USE OF A GIS TOOL FOR THE ASSESSMENT OF WIND POTENTIAL AND LOCATION OF WIND FARMS: ADJUSTMENTS TO DEMAND PROFILES

by

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To my lovely family who awaits back home

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Use of a GIS tool for the assessment of wind potential and location of wind farms: Adjustments to demand profiles

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The threatening impacts of climate change are driving a global revolution towards cleaner sources of energy. In South Africa, strategies for energy security and emissions reduction are focusing on renewables, wind energy being one of the most promising ones.

The construction of wind energy projects has attached limitations in the identification of suitable areas that respect the environment and are technically feasible. Herein, site selection criteria has been grouped into the *Site Identification* group (SIG), and the *Resource & Energy Generation* group (R&E). The SIG incorporates technical, environmental and restricted criteria within a spatial frame; while R&E accounts for the wind resource, estimated energy generation and fitting to energy demand profiles under a spatial-temporal frame.

The average wind resource is usually found to be analysed together within the technical factors to determine the feasibility of a site; however for this study, a different and independent treatment of the wind resource and its energy generation profile was undertaken. It consists of evaluating the unique hourly wind power profile of each site against the energy consumption profile for the same period.

The need is for selecting places with the smallest variation between the electricity produced and the electricity demanded. The Production to Demand Difference (PDD) has been chosen as the indicator of such variations. Therefore, the new purpose is to identify spots where the combination of the PDD and the results from the SIG become smaller with time. The Mean Difference (MD) is also taken into account to obtain further information regarding the trends of the differences. Geoprocessing, overlays and mathematical combinations of datasets are all performed under a GIS environment.

Key words: GIS, wind farm location, wind energy potential, electricity demand.

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List of Acronyms

CO_2	Carbon Dioxide
COP 15	Congress of Parties 15
DOE	Department of Energy
EIA	Environmental Impact Assessment
GHG	Greenhouse gas
GIS	Geographic Information System
GTZ	German Technical Corporation
IPP	Independent Power Producers
ISMO	Independent System and Market Operator
MW	Mega Watt
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
RE	Renewable Energy
REFIT	Renewable Energy Fed-in-tariff
REIPPP	Renewable Energy Independent Power Producer Procurement Program
SAMBI	South African National Biodiversity Institute
SAWEA	South African Wind Energy Association
SAWEP	South Africa Wind Energy Programme
SAWS	South African Weather Services
SEA	Strategic Environmental Assessment
SEF	Strategic Environmental Framework
SRTM	Shuttle Radar Topography Mission
TAPM	The Air Pollution Model
TWh	Tera Watt hour
UNEP	United Nations Environment Program
UNFCCC	United Nations FCCC
WASA	Wind Atlas South Africa
WTG	Wind Turbine Generator
WWEA	World Wind Energy Association

1. INTRODUCTION

This chapter presents the drivers and the justification for undertaking this study. It highlights the influence of global and local situations for the introduction of renewable sources of energy such as wind within the electricity mix. It describes the objectives pursued with the dissertation and an overview of the contents of the document.

1.1. BACKGROUND

Climate change has become a threat to our specie. Its implications are negatively affecting global biodiversity, human health, food and water security, and even threatening our culture.

It has been argued that variations on the global climate are normal, natural changes of the Earth System; however, the human contribution to such variations cannot be denied. The concentration of carbon dioxide in the atmosphere has exponentially increased since late 1700's; the age of the industrial revolution, that also brought intense energy requirements supplied now mostly by the endless burning of fossil fuels (NRC, 2010).

According to the United Nations Environment Program (UNEP) anthropogenic carbon dioxide emissions have increased four times faster, since 2000, than in the previous decade. Most of the emissions come from burning of fossil fuels and manufacturing of cement (UNEP, 2009) Current strategies for facing climate change focuses mainly towards the reduction of greenhouse gas (GHG) emissions. In South Africa, where 93% of the electricity is produced in coal-fired power stations (Eskom, 2009), the strategies for energy security and emissions reduction focus on shifting to renewable energies (DME, 2007). Renewables may allow the country to accomplish its commitment to the CO_2 reductions under the Copenhagen

Accord, while assuring energy supply that supports the economic growth of the nation during the following years.

During the Congress of Parties 15 (COP15) session in Copenhagen 2009, South Africa committed itself to reduce its GHG emissions by 34% by 2020, and by 42% by 2025 of the Business as Usual (BAU) scenario (UNFCCC, 2010). This commitment has been reinforced by the Revised White Paper on Renewable Energy Policy (DOE, 2011) where the national government has stated the goal of having at least 27% of the national energy demand in 2030 supplied by renewable sources.

Besides the environmental concerns, South Africa faces a threat associated with energy security. Although most of the national energy supply comes from coal (approx. 70%), 19% is supplied mainly from imported oil refined locally (EIA, 2013). Having a fossil fuel dependent economy, makes the country very sensitive to foreign policies such as the price of crude or the depletion of fuel reserves after reaching the peak of oil production.

Geographic conditions give South Africa very good potential for the development of renewable energies. The World Wide Fund for Nature (WWF), in an optimistic note, affirms that it is feasible to generate 50% of South Africa's electricity from renewable resources by 2030 (WWF, 2011). Of these renewable sources Wind Energy is one of the most promising ones. According to the South African Wind Energy Association (SAWEA), under the right policy framework, wind energy could provide 20% of the country's electricity generation by 2025, about 30,000MW of installed capacity (SAWEA, 2010).

The introduction of wind energy to the grid poses some extra challenges compared to traditional coal fired power stations. Wind power is not as easily dispatched compared to coal-fired turbine generators or hydroelectric power generation, and the performance of the wind energy depends on the availability of wind, irrespective of whether the electricity demand exists or not (Chaudhry & Hughes, 2012). Such an intermittent characteristic is what brings technical and economic concerns to large scale wind projects (Albadi & El-Saadany, 2010; Mel & Rangan, 2011; Tarroja, et al., 2011).

Variability of the wind is indeed a key concern when evaluating introduction of wind energy; however it does not necessarily have to make the grid unmanageable. The following are proposed options for mitigating the variability inherent to wind generated energy (Milborrow, 2009):

- Improved methods for wind prediction,
- management of the demand,
- use of smart grids and super-grids,
- pumped storage,
- inter-connection of renewable energy sources and generation connections, and
- geographic diversification.

The increase in the number of large scale wind energy projects also brings space constraint limitations in the identification of good areas for development that must respect protected areas, water bodies, etc. making the site selection a complex search (Grassi, et al., 2012). Site selection methodologies capable of dealing with the variability of the wind power output, will bring a competitive advantage for wind developers. Such an approach may further promote the optimal management of the electricity system, and facilitate the integration with other energy sources.

1.2. PROBLEM STATEMENT

Is it possible to identify areas for the development of large scale wind energy projects that reduce the impact of variable output on the electrical grid system through the generation of energy profiles that correspond better to the demand variations?

1.3. PURPOSE OF THE DISSERTATION

The development of a methodology for the determination of technically feasible areas for the advancement of wind energy projects that allow the mitigation of the impact in the energy system by the use of the diverging wind profiles across a region and the energy demand profile.

