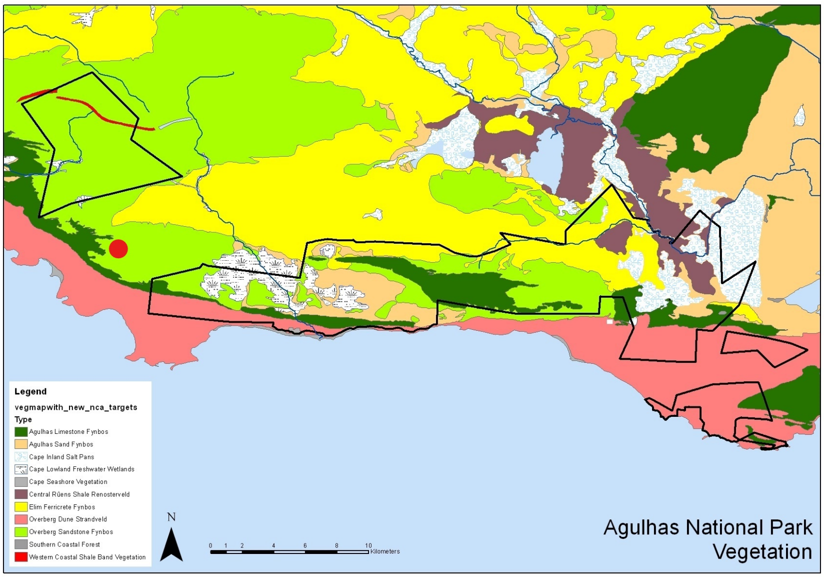

Figure 30: Map of vegetational distribution for Agulhas National Park (and nearby areas) [23]. Proposed WF site indicated with a red dot.

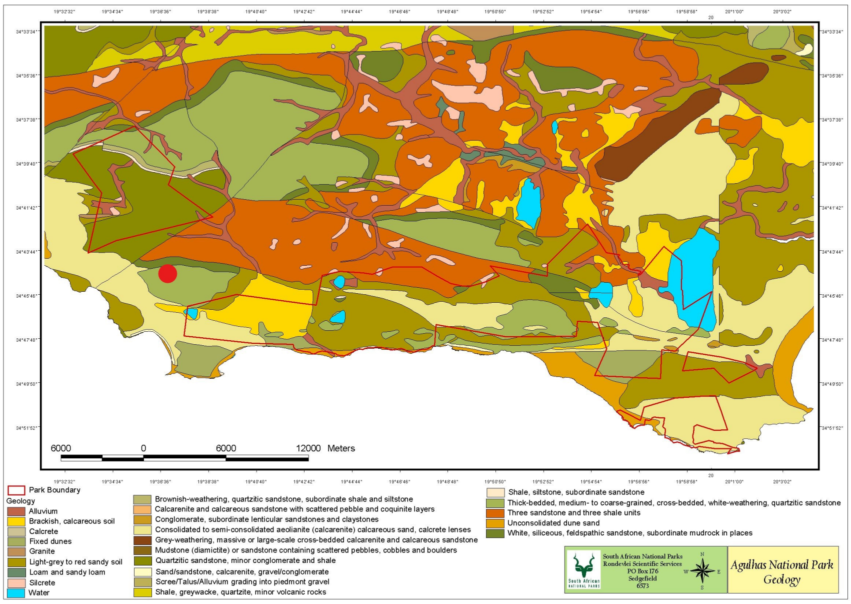

Figure 31: Geological map of the Agulhas National Park [23]. Proposed WF site indicated with a red dot.

D.2 Birds and bats

The following site screening measures are largely based on [30] and [32]. A monitoring program should be conducted in order to observe the numbers of bats and birds affected by the wind farm. Site screening prior to the construction is very important. Negative impacts can be minimised by placing turbines well away from areas regularly used by the Cape Vulture. The location and status of known breeding colonies and roost sites of the Cape Vulture and Black harrier should be confirmed, and the area surrounding the proposed wind farm should be thoroughly surveyed for previously unrecorded breeding and roost sites. A buffer of approximately 50 km around all vulture colonies, and a buffer of approximately 18 km around breeding colonies should be considered as very high sensitivity. The number of operational and potential wind farms within a radius of at least 100 km of the proposed wind farm should be considered, to estimate the potential for cumulative negative impacts. Nearby caves should be mapped and checked for existing bat colonies.

