A case study of climate variability effects on wind resources in South Africa

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Abstract

The wind energy sector is one of the most prominent sectors of the renewable energy industry. However, its dependence on meteorological factors subjects it to climate change. Studies analysing the impact of climate change on wind resources usually only model changes in wind speed. Two elements that have to be calculated in addition to wind speed changes are Annual Energy Production (AEP) and Power Density (PD). This is not only because of the inherent variability between wind speed and wind power generated, but also because of the relative magnitudes of change in energy potentially generated at different areas under varied wind climates. In this study, it was assumed that two separate locations would experience a 10% wind speed increase after McInnes et al. (2010). Given the two locations' different wind speed distributions, a wind speed increase equal in magnitude is not equivalent to similar magnitudes of change in potential energy production in these areas. This paper demonstrates this fact for each of the case studies. It is of general interest to the energy field and is of value since very little literature exists in the Southern African context on climate change- or variability-effects on the (wind) energy sector. Energy output is therefore dependent not only on wind speed, but also wind turbine characteristics. The importance of including wind power curves and wind turbine generator capacity in wind resource analysis is emphasised.

Keywords: wind resource, annual energy production, Calvinia, Alexander Bay

1. Background

1.1 The need for renewable energy in South Africa

South Africa is a signatory to the United Nations Framework Convention on Climate Change (UNFCCC); the country committed to reducing greenhouse gas (GHG) emissions by 42% by 2025 (DEA, 2010). Apart from the climate change question, the necessity for the expansion and tweaking of South Africa's energy resource industry has been marked by the electricity crisis of 2008 (Bayliss, 2008).

The Department of Science and Technology has acknowledged the exigency of utilizing additional resources (Brent & Pretorius, 2011). A target of 3725 MW from renewable resources has been established by the Department of Energy (DoE) (IPP Procurement Programme, 2012). The Renewable Energy Independent Power Producer Procurement Program (REIPPPP) has been created to support this target and to encourage growth of the renewable energy industry in South Africa. In the first round of the REIPPPP, 634 MW of wind power was awarded to eight Preferred Bidders at an average R1.14/kWh, and in the second round, 562.4 MW was awarded by the DoE to seven planned wind farms at R0.89/kWh. The REIPPPP aims to have 1850MW wind power capacity connected to the grid by the end of 2016 (Hagemann, 2013).

The sources of renewable energies are locally available and can contribute to moderating fossil fuel dependency (Balat, 2009). In support of GHG reduction targets wind power requires no fossil fuels to continue operation, does not emit GHGs directly when producing electricity, uses basic materials in construction and transportation, and does not require the circulation of large amounts of water for cooling during the generation process (Kaygusuz, 2009; Diamond, 2011).

1.2 Feasibility of wind energy technology

Securing financial support for wind energy projects is often harder than for conventional power projects. It is therefore imperative to have a thorough knowledge of a country's complete wind resource, as well as access to dependable methods for wind farm siting (Petersen *et al*., 1998). Wind characteristics must be investigated exhaustively at potential sites (Gungor & Eskin, 2008).

One of the most crucial hindrances in the exploitation of global wind power is the lack of steadfast wind resource data. This is vital for government and industry to establish wind power potential (Hammons, 2004). Mitigating this problem will help determine whether wind power is worth consideration as a large-scale contributor to gridded electricity, especially in a country like South Africa, where renewables are primarily restricted to the off-grid sector (Winkler, 2005).

1.3 Climate variability and wind resources

Weather patterns shift yearly between successive decades. Variability is an inherent component of climate which must be taken into consideration when assessing the fiscal viability of wind power (Petersen, *et al*., 1998). If South Africa is to reach its goal of GHG mitigations between 2020 and 2025, then 27% of the electricity supply should be contributed by renewable energy sources, with wind energy contributing a capacity of 14 GW by 2030 (Winkler, 2007 in Edkins, *et al*., 2010).