1.4. DOCUMENT OVERVIEW

This first chapter describes the motives that initiated this study. It describes the local and international drivers for the inclusion of wind energy within the national electricity mix and the challenges in terms of site selection and variable output that it represents.

Chapter 2 presents an outline to the basis of wind energy and wind energy production. It also gives a perspective of the growth of wind energy in the world, and the local panorama for South Africa, including policy and legislation that promote and rule its implementation. The challenges that wind energy brings in being a variable source of energy are also discussed.

Chapter 3 is an overview of the international best practices for site selection and the approaches followed in the South African context. A desktop review of site selection methodologies is presented and concludes with a complete list of variables and their justification to be included in macro-siting of wind farms.

Chapter 4 describes in full the methodology proposed for the assessment of environmental and technical feasible candidate sites for wind farming, and the sources of information. It also presents the methods for verification and evaluation of results from wind and energy estimation.

Chapter 5, through a case study, gives a clearer understanding of the described method in Chapter 4. It presents step by step the results obtained and runs a scenario evaluation to demonstrate flexibility and response of the tool.

Finally, the results are presented and the factors that have a strong effect on the model output are identified. A discussion regarding advantages and shortcomings of the methodology is undertaken together with some suggestions for further implementation.

2. WIND, WIND ENERGY AND SOUTH AFRICAN STATUS

This chapter presents an overview of the technical concepts related to wind energy production, its history and worldwide panorama. It describes the evolution of the integration of wind energy in the South African energy mix, the current situation of the wind projects in the country, and the policies and legislation in place to address its inclusion. A further discussion is undertaken about the intrinsic challenges of this variable source of energy, and the strategies for continuous balancing out of the supply and demand.

2.1. The Wind Characteristics and Wind Energy

Air density is inversely proportional to temperature. As a result of the increase in temperature at the equatorial regions, the air becomes lighter and spreads along the globe attracting cooler air from the poles to the equator, to be warmed again. Air flows from high pressure regions to low pressure ones; this pressure gradient along with the Coriolis Effect are the origins of wind cells. Wind cells together with buoyancy, friction forces and the variations in terrain produce what we know as wind. Figure 1 depicts a description of the global winds systems.

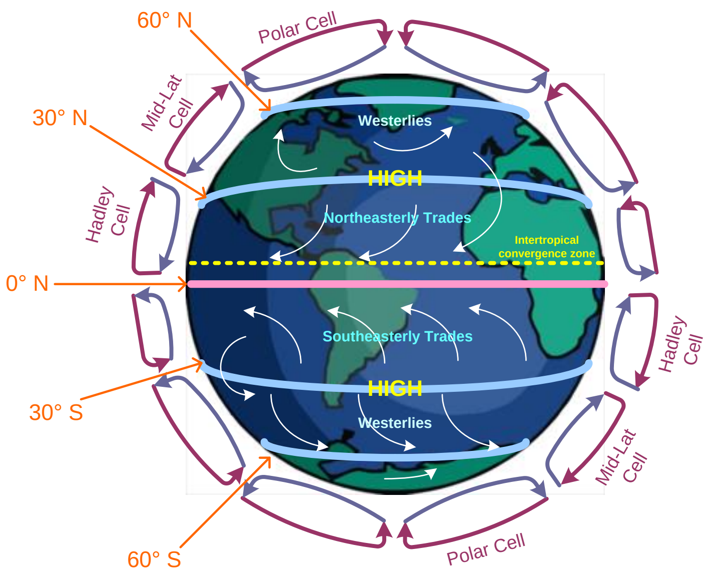


Figure 1: Representation of global wind systems (after sealevel.jpl.nasa.gov, globe image from www.clker.com)

Wind has associated kinetic energy which can be extracted and converted into electricity with the help of wind turbines. The flow of the wind over the blades causes lift, which results in rotation. The motion of the blades passes energy to an electricity generator through a gear box. The resulting electricity is routed to a transformer and subsequently to the grid network

The potential for energy depends mainly on the wind speed, as it can be inferred from the wind power equation below:

$$P = \frac{1}{2}\rho v^3 A$$ **Equation 1**

Where P represents power potential available in the wind, usually given in watts; ρ indicates the air density (kg/m^3), v the wind speed (ms^{-1}) and A the cross-sectional area swept by the blades of the turbine (m^2). However this is only a theoretical maximum; there are multiple inefficiencies along the energy generation process that should be taken into account and will be discussed later.

For now, it is important to keep in mind that the assessment of the wind resource includes the evaluation of the wind speed, wind speed distribution and power density. The average wind speed gives an indication of the feasibility of the site for wind farm locations. Usually the cut-in wind speed to activate energy production in a turbine is set above 3-4.5 ms^{-1} (Mostafaeipour, et al., 2011).

It is also worth mentioning that wind speed is affected by the height and the roughness of the terrain (height of vegetation or buildings) by a logarithmic relationship as seen in Figure 2 and demonstrated in the Equation 2 below:

$$\frac{v_{(Z)}}{v_{(Z_r)}} = \frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_r}{Z_0}\right)}$$ **Equation 2**

Where $v_{(z)}$ is the wind speed at height Z, $v_{(Z_r)}$ is the reference wind speed at reference height (Z_r), and (Z_0) represents the surface roughness length.

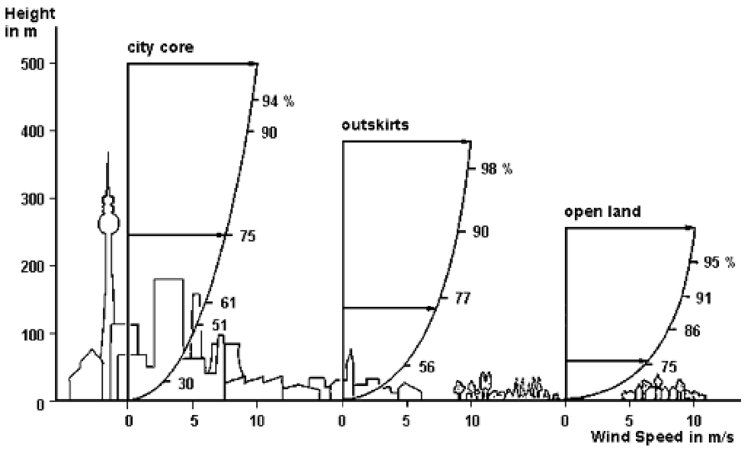


Figure 2: Changes in wind speed as influenced by height and roughness of the terrain (according to Baumbach, 1991)

The wind speed distribution is a statistical analysis used to determine the wind energy potential of any given site, and hence, the technical and economic feasibility of a project can be easily derived. According to Gumbel (1958), the Weibull distribution is the one that best represents the wind regime within an acceptable accuracy level. The probability density function for wind speed $f_{(v)}$ is given by Equation 3 below:

$$f_{(v)} = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{\left[-\left(\frac{v}{c}\right)^{k}\right]} \quad ,\{k > 0, v > 0, c > 1\}$$ **Equation 3**