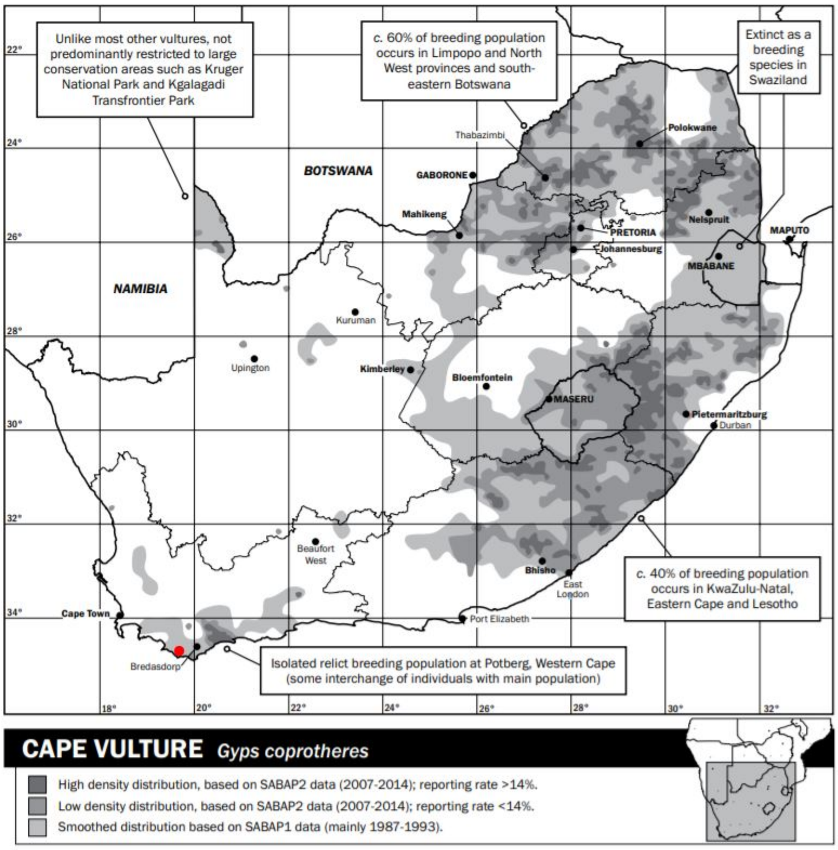

Figure 32: Distribution of the Cape Vulture in South Africa. Taken from [30], data based on the South African Bird Atlas Project [36]. Proposed WF site indicated with a red dot.

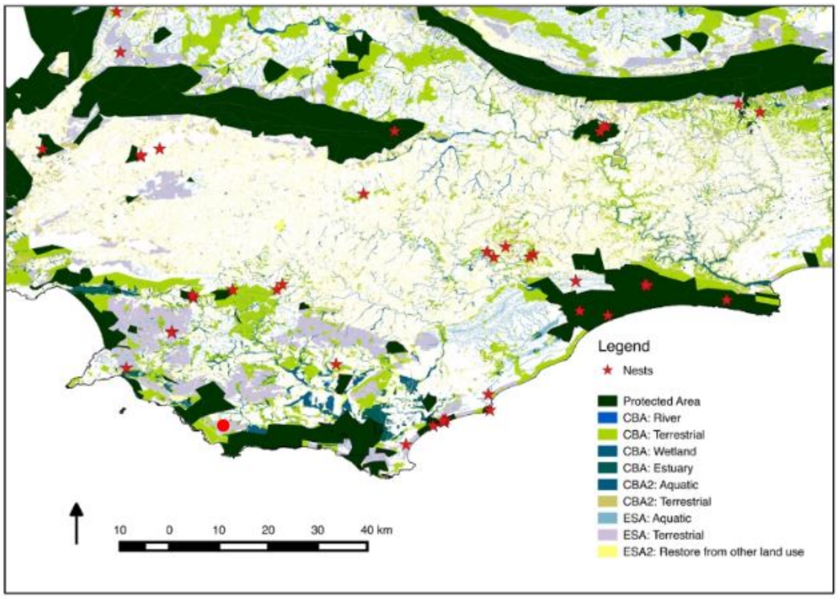

Figure 33: Map of known nest locations (red stars) of the Black harrier in the Overberg region. Taken from [32]. The proposed WF site indicated with a red dot.

D.3 Visuals

The following images are captured using the online tool Windplanner. The points of view were chosen with respect to where the wind turbines could be disturbing residents or park visitors.