A number of wind characteristics could change as a result of natural or anthropogenic climate change, of which speed and direction are most commonly modelled. Shifting probabilities of extreme wind speeds have also been evident in some studies (Pryor *et al*., 2005; McInnes *et al*., 2011). In the Southern African region, a number of studies indicate possible changes in circulatory systems or the components impacting them (Rouault *et al*., 2009; Hänsler, 2011; Jury, 2013). For large parts of South Africa (including the Northern Cape and Western Cape), a 10% increase in wind speed can be expected relative to a 1981-2100 control period at 10m above ground level (agl) (McInness *et al*., 2011).

To be able to supply electricity reliably and at affordable rates, one needs to assess wind characteristics and wind energy in detail (Li, 2011 in Ayodele *et al*., 2013), which translates to collecting information on wind distribution and wind power potential in South Africa (Ayodele, *et al*., 2013).

1.4 Considerations in wind resource assessment

The power available from the wind is dependent on cubed wind speed and is proportional to air density:

$$P = \tfrac{1}{2} \cdot \rho \cdot A \cdot \upsilon^3 \qquad (1)$$

where P is electrical power, ρ is air density, A is the surface area of the wind turbine rotor and υ is the wind speed. A number of wind resource assessment studies mention this equation as an indicator of wind energy (Sailor *et al*., 2008; Hocao□lu & Kurban, 2009; Orosa *et al*., 2012). However, this equation only describes the amount of mechanical power in moving air (Hocao□lu & Kurban, 2009), and not the electricity that could be extracted from moving air. In fact, numerous studies that test the effect of climate change on wind energy resources focus solely on wind speed changes, and thus only the total potential available energy in wind (Breslow & Sailor, 2002; Sailor *et al*., 2008; Pereira de Lucena *et al*., 2010; Nolan *et al*., 2011; Pašičko, *et al*., 2012), without taking into consideration other factors important in understanding how much of this potential is really available for transmission as electricity, such as wind turbine capacity factors.

The amount of electricity generated from the potential energy in wind is a function of the wind turbine's power curve (showing wind power generation as a function of wind speed) as well as wind shear or the wind speed distribution, described by Weibull probability distribution functions (pdf) (Pereira de Lucena *et al*., 2010).

When assessing an area's wind resource, one must, therefore, consider the influence of wind turbines themselves on the amount of electrical energy that can be extracted from the kinetic energy available in the wind. Wind turbine generator efficiency and mechanical transmission efficiency, for instance, also play a role in the electrical power output of a particular turbine (Ayodele *et al*., 2012).

Changes in climate could possibly have two main effects on wind power plants: a change in mean wind speed could influence electricity produced as well as the timing and the period for which a plant can operate; and increased maximum wind speeds could affect the safety and reliability of turbines (Pašičko *et al*., 2012). The aim of this study in particular was to determine whether energy production from wind resources can change over time due to climate change itself with the objective of quantifying the AEP and PD using data on two randomly selected locations in South Africa, assuming the 10% wind speed increase mentioned before. The two randomly selected locations represent the two case studies alluded to before.

At this point we should point out that an inherent discrepancy exists between turbine lifespan (±20 years) and climate change projection horizons (±100 years). To reiterate the objective of the study: the effects of climate variability on wind speed and consequently wind energy are tested here. Wind *turbine* characteristics are included in this study purely as a tool to describe energy output from particular wind resources, not to test how a given turbine will perform many years from now.

2. Literature review

A number of studies based on circulation models have found changes in wind speeds over an extended period. In France's Northwest region, for instance, increases of up to 2.6% and decreases of up to 5.8% in its Mediterranean region can be expected between 2046 and 2065 (Najac *et al*., 2011). Nolan *et al*. (2011) assessed the impact of climate change on Ireland's wind resource using a Regional Climate Model (RCM) simulation ensemble for 2021 to 2060. For this study, winter wind speeds were projected to increase by up to 3.5% and summer wind speeds decrease by up to 5%. Pašičko *et al*. (2012) found a significant change in wind speeds during summer in coastal and neighbouring areas of Croatia: an increase of 20% in the mean wind speed is projected for 2011-2040, and more than 50% for 2041-2070. Breslow and Sailor (2002) used General Circulation Models (GCMs) to predict wind speed reductions of 1.0% to 3.2% in the next 40 years; and 1.4% to 4.5% over the next 90 years in the United States. A similar study by Sailor *et al*. (2008) using statistically downscaled output from four GCMs found that summertime wind speeds in the region may decrease by 5–10%, while wintertime wind speeds may decrease by relatively little, or possibly increase slightly in the north-western United States. Pereira de Lucena *et al*. (2010) projected wind speed increases of more than 20% over north-eastern Brazil, and decreases of more than 20% in a smaller part of north-western Brazil in 2071-2100. A paper by Pryor *et al*. (2005) predicts that near-surface wind speeds for 2071-2100 are expected to increase in most parts of northern Europe by 5-10%.