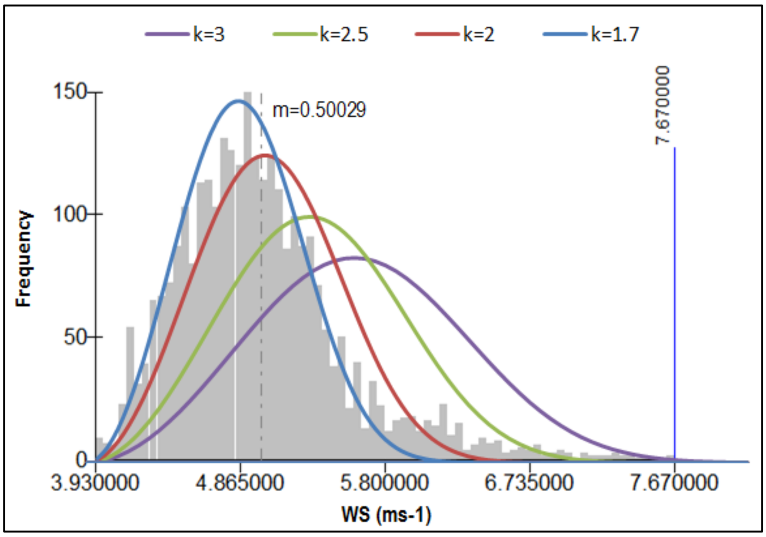


Figure 3: Weibull density function with various shape factor (*k*), and mean wind speed = 5 ms^{-1}

Where k and c are parameters that modify the shape of the distribution. k is known as the shape parameter (dimensionless) which indicates how peaked the distribution is, and c (ms^{-1}) is the scale parameter which indicates how "windy" the location under consideration is.

The Wind Power Density is obtained from the quotient of the wind power (from Equation 1) and the blade sweep area (see Equation 4). It indicates how much energy is available for conversion to electricity by a wind turbine (Mirhosseini, et al., 2011).

$$WPD\left[\frac{\mathrm{W}}{m^2}\right] = \frac{P}{A} = \frac{1}{2}\rho v^3$$ **Equation 4**

Areas with annual average wind power density above 200 $\frac{W}{m^2}$ are considered to be suitable for most wind turbine applications. Values below 100 $\frac{W}{m^2}$ are an indicator for unsuitable areas. Zones with values between 100 and 200 $\frac{W}{m^2}$ may be used only if the project involves the use of tall towers (Manwell, et al., 2002) (refer also to Table 5).

As mentioned earlier, Equation 1 and Equation 4 are just theoretical values; real efficiencies would be much lower. The transformation of the energy in the wind must pass by two main stages: From kinetic to mechanical energy through the turbine, and from mechanical to electrical energy through the generator. Obeying the Second Law of Thermodynamics, the efficiency of the system (the ratio between energy output and energy input) will never be 100%.

Looking at Equation 1, a person may infer that it is not possible to convert all kinetic energy in the wind into mechanical energy. Some energy has to remain in the air leaving the turbine and also promoting the movement. This observation was first made by the physicist Albert Betz (Betz, 1966) and is today widely known as the Betz's limit.

The Betz's limit states that a wind turbine will never extract more than 59.3% of the available energy in the wind (Abea, et al., 2005). If all energy from the wind were extracted as useful energy, the wind speed after leaving the turbine would drop to zero, impeding the entrance of new wind into the turbine and preventing it from continuous movement. Betz demonstrated that to maintain the wind movement, the exit speed should be at least 1/3 of the upstream velocity, which translates into a maximum of 59.3% of energy that can be extracted from an ideal stream. The real performance efficiency of wind turbines, however, is still below this number.

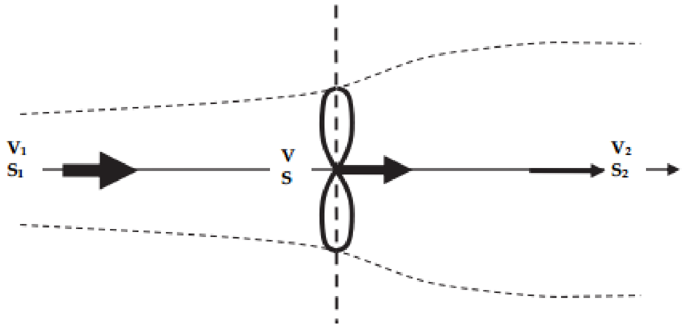


Figure 4: Schematic diagram of a wind turbine stream, where v=wind speed passing through the turbine rotor, and s= air stream cross sectional area (Ragheb & Ragheb, 2011).

Once the blades have produced mechanical energy, this has to be converted into electrical energy with the help of a generator. Generator efficiencies are also around 90%, and there are still other losses in the conversion electronics and lines.

Wind turbines are also set to operate between a wind speed range. If the wind speed is below or above the specified range, the turbine will switch off and therefore the efficiency would be zero. Turbines reach the maximum efficiency at a determined speed (supplied by the manufacturer), variations of which will keep the turbine in movement but with a lower efficiency.

All the combined losses across the system summarize that the overall energy delivered from the wind, ranges between 20 and 40% of the actual energy of the wind; this value is usually referred to as Capacity Factor.

However, wind resource information is the most important aspect for the evaluation and economic feasibility of commercial scale wind projects. Nevertheless it is also very sensitive to uncertainties and errors in estimations. To reduce errors in the wind estimations, numerical methods for simulation and forecast are used. The one used for this study is TAPM, described further in sections 2.3 and 4.1.2.

2.1.1. Variability of Wind Power

Renewable sources of energy, by their very nature, are variable with time and conditions. As seen earlier, the wind power potential is dependent on the wind speed, thus making the reliability of wind energy questionable by the non-presence of wind or the presence of very strong winds.

A common question is: What happens if the wind stops blowing? A short answer could be that such a situation will never arise as wind won't ever stop blowing instantaneously over the whole country. Contrary to popular belief, wind is not totally random and unpredictable (Milborrow, 2009). For the case of very strong winds, current turbines are designed to operate in wind speeds of up to 25 m/s, which is already above the average in many places in the world.

However, the rapid growth and introduction of wind energy, and the natural cycles of fluctuation with time, make variability an important factor to take into account when planning the stability of the network (IEA, 2005).

2.1.2. The load factor

Electricity demand is influenced by the season, the day of the week and hour of the day. Although the biggest user of electricity is the industrial sector (see Figure 5), Dalgleish (2009) in his study for Power Alert, concluded that it is the residential sector which has more influence on the demand profile. According to Eskom (Eskom, 2011) , around 20% of the generated electricity is consumed by residential customers, and these numbers increase to about 30% during peak periods.

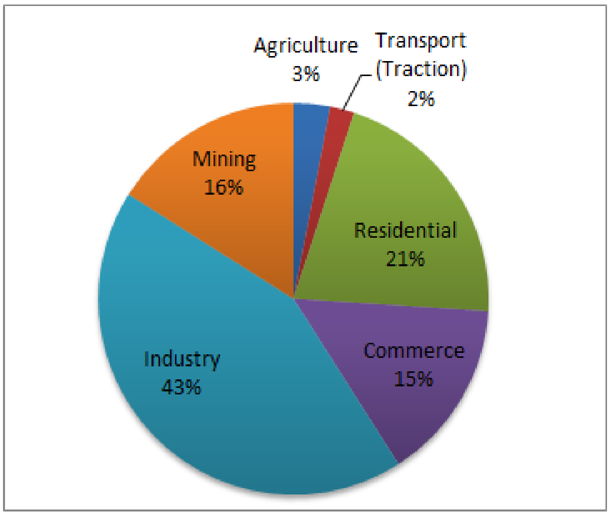


Figure 5: South African electricity consumption by sector (Eskom, 2011)

The typical daily pattern of electricity demand presents two peaks; one in the morning and a higher one during the evening (see Figure 6). The residential evening peak is primarily caused by water heating, cooking, space heating, lighting and appliances. During winter, the demand is more pronounced than that in summer, this difference is mainly driven by space heating requirements (Dalgleish, 2009; ERC, 2006; Venter & van der Walt, 2007).