Figure 34: Hardly any turbines can be seen in this image due to the tree covers. Height of camera is 2.5m

Figure 35: Within the wester part of Agulhas park the turbines are very visible, however their layout is orderly and pleasing to the eye. Height of camera is 2.5m

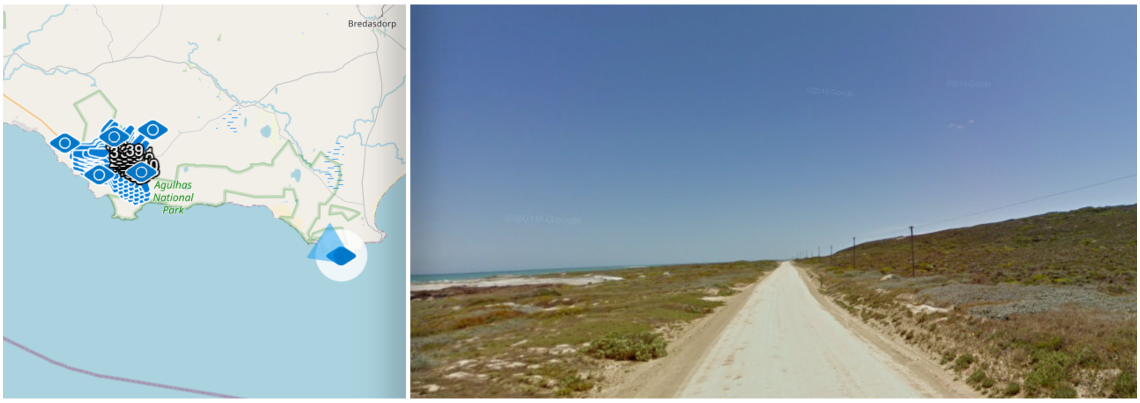

Figure 36: The turbines are most likely not visible at this notable and popular spot, the southern most tip of the African continent. Height of camera is 2.5m

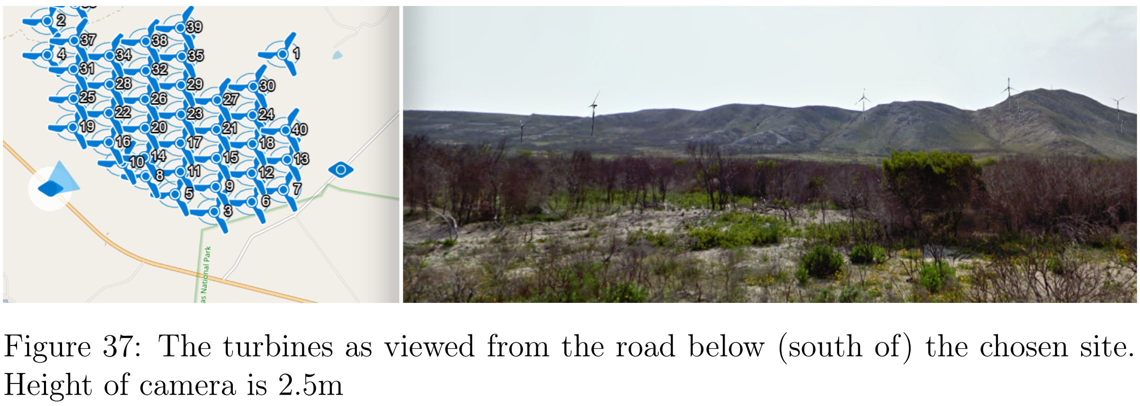

Figure 37: The turbines as viewed from the road below (south of) the chosen site. Height of camera is 2.5m

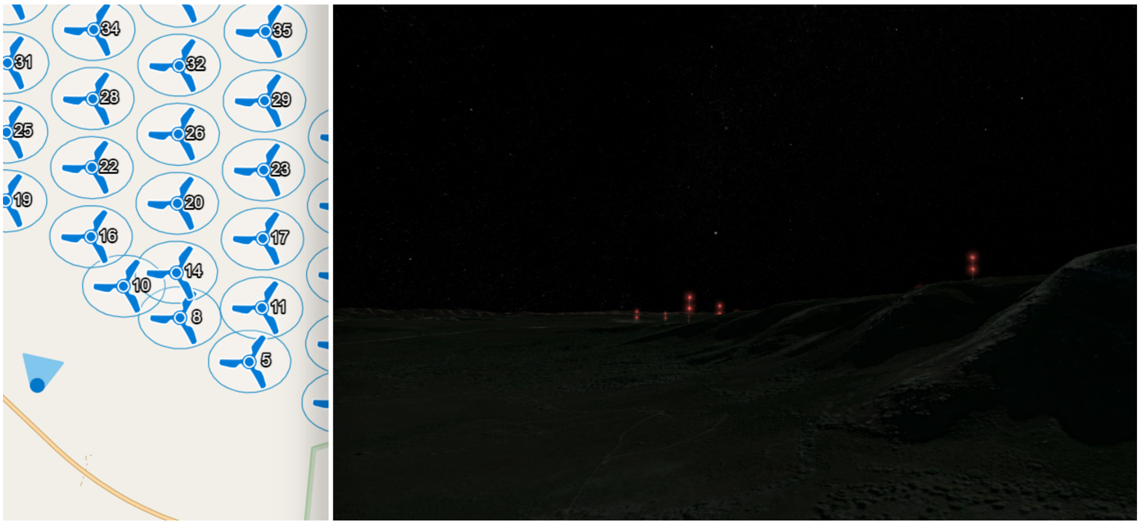

Figure 38: The turbines as viewed at night from south of the chosen site. Camera is 100m above ground level.