Diamond (2011) discusses how climate change induced wind patterns and turbine productivity could affect financial risk mitigation measures and how these may have to be re-evaluated. She recommends that wind project developers take the effects of climate change into account if wind farms are to remain profitable for their entire lifetimes. If turbines are shut down to avoid damage from extreme winds, less energy is produced from utility-scale wind turbines. She further warns that wind farm developers may have unrealistic expectations of turbine output if they are unaware of future wind patterns.

Similar studies have not been performed for South Africa. The study described by this paper represents the first results of what promises to become an expanded research project.

3. Methodology

In this study, WAsP™ was employed as modelling and simulation tool to combine meteorological data with digital surface roughness and height contour data to determine potential AEP and PD in two regions at specified heights. Similarly, potential AEP and PD under different wind speed conditions were determined after wind speeds were modified based on previous work on wind speed changes according to 19 GCMs (McInnes, *et al*, 2011).

Two locations on the west coast of South Africa within the WASA domain (Figure 1) were selected for analysis in the latest version (11) of WAsP™. Their Weibull pdfs are shown in Figures 2 and 3.Observed wind data collected close to these areas were used in the study to model the current and projected situation regarding energy production

Figure 1: The WASA domain, demarcated by a black line. The two selected sites are located within this region and are indicated by boxes
Source: Adapted from WASA (2012)

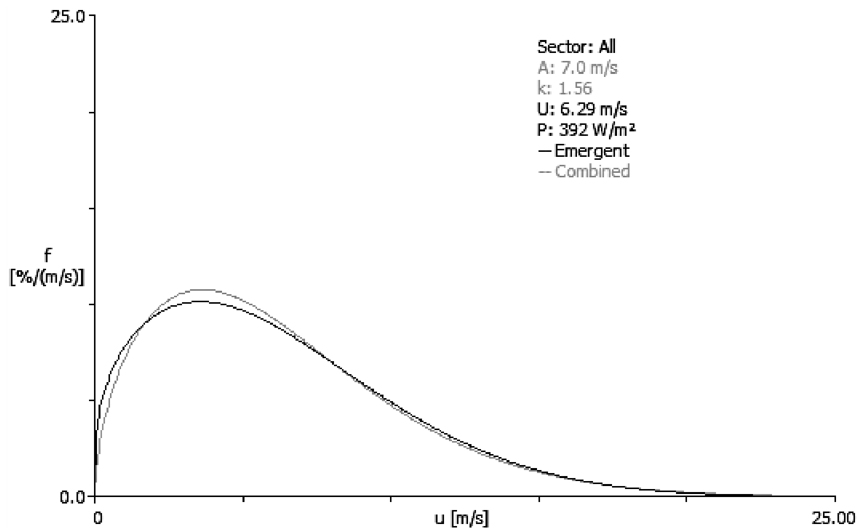

Figure 2: Weibull probability distribution at Alexander Bay (WM01)