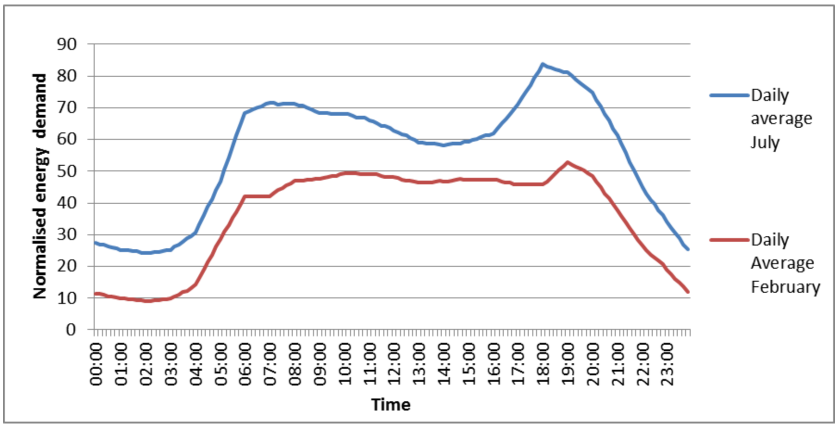


Figure 6: Daily electricity demand (normalised to supply capacity) for an average weekday in winter (Jul.), and summer (Feb.) (adapted from Power Alert)

There are mainly two factors that influence size and composition of energy demand in a country: population growth and economic growth. It is estimated that

1% increase in the GDP increases energy consumption by approximately 0.6% (EREC & Greenpeace, 2011).

With so many variables acting on the load, the ultimate goal of grid system operators is to maintain a balance between the changing load and the electricity available for delivery (IEA, 2005).

2.1.3. Penetration

The term energy penetration is used to characterize the ratio of the amount of energy delivered from wind to the total energy delivered. It is calculated from the formula:

$$\frac{Energy\ output\ from\ wind}{Electrical\ energy\ load} \text{x}100\% \qquad \textbf{Equation 5}$$

There is not a maximum value for wind penetration; but studies suggest that up to 20% may be safe without compromising the electricity supply (Zender & Warhaft, 2011). At present, some countries, like Denmark and Spain, have a high penetration level, which is made possible through a solid grid managing system and international exchange of electricity.

2.1.4. Annual energy production, capacity factor and capacity credit

Given that the wind is not constant through time, the annual energy production (AEP) of a wind farm never corresponds to the addition of the theoretical production from each generator multiplied by the number of hours in the year (IEA, 2005). In terms of wind energy, the calculation of the AEP is given by the formula below:

$$AEP\left[\frac{MWh}{annum}\right] = 8760\left[\frac{h}{annum}\right] * CF * GS[MW]$$ **Equation 6**

Where CF = Capacity factor and GS indicates the rated power of the generator size.

The ratio of actual productivity in a year to the theoretical maximum is known as the capacity factor. Wind power's CF ranges between 25% to 40%, in contrast the CF of a fossil-fired power plant is around 85%, mainly affected by fuel supply reliability (IEA, 2005).

The capacity credit (CC) concept evaluates how the generation adequacy of the system (LOLP) is affected if another unit is added. A recent study commissioned by the DOE, Eskom and the German Technical Corporation (Pöller, 2010) concluded that the capacity credit of wind generation in South Africa can be expected to range around 25%. For a case of 10 000 MW installed wind capacity with a CF of 30%, this means that a reserve capacity in the system of 750 MW (0.25 x 0.30 x 10 000 MW) could be safely removed when such wind energy is included, without affecting the system security.

Penetration and capacity credit are inversely related. A higher penetration level has a relative reduction in the CC. Alternatively, increases in CC reduce the extra back-up costs. If a new wind project has zero CC then no plant can be retired; but it also means that no new plant needs to be built for backup. Regarding CC, it is demonstrated that increases in it bring reductions in almost the same proportion over the additional short-term balancing cost (Milborrow, 2009).

The probability of having a capacity factor not smaller than 0.35, is 50% for each one of the selected round two projects. There are sites in South Africa that exceed by a wide margin the average global capacity factor of 25% (or 0.25) for onshore wind projects, and as a result South Africa is getting wind power at a very competitive price (Ruffini, 2013).

2.1.5. Grid characteristics

According to the IEA, grid operation comprises the daily and long term grid-management on a distribution and transmission level (IEA, 2005). It is thought that the variability of wind energy has a large impact on operation of the transmission system (Eskom, 2010); yet it is proposed that the integration of wind energy won't compromise the performance of the system.

Any grid is designed to bear outages and increase in load of certain magnitudes without stopping the service. Variations in frequency and voltage are kept within a certain range to prevent damage of the infrastructure; but all networks deal with unpredictable fluctuation either from the consumer demand or from the plant supply.

According to the *Capacity Credit of Wind Generation in South Africa* study (Pöller, 2010), the impacts on the system operations are due to the limitations in the forecasting of supply and demand, rather than to the variations present in the energy from wind.

The reliability of the network is measured by the loss-of-load-probability (LOLP). This is defined as the probability that the load will exceed the available generation (Jenkins, et al., 2000). There are reserves aimed to balance the long term output fluctuations, known as capacity reserves; while the reserves that balance short term fluctuations are called operational reserves.

In the case of wind energy, the operational reserve makes reference to the additional generating reserves needed to ensure that differences between forecast and actual volumes of generation and demand can be met (IEA, 2005).

Grid operators have to make use of reserves to be able to maintain the security and quality of electricity supply in the presence of any event. Typical events usually consist of an outage in a large generation unit or the loss of a significant transmission line. The introduction of RE will require the implementation of new long term strategies in order to accommodate for variable energy generation.

2.1.6. Management of variability

The integration of wind farms into the electricity mix implies that each farm has to be planned to enable full output; but ensuring that local load is met all the time, even if there is not instantaneous output from the wind farm. In this case, the other sources of energy in the mix must be able to supply such demand.

The impact of the variation in produced electricity may be alleviated by geographic dispersion of wind farms, grid integration and improved weather forecast techniques.

One of the favourable characteristics of wind is that not all sites present identical generation profiles at the same time. The wind power variations in one site can balance out variations in another site (Drake & Hubacek, 2007). Should all the wind installations be concentrated in one area, this naturally built in diversification factor would remain untapped (SAWEA, 2010).

Grid integration is also effective in reducing individual output variations. As individual wind farms average out the electricity supply, users also average out each other in electricity demand. The energy system can incorporate power from different sources in different locations; and the larger the system, the less capacity reserve is required.

Countries such as Denmark have reached a penetration level from wind energy higher than 20%. This has been possible by trading excess energy with other countries in times of high supply, and purchasing extra energy at times of low wind generations.