Figure 39: The turbines as viewed from the road by Pearly Beach nature reserve, they are just barely visible. Height of camera is 2.5m

Figure 40: The turbines as viewed from inside Agulhas National Park. Height of camera is 2.5m

Figure 41: The view within Wolvengat village. The treeline covers the turbines. Height of camera is 2.5m

D.4 Agulhas Expansion Plans

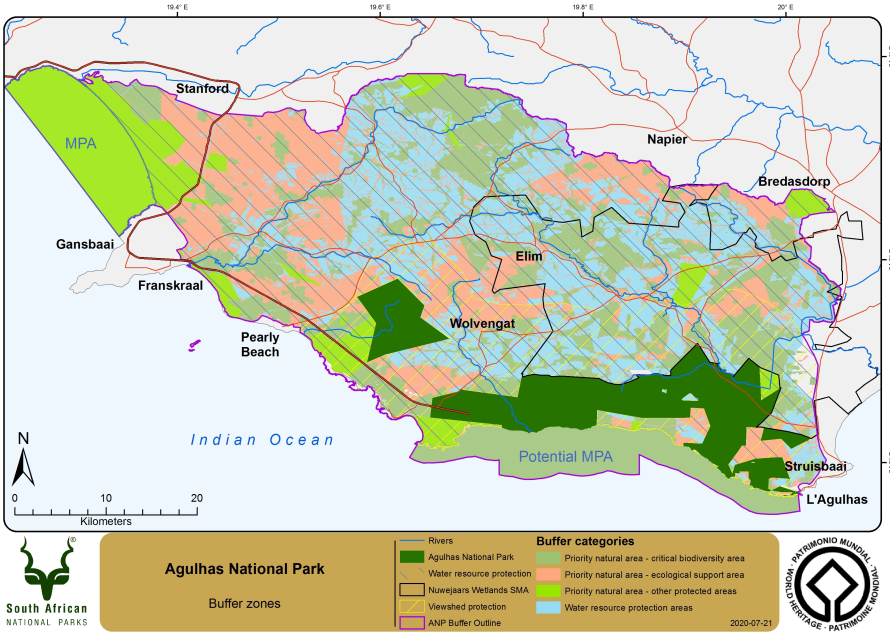

Figure 42: Buffer zones and zones declared interesting for expansion of Agulhas national park.

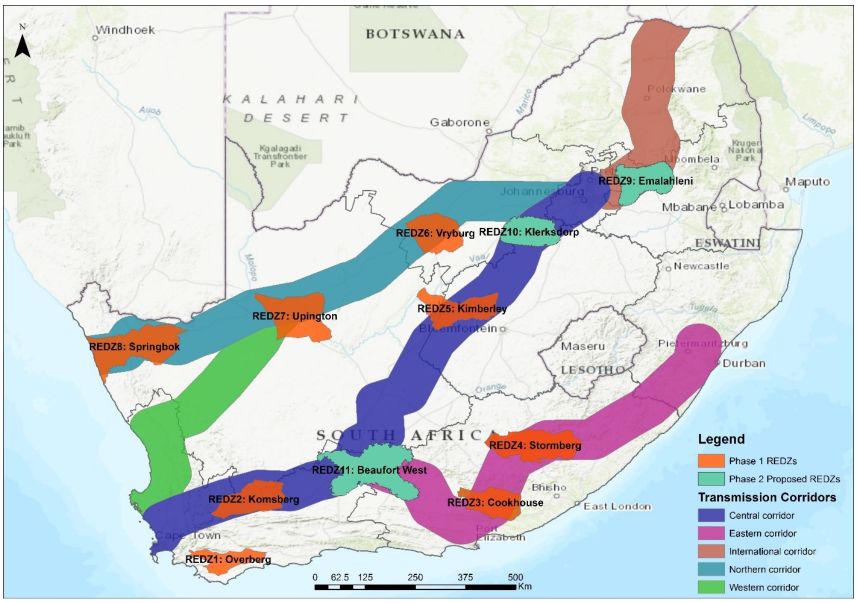

Figure 43: Government defined renewable energy development zones