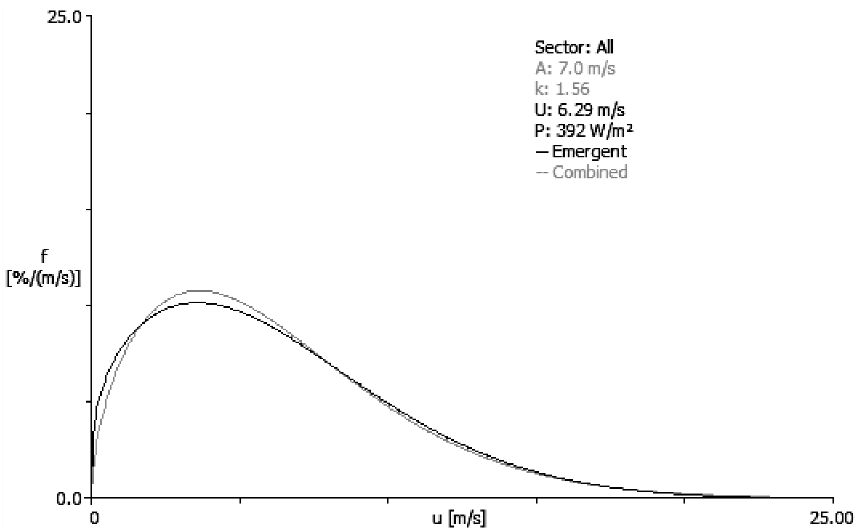

Figure 3: Weibull probability distribution at Calvinia (WM02)

from wind. This part of the method is similar to that of Hocaoglu and Kurban, (2009), where data measured at a site was employed to estimate a wind resource at that exact same site. Projected wind speeds were determined by modifying observed wind data according to projected changes in wind speeds.

3.1 Wind data

The use of raw wind data is preferred in WAsP™, as it allows for the detection of errors in the data which may be indiscernible in data summaries (DTU, 2013). It is also recommended that data of at least one year, with ten minute averages of wind data is selected. Raw wind data was therefore downloaded from the Wind Atlas of South Africa's website for WM01 Alexander Bay and WM02 Calvinia (http://wasadata.csir.co.za/wasa1/WASAData) (CSIR, 2010). 'WM01 Alexander Bay' and 'WM02 Calvinia' refers to the names of the masts from where data was collected, and are located at 28°36'06.7"S, 16°39'51.9"E and 31°31'29.7"S, 19°21'38.7"E respectively. The elevations of WM01 and WM02 are 2m and 543m respectively.

The data employed in the study was collected between October 2010 and September 2012 (at most only two years' worth of data was available at the time that the study took place). To create data files for at least one whole year, the data from subsequent months were concatenated into a single file by importing the data as text files into the starting month's (October) file in MS Excel. Four such files were created – October 2010 to September 2011 and October 2011 to September 2012 files for both Alexander Bay and Calvinia.

In order to make said modifications to the observed data for the future scenario, winds measured at 10m height were employed throughout. Measured wind speeds at 10m were used because projections were only available for this height agl. Wind speeds at 60m were calculated from 10m winds so as to provide measurements at a height that is as close as possible to average wind turbine hub heights, but also at a height comparable to the observed data. The common power law was employed in the calculation of wind speed at 60m:

$$v_H = v_{ref} \bullet (H/H_{ref})^{\mu} \quad (2)$$

where v_H denotes the wind speed (in m/s) at a given height H (in m), v_{ref} is the wind speed (m/s) at a reference height H_{ref} (usually of 10m), and α is the wind shear coefficient (Honrubia, *et al*., 2010) with 1.7 used in this case as the masts are located on fairly flat terrain (Ray, 2006). A wind shear coefficient of 1.7 was used as is often approximated by the European Wind Atlas for open, flat sites (Cavallo, *et al*., 1993). The wind shear coefficient changes with time of day, wind direction and atmospheric stability, and should therefore be kept in mind when interpreting the results.

An increase in 10m wind speeds was assumed based on the work of McInnes, *et al*. (2011). They found that, in the region including the Alexander Bay and Calvinia anemometers, an increase of at least 10% in mean wind speeds at 10m could be expected in 2081-2100 (66% of the data from the GCMs agreed upon the sign of change in wind speed). Dominant wind directions are also predicted to change; this aspect will be addressed in ongoing research. To create the modified/future data sets, 10m winds were increased by 10% and consequently converted to 60m winds using Eq. (2).

To create Observed Wind Climate (.owc) files that are compatible with WAsP, the raw data was processed in WAsP Climate Analyst 2. This process included the creation of a so-called ‘protocol’, for which time stamps and only necessary wind speed and direction data were extracted from the raw data. Observed Wind Climate files were created using data from October 2010 to September 2012, and then exported for use in WAsP™ after the generation report was scrutinised for possible errors in the importation process.