Weather forecast also plays an important role in planning the supply/demand. Energy production changes are observed in short time-intervals; thus, the system operator could ask for the energy output in an hour's time and plan the operational reserve accordingly (IEA, 2005). Although variable, wind can be predicted. If the confidence in the forecasting model increases, then the need for operational reserves is reduced.

Yet even with grid integration, geographic distribution and improved weather forecasting methods there is still a residual unpredictability and general variability that must be addressed (IEA, 2005). Some proposed strategies for balancing of the supply and the load are:

- Power plants providing operational and capacity reserve,
- electricity storage,
- distributed generation for local distribution of energy that reduces grid congestion, transmission losses and cost for ancillary services,

- demand-side response strategies to reduce the peak of the load, including programs such as power-alert, differential electricity tariffs through the day, automatic load configuration of household appliances, etc., and
- curtailment of intermittent technologies (switching off of the turbines) to ensure system stability when transmission and distribution capacity is congested.

The principle behind all these options is the same: balancing demand and supply continuously. Both over long-term timeframes and where necessary supplementing demand with other alternative energy capacity over very short lead times (IEA, 2005).

Wind initiatives in South Africa have received some bad press by pointing out its "intermittent" nature which entails running a parallel base load plant and this is not cost effective (van den Berg, 2013); however SAWEA studies done over sufficient time have proved that the dispersion of the wind projects across South Africa with their different wind patterns provide levels of counterbalance.

The degree in which wind variability may affect the electrical system depends on the market penetration of the technology, the availability of the resource and the addressing of challenges from managing the grid. International experience has shown that penetration levels lower than 5% do not represent a threat to the system; in fact only when it is higher than 20%, does variability become an issue (van den Berg, 2013; IEA, 2005; Milborrow, 2009).

Some proposed strategies for the management of the system are: geographical aggregation, forecast improvements, liberalisation of the market and integration with other renewables.

Cost wise, variability is accountable for increasing the cost of additional reserves, back up cost and constraint cost due to surplus wind (IEA, 2005). In the UK case, the electricity prices are estimated to increase by only 2% if the wind energy shares 21% of the total energy market may reduce (Milborrow, 2009).

Electricity supply from wind is time dependant, and so is the electricity demand. The weather affects the amount of energy required by users in the same way as wind speed relates to wind generation. In principle, the only way of addressing variability is by the continuous balance of supply and demand, not looking at the performance of each turbine itself but looking at the complete system as a whole (Drake & Hubacek, 2007; Tarroja, et al., 2011; Jackson, 2010; EIA, 2013; Milborrow, 2009).

2.2. History of Wind Energy

The power of the wind has accompanied human activities for centuries. Used mainly in mills for grinding grain or for water pumping, wind provided energy on a small scale for communities all around the world. In the course of the nineteenth century, more than 6 million wind mills were installed on farms across the United States (Burton, et al., 2011).

During the 1900's there was significant experimental advance in wind energy and wind turbines. Some of the earliest wind initiatives took place in Denmark. The Danish influence is still evident today as all commercial wind turbines resemble the light-weight 3 blades up-wind Danish design.

Golding (1955) and Spera (1994) provided information regarding the evolution of the wind turbines; they make reference to one of the first utility-scale wind turbines, the WIME D-30 fabricated at the former USSR in 1931. This 100 kW and 30m diameter wind turbine was connected to the local distribution system. During the Second World War, small wind generators were attached to German boats to recharge submarine batteries. In 1956 Denmark built a 200 kW turbine of 24m diameter, while France tested a 35m diameter wind turbine in 1963 (1.1MW). Germany joined the race of utility-scale turbines with Professor Hutter, who designed and constructed several models of light weight turbines during the 50's and 60's.

Despite the technological advances during the first half of the 20th century, the development of wind energy was limited. There was a general lack of interest in new sources of energy when cheap fossil fuels and conversion were at their peak. It was only in 1973, when the oil embargo proclaimed by the Organisation of the Petroleum Exporting Countries (OPEC) raised oil prices dramatically, that governments from consumer countries became motivated to fund the research and development of other sources of energy (Burton, et al., 2011).

Since 1975 the United States of America, with funding from the National Science Foundation (today US Department of Energy) started the research and development of commercial wind turbines. Their first design consisted of a 100kW turbine of 38m diameter; by 1987 the turbine design reached 97 meters diameter and up to 3.2 MW.

Similar advances were happening in the UK, Germany, Sweden and Canada. Canada constructed the first vertical axis turbine, which claimed to be capable of operating from any direction and under adverse conditions; however, the concept found limitations in costs and performance when competing with horizontal large utility wind turbines.

Any increase in the rotor diameter translates into an increase of three times more in power output. This explains why modern commercial wind turbines are designed with blade diameters of 100m, compared to 30m of the initial prototypes. In some countries high mast or higher foundations are built to take advantage of the increase of wind with height.

Modern wind turbines use the lift force derived from the blades to drive the rotor. An energy balance of a 3MW turbine concluded that it takes 6 to 7 months for the turbine to generate the same amount of energy that is used in producing the turbine including the manufacture, operation, transport, dismantling and disposal (EWEA, 2009).

Previously, oil price concerns and security in energy supply were the only reasons leading to the development of renewable energy. However, from the 1990's, the main driver has been the reduction of CO_2 emissions and the need for climate change mitigation actions.

Since 2006, ongoing increases in the price of oil and concerns regarding security of energy led to an even further interest in wind energy. Governments of different countries have introduced energy policies to facilitate the implementation of support mechanisms for cleaner alternatives such as wind generated electricity.

2.2.1. Wind Energy in the world

According to the World Wind Energy Report (WWEA, 2011), by the end of 2011 the worldwide wind energy capacity reached 237 016 MW, of which 40 053

MW (20.3%) were added during the last year (6% more than in 2010). All current installed global capacity can provide around 500 TWh per annum; approximately 3% of the global electricity consumption (see Figure 7).

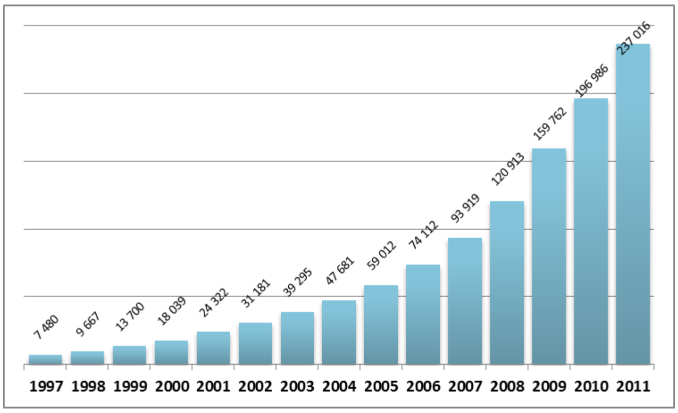


Figure 7: World Total Installed Capacity in MW (Reproduced from WWEA, 2011)

As observed in Figure 8, during the last two decades China, USA, Germany, Spain and India have represented the largest share in wind power installed capacity; they account for almost 74% of the world wide wind capacity. Europe is the leading continent as it possesses nearly 60% of the world's wind power capacity. Penetration levels (the percentage of energy delivered from wind from the total energy delivered) reach up to 21% in Denmark, followed by 12% and 7% in Spain and Germany respectively (EWEA, 2009).

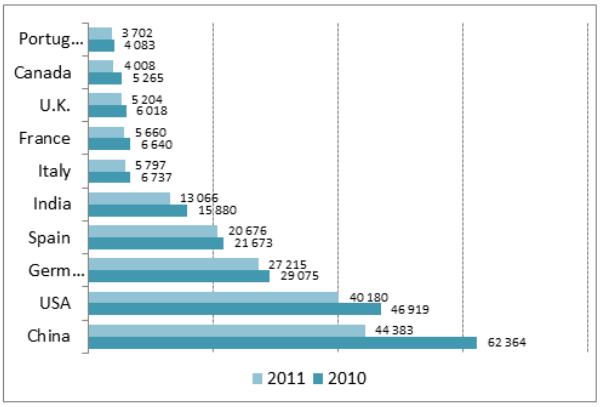


Figure 8: Top 10 countries by total capacity in wind production-MW (Reproduced from WWEA, 2011)

Through the last decade, the positive trend of the growing of new installed capacity is obvious as presented by Figure 9. During the year 2011, the wind sector had a turnover of $65 billion USD, with a promising growth in the Latin American and Eastern European countries.

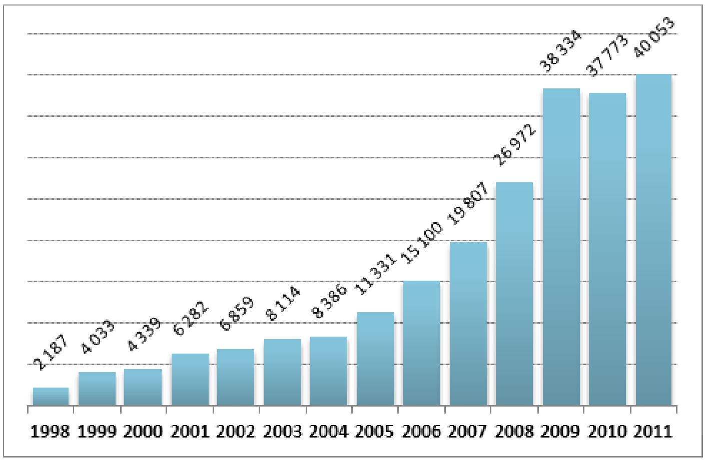


Figure 9: Total worldwide annual new installed capacity in MW (Reproduced from WWEA, 2011)

2.2.2. South African wind potential

The African contribution to the global installed capacity is minimal, and as such corresponds mostly to the North African countries. However, changes in South African policies and plans are encouraging the development of Renewable Energies (REs) in the country. It is expected that South Africa will contribute to a third of the continental wind capacity by 2030 (Roodbol, 2013).

Atmospheric Circulation Patterns

South Africa's wind resource is influenced by the mean circulation of the atmosphere, known as climate; and the smaller-scale disturbances or deviations known as weather. The following paragraphs outline the basic concept of such influences on the southern African winds; however, climate systems are rather complex and dynamic, and their detailed description goes beyond the scope of this dissertation. For additional information the reader is invited to review the work of Tyson & Preston-Whyte (2000) and Hurry and Van Heerden (1987).

The country's location around the subtropical high pressure belt makes it susceptible to the circulation systems prevailing in the tropics to the north and temperate latitudes to the south (see also Figure 1). The persistent global motion over Southern Africa is winds with a westerly component known as the westerlies; these occur near the earth surface between 30° and 60° latitude (Tyson & Preston-Whyte, 2000; van Zyel, 2003).

The seasonal differences in the circulation features are mainly due to the northward displacement of the subtropical high pressure belt by almost 5 degrees in winter. Changes in the subtropical high pressure belt, the westerlies, and the cold fronts coming from the polar cells, influence the presence and variations of the wind at earth surface (Kruger, et al., 2010).

Hurry & Van Heerden (1987) described the most common behaviour of the wind according to the season and the circulation patterns. Capital letters mentioned in the following paragraphs refer to sections of Figure 10.

During summer (Figure 10, left) the westerlies are situated right at the south of the continent, limiting the presence of strong winds to the southern regions of the country. Strong westerlies influence the western, southern and south-eastern coastal areas and immediate interior.

The Indian Ocean has associated south-easterly trade winds (A) which influence the north-east of the region. These winds can be strong, curving sometimes from Limpopo Province into the Free State Province (F), or moving far north over the areas of Zimbabwe or Zambia.

The ridging of the Atlantic high pressure system causes the south-eastern trade winds, (B) these are strong and persistent. The south-eastern trade winds sometimes curve and change to the south-western *Monsoon* winds.

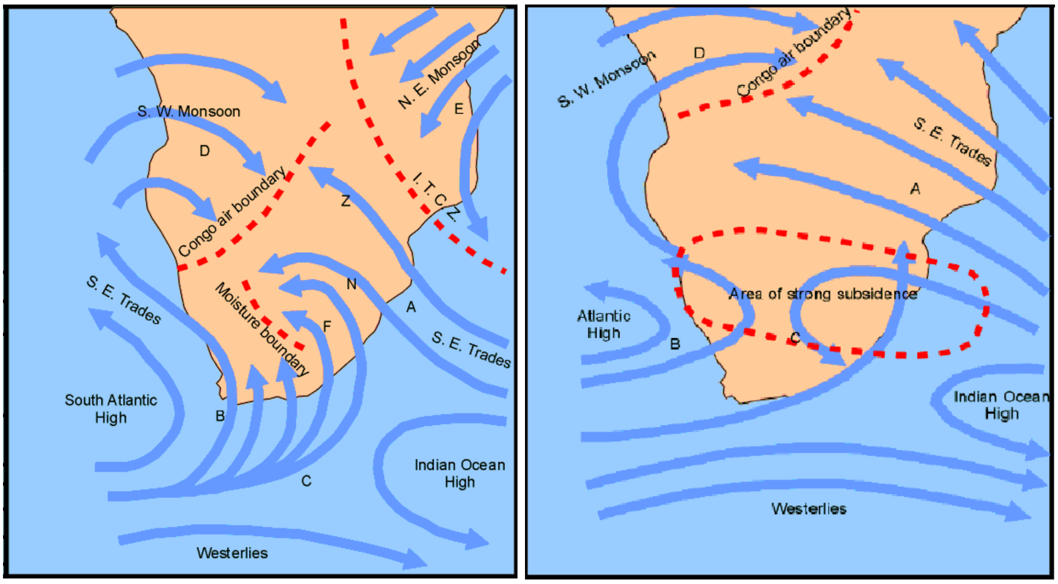


Figure 10: Left) summer, right) winter winds over southern Africa, (Szewczuk & Prinsloo, 2010) after Hurry & Van Heerden)

In winter, all the circulation features are located more to the north due to the northern displacement of the westerlies (see Figure 10, right). The southern-eastern trade winds from the Indian Ocean still occur, but there is no convergence due to the absence of the north-eastern Monsoon winds (A).

Strong winds and gusts occurring during winter are usually caused by strong cold fronts, moving over the southern half of South Africa but may reach far north, and also by the ridging of the high-pressure system behind the fronts.