3.2 Orography and roughness data

‘Orography’ refers to terrain height (elevation) variations, such as mountainous areas or smooth hills, whereas ‘roughness’ refers to terrain surface characteristics, such as vegetation, water or buildings (Mortensen *et al*., 2011). Orography is represented by height contour lines, indicating the elevation

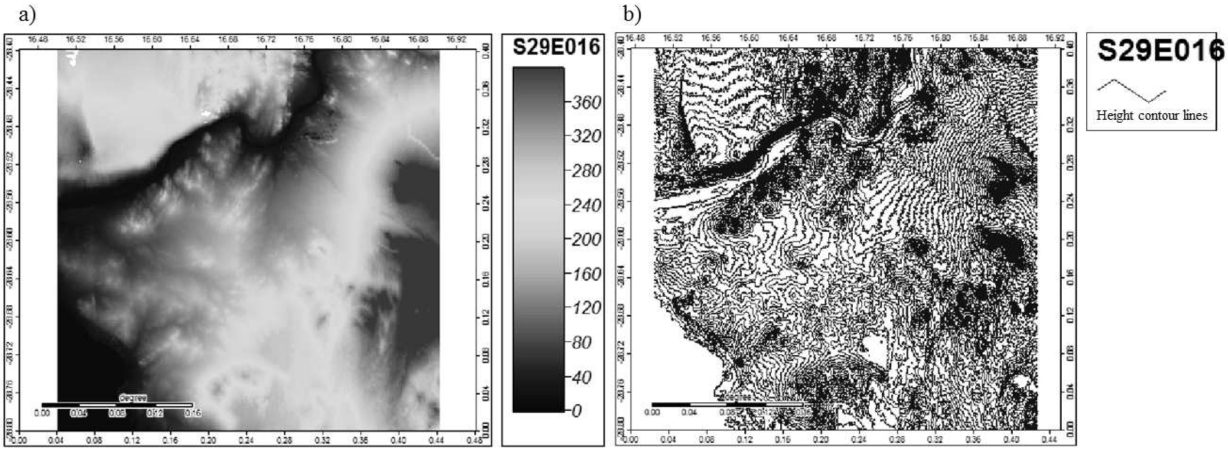

Figure 4: Alexander Bay’s ‘cut’ 0.4º x 0.4º tile in (a) raster- and (b) vector formats