At this time of the year, gale force winds are experienced in the Cape Peninsula, as well as the southern and south-eastern coasts. When the Atlantic high pressure system is situated south of the country, strong south-easterly to easterly winds can be experienced along the west coast.

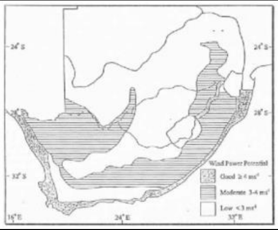
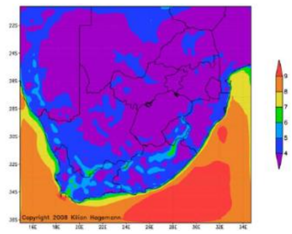
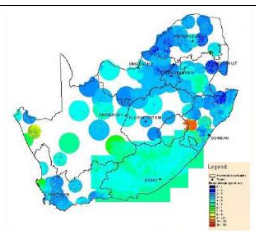
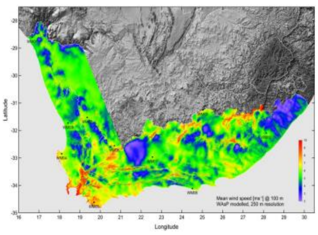
When the Atlantic high-pressure system moves eastwards and stays strong, gale-force winds can spread to the KwaZulu-Natal coast, and as far north as the Mozambique Channel.

The South African wind potential

During the last 20 years, efforts have been undertaken with the aim of estimating the wind power potential of South Africa. Results from such studies are summarised in Table 1. A high resource is evident in large parts of the country, especially along the coast. Good possibilities for inland development have also been demonstrated.

From privately funded studies quoted by the SAWEA, it is estimated that South Africa would have enough feasible sites to generate 70 000 MW of wind energy if there were no network, political or economic constraints. Under the suitable regulatory scheme, wind could provide 30 000 MW, equivalent to 20% of the energy demand by 2015 (SAWEA, 2010). More recent studies, as in the mesoscale model of the Wind Atlas for South Africa (WASA), concluded that the "realistic" capacity for the country is in the order of 26 000 MW (WASA, 2012).

Table 1: Summary of South African studies to estimate wind power (after Szewczuk & Prinsloo, 2010)

Author	Main findings	Overview
Diab (1995)	• Wind power potential is generally good along the coast. • Good areas may have a power potential higher than 200 W/m^2 • It differentiated between areas of good, medium and low power potential.	
Hagemann (2008)	• It used climate models (MM5) to produce a mesoscale wind map for the country. • Significant inland resources were discovered, and suggested that South Africa's wind resources were higher than previously estimated, comparable to the highest in the world. • Presented scenarios for wind development (low, central and high case). Estimations for annual electricity generation vary from 20 to 157 TWh, according to the site.	
DoE, Eskom and CSIR. R.Ragoonathum et al, (2001)	• Result from the combined effort for the development of off-grid electrification planning tool. Bulk resource assessment for South Africa. • Wind resource assessment covering the bulk of SA is represented by a number of circles. • A second stage of the project included a resource assessment that covers the whole Eastern Cape.	
WASA (2011) SANEDI, UCT CSAG, CSIR, SAWS, Riso DTU WE	• Project consists of the development, verification and employment of numerical wind atlas methods, to develop capacity for large scale exploitation of wind energy in SA. • Micro-mesoscale modelling using 10 units tall mast.	

With WASA, the country advanced significantly in the introduction of wind energy. This is the first large-scale high-resolution map in the country; it currently covers the Western Cape and parts of the Eastern and Northern Cape provinces.

Wind energy in South Africa: History of development and current situation

The abundance of coal resources and a low production cost infrastructure allowed South Africa to generate some of the world's cheapest electricity in the past (DOE, n.d.). This, together with a monopolist power sector and the lack of energy policies and regulations in favour of renewable energy, resulted in the negligible development of wind energy or any other form of energy different from coal transformation. However, during the last two decades, other factors have caused the consideration and incursion of renewable sources of energy into the electricity mix.

The following points have provided sufficient reason for the government to see opportunities regarding renewable energy for the growth of the country:

- Dependence on oil and its vulnerability to the volatility of the global market,
- concerns about energy security in a growing economy,
- environmental commitments undertaken by the country, and
- even the need to save water during energy production.

It was only in 2000, when the construction of the experimental Darling wind farm in the Western Cape was started, that wind energy was introduced into the national agenda. The Darling wind farm has been operating since 2008 as a National Demonstration Project, being a catalyser for the national wind industry. With four 1.3 MW generators, the project provides the public and stakeholders with a closer view of the turbines, alleviating insecurities and concerns regarding wind energy (Kings, 2013).

What began as an independent initiative was later embraced and supported by the Department of Minerals and Energy and international assistance, and is now known as the South African Wind Energy Programme, SAWEP. The wind industry in the country is still in early stages; however, the panorama looks promising. The private sector and foreign investors have turned their interest into the renewable energy development opportunities opened by the government (see Section 2.4).

In 1998 the Department of Energy indicated for the first time, through the White Paper on Energy, their official support for renewable initiatives. Later in 2003, the White Paper on Renewable Energy set a target of 10 000 GWh by 2013 from REs. Although this goal was never accomplished, it stimulated the design and implementation of the Renewable Energy Strategy. The Strategy defined the integration of RE into the mainstream economy, bringing an encouraging panorama for renewable initiatives.

The legal framework in South Africa was providing the context and commitment from Government for the implementation of renewable energy projects. However, the energy market was, until recently, almost inaccessible to new generators of renewable energy (SAWEA, 2013). To facilitate the mechanisms for financing, in 2009, the energy regulator (NERSA) published the Renewable Energy Fed-on-tariff (REFIT).

The 2009 REFIT published the tariffs at which the government was willing to purchase the renewable electricity generated from different types of technologies. The REFIT tariffs were reviewed again in 2011. However, those were never implemented, as the Government decided to migrate to a competing bidding scheme, known as the Renewable Energy Independent Power Producer Procurement Program (REIPPPP or IPP program).

The REIPPP is the official mechanism from the government to allocate the energy goals set in the Integrated Resource Plan (IRP). Published by the Department of Energy in 2011, the IRP organises the energy supply for the country over the next two decades (until 2030). It mandates that 42% of the new built capacity must come from renewable sources; this is 17 800 MW, of which wind is expected to contribute to 8 400MW. Provision has also been made to incorporate 5 MW from small scale projects.

For the first phase, the national government established the need of 3 725 MW from REs to ensure the continued uninterrupted supply of electricity by 2016 (DOE, 2013). Out of these, 1 850 MW are destined for on-shore wind projects. Selection of preferred bidders is completed by the government in different rounds (windows) of the IPP program.

Bidders are selected not only based on the proposed price but also according to the influence of the project on local development. Renewable energy has been identified as one of the key means to address socio-economic imbalances in the country, boost manufacture, and create new jobs (RSA, 2010).

Currently in the country there is 10.2 MW of installed wind energy capacity, and more than 2,000 MW in construction or appointed for the next three years. Committed capacity includes the 100 MW from Eskom's SERE wind farm, 634 MW from the IPP window, 1,562 MW from round 2 and 787 MW from the latest bid. Table 2 describes more details of these projects.