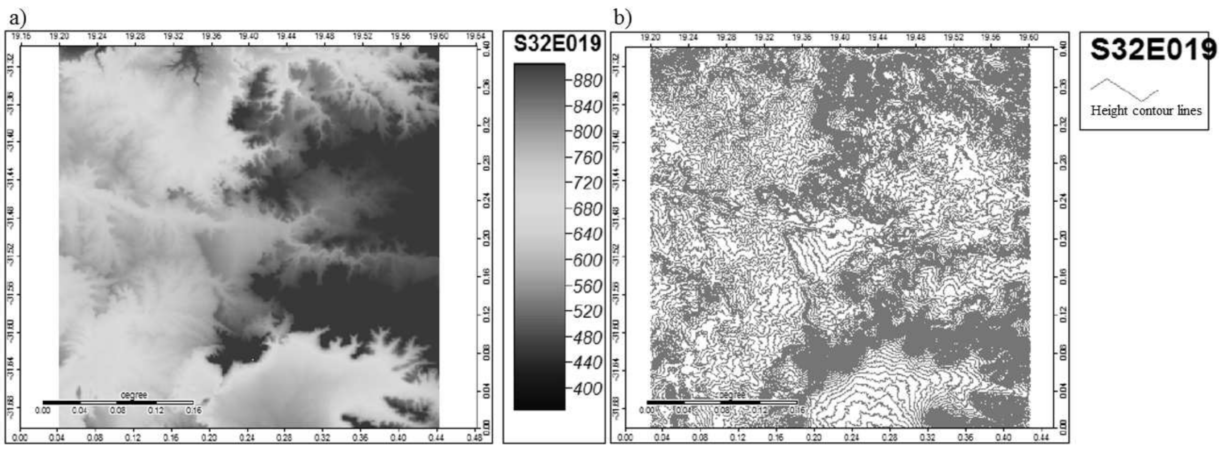

Figure 5: Calvinia’s ‘cut’ 0.4º x 0.4º tile in (a) raster and (b) vector formats

above mean sea level. Elevation data was downloaded as Shuttle Radar Topography Mission data from http://dds.cr.usgs.gov/srtm/version2_1/SRTM3 /Africa/. These files are provided as 1° x 1° tiles of digital elevation models (DEMs) and are therefore in raster format (see Figure 4,5 (a)).

Tiles including Alexander Bay and Calvinia were processed in the SAGA (System for Automated Geo-scientific Analyses) GIS. Firstly, the tiles were 'cut' into smaller areas of ± 0.4° x 0.4° (Figure 4, 5 (a)). They were then converted to vector format (Figure. 4, 5 (b)) for use in WAsP Map Editor 10.

Using WAsP™ 11, the area was then located in Google Earth (GE). GE-images could then be used as background images for the demarcation of areas of different land cover (roughness). The areas of different land cover were demarcated as polygons, and internal and external roughness lengths were specified for each polygon (WASA, 2012). After checking and correcting for errors (cross-points of lines, for instance), the map could be exported for use in WAsP. Hence, a single map contained both elevation and roughness data.

3.3 Wind turbine generator files

Wind turbine generator files were downloaded from WAsP's Power curve download site (WAsP, 2012). The files provide information on wind turbine generator performance for particular makes and capacities of wind turbines, such as the amount of power generated at certain wind speeds (Figure. 6). In this study, a Vestas V90 2 MW turbine was selected as a typical wind turbine representation. This turbine is a popular choice among wind project developers worldwide – Vestas shares the largest global market share of wind turbine manufacturers with General Electric (Bloomberg New Energy Finance, 2013).

3.4 Modelling the wind resource

The elevation/roughness map, observed wind climate file and wind turbine generator file could then be combined in WAsP™ 11 to calculate AEP and PD for a particular resource grid. The resource grid includes the complete area to be assessed.

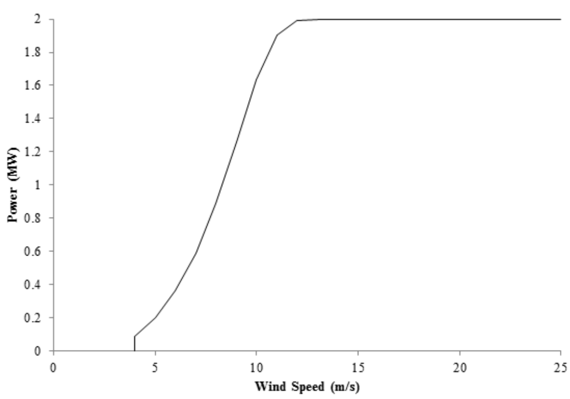

Figure 6: Power curve for Vestas V90 2 MW wind turbine
Source: Adapted from WAsP (2012)

4. Results

Table 1 shows the overall AEP and PD of the two locations under current and projected conditions, as produced by WAsP™. Relative changes in the two variables are also indicated.

Note that relative changes in AEP differ for the two locations assessed, a constant 10% wind speed increase notwithstanding. Such a difference can be explained by considering the relative wind speed distribution functions of the two locations. Calvinia provides a generally weaker wind resource than Alexander Bay, but can expect a more dramatic increase in AEP even if a similar wind speed increase is projected.

Table 1: AEP and PD in Calvinia and Alexander Bay

		AEP (GWh)	*PD (W/m²)*
Calvinia	Reference	4.670	234
	Future	5.644	306
	Change	+17%	+24%
Alexander Bay	Reference	5.563	392
	Future	6.381	518
	Change	+13%	+24%

5. Discussion

In this study, AEP and PD were modelled at 60m heights based on wind speed increases. These indicators take more factors into account than traditional studies that only provide indications of wind speed changes. Electrical power output is given as follows:

$$P_e = \tfrac{1}{2}\rho A C_p \eta_m \eta_g v^3 \quad (3)$$

where ρ, A and v are the same as in Eq. (1), C_p is the coefficient of performance of the turbine (of which the maximum value is the Betz limit: 0.59), η_m is the mechanical transmission efficiency and η_g is the generator efficiency. Figure 7 demonstrates the importance of calculating P_e for wind resource assessment rather than using only the power available in wind as an indicator thereof. It has been observed that considerable variability exists between wind speed and wind power (Sánchez, 2006) and it is therefore important to bear this type of uncertainty in mind when interpreting the results of wind speed projections in the wind energy industry (Jeon & Taylor, 2012).

The overall AEP and PD are projected to increase by 17% and 24% in Calvinia respectively; and by 13% and 24% in Alexander Bay. The different magnitudes of change are related to the manner in which electricity is generated by wind turbines:

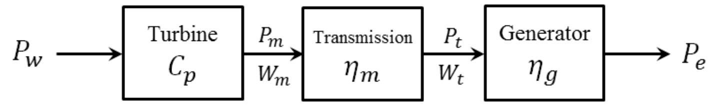

Figure 7: Wind power conversion process
Source: Ayodele et al. (2012)

there's not a linear relationship between wind speed and power generated (Figure 6). The two locations have different wind speed distributions (Figures 2, 3), translating to different output by the same turbine.

6. Conclusion

Climate change is projected to have a substantial effect on wind speeds globally. Furthermore, the geographic distribution and variability of wind resources may shift as a result of variability in climate (Pryor & Barthelmie, 2010). The wind resources of a region is mainly dependent on wind speed and therefore the amount of energy available in the wind, as well as local features of the area in which a particular turbine is located (orography, surface cover, obstacles etc.) (Honrubia *et al.*, 2010). The wind resource should be determined on a small scale in order to avoid incorrect placement of wind turbines, and the possibility of changing weather patterns should also be taken into account when planning wind farm projects. This is especially important for a long-term view on correct wind farm positioning.

WAsP™ was employed in this study to model the effect of possible changes in wind speed on AEP and PD. Only wind speed was modified, although in reality, if climates are to change, a number of other factors may also be affected (this is the topic of on-going research), consequently impacting on electricity output from individual wind turbines and/or wind farms as well. These factors include air density, heat fluxes and wind direction (Orosa, *et al.*, 2012). Little projection data is available on these variables, which were therefore kept constant during the study. An increase of 10% in all wind speeds is applied to observed data from October 2010 to September 2012 to represent the modification of wind speed. This implies an alteration in the amount of energy available in the wind (Breslow & Sailor, 2002).

Studies analysing the impact of climate change on wind resources usually only model changes in wind speed. This study took it a step further by determining how different wind speeds affect AEP and PD. It provides a more accurate description of how altered wind speeds could affect that which will be most important when determining a project's feasibility: the electrical energy output. Determining the AEP in WAsP takes into consideration the power curve of whichever turbine(s) occur in the resource grid (area assessed).

WAsP™ models AEP and PD based on the mentioned models as well as wind turbine generator files including power curves. The objectives of quantifying the relative changes in AEP and PD in two locations were met. The results emphasise that a number of factors (such as wind turbine generator efficiency and mechanical transmission efficiency) play an important role in the generation of electricity from wind. To get a more complete picture of wind resources, one must test the feasibility of wind projects by considering more variables than only wind speed. Past studies have found significant discrepancies in the relationship between wind speed and wind power (Sánchez, 2006); this type of uncertainty must be borne in mind when drawing conclusions from wind speed projections.

The work carried out in this study is a *preliminary* look at possible effects of changes in climate behaviour on electricity generation. In future it can be significantly expanded to include larger geographical areas of the country. Analyses of wind velocity distribution and/or wind shear may be included in future work as opposed to only wind power generation potential as a function of wind *speed*. Such expansion is required before the results of a study such as this one can be used to generalise for the entire country/region. Nevertheless, its value lies in quantifying some of the increases in wind energy resources that could potentially be encountered. It should therefore serve as motivation for further investigation into energy sector diversification and expansion into areas without grid supply.

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