Most of the projects awarded are located in the Eastern Cape, and the rest in the Western and Northern Cape Provinces. Better wind in such locations is a determining factor; capacity factor of the projects range from 27 to 45%. However, the SAWEA suggests that current distribution may reflect the availability of the grid capacity to accommodate the power, in particular the Poseidon substation in the Eastern Cape, rather than a reflection of the overall wind regime distribution (van den Berg, 2013).

The national government is also looking at the introduction of an Independent System and Market Operator (ISMO) Bill, to ensure an equitable electricity market. ISMO consists on the establishing of an autonomous state-owned company to undertake the development of the generation resource planning, purchasing of power from generation facilities, and enabling electricity trading at a wholesale level. ISMO's objective is trading electricity on a willing buyer/willing seller basis, which may liberate trading of electricity.

Table 2: IPP bid projects

Window	Project	Capacity (MW)	Province	Company	OEM supplier
n/a	SERE wind farm	100	Western Cape	Eskom	Siemens
n/a	Klipheuwel (experimental)	3.2	Western Cape	Eskom	Vestas / Jeumont
n/a	Darling	5.2	Western Cape	Eskom	Fuhrlaender GmbH
n/a	Coega	1.8	Eastern Cape	Electrawinds	Vestas
1	Dassiesklip	26.19	Western Cape	BioTherm Energy	Sinovel
1	Van Stadens	26.19	Eastern Cape	Metrowind	Sinovel
1	Hopefield Umoya	65.4	Western Cape	Umoya Energy	Vestas
1	Noblesfontein Gestam	72.75	Northern Cape	Gestamp Wind	Vestas
1	Kouga	77.6	Eastern Cape	Red Cap	Nordex
1	Dorper	97	Eastern Cape	Rainmaker Energy & Sumimoto Corporation	Nordex
1	Jeffreys Bay	133.86	Eastern Cape	Mainstream	Siemens
1	Cookhouse ACED	135	Eastern Cape	African Clean Energy Developments	Suzlon
2	West Coast 1	90.8	Western Cape	Micawber 862	Vestas
2	Gouda	135.2	Western Cape	Aveng/Acciona	Acciona
2	Amakhala Emoyeni	137.9	Eastern Cape	Cennergi / Wind lab	Nordex
2	Tsitsikamma	94.8	Eastern Cape	Cennergi	Vestas
2	Grahamstown	23.4	Eastern Cape	InnoWind	Vestas
2	Grassridge	59.8	Eastern Cape	InnoWind	Vestas
2	Chaba	20.6	Eastern Cape	InnoWind	Vestas
3	Gibson Bay	110	Eastern Cape	RedCap	Nordex
3	De Aar 2 North Wind Energy Facility	139	Northern Cape	China Longyuan Power, Mulilo Renewable Energy & Black Community Company	Guodian
3	Nojoli	87	Estern Cape	African Clean Energy Developments	-
3	Maanhaarberg Wind Energy Facility	96	Northern Cape	China Longyuan Power, Mulilo Renewable Energy & Black Community Company	Guodian
3	Khobab	138	Northern Cape	Mainstream	-
3	Noupoort	79	Northern Cape	Mainstream	-
3	Loeriesfontein 2	138	Northern Cape	Mainstream	-

2.3. MESOSCALE MODELLING OF THE WIND

The rapid growing of the wind energy industry requires the use of more sophisticated tools for the evaluation of the wind resource and site selection. These tools usually consist of numerical weather predictions of which mesoscale modelling is one.

The motion of the atmosphere is mathematically formulated in non-linear, partial, differential equations denominated *primitive equations*. Those equations are used to solve the density, pressure, temperature, wind speed and wind direction of the atmosphere as a function of time (Pielke, 2002). The weather systems studied in these types of models are the ones formed in a horizontal dimension of a hundred meters up to 5 km.

Mesoscale models have the ability of simulating, with reasonable accuracy, complex wind flows in areas where measurements are scarce or non-existent. Common sources that affect quality of the results are: surface roughness, atmospheric stability and the mesoscale model resolution (Brower, et al., 2004). Results from the resource assessment provide valuable information for wind farm site selection (Vincent, et al., 2010) regarding:

- Wind climate at the site,
- maximum expected speed,
- future wind power production, and
- wind variations during the day.

2.4. Policy and Legislation

This section includes policy, legislation and strategies that delineate the context within which the renewable energy in the country should be conducted. Although there are provincial laws, local bylaws and policies that must be taken into account in a feasibility assessment, only national regulations are contemplated for the purpose of this study. Figure 11 depicts a representation of the legislative framework relevant for national wind developments; the most important ones are detailed further below.

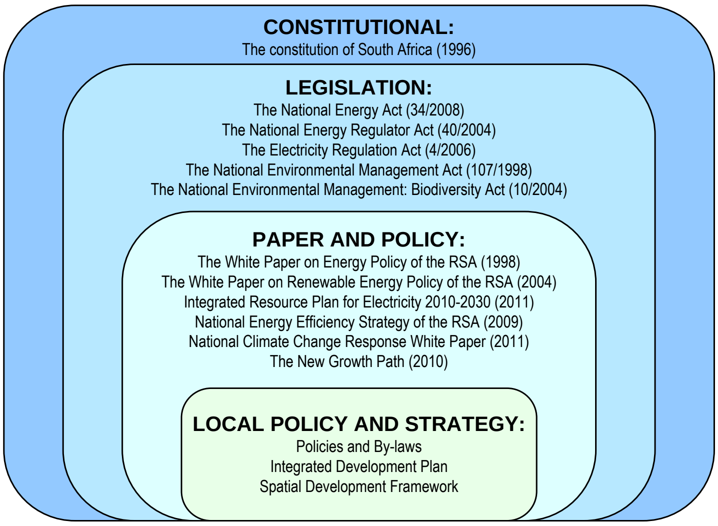


Figure 11: Schematic of legislative framework applicable to site selection studies

2.4.1. The South African Constitution (1996)

As the supreme law of the country, there is no other law or government action that can supersede it. The national constitution has made provision in Chapter 2 to advocate for the environmental rights.

> *"24. Environment*
> *Everyone has the right -*
> *a. to an environment that is not harmful to their health or well-being; and*
> *b. to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that -*
> *i. prevent pollution and ecological degradation;*
> *ii. promote conservation; and*
> *iii. secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development."*
>
> *(From the Constitution of South Africa, Chapter 2, Section 24)*

Part b sets the concept of sustainability and accentuates the responsibility from the government and the citizens of undertaking practices that promote conservation, equity and development.

Although the Constitution delineates functional areas of concurrent national and provincial legislative competence (schedule 4), and of exclusive provincial legislative competence (schedule 5), there is not an explicit reference to energy or renewable energy issues; save by "electricity and reticulation" mentioned in schedule 4, Part B. According to Glazewski (2009), such exclusion implies that energy matters and renewable energy in particular is by default administered by the national Department of Mineral Affairs. Others, as Brent et al. (2012) argue that such omissions are only due to the fact that the constitution was drafted before the current energy crisis.

2.4.2. The National Energy Act (34/2008)

The National Energy Act (34/2008) advocates for diverse, sustainable and sufficient energy resources that promote the national economic growth and the improvement of the quality of life of the residents; taking into account environmental and social factors. It clearly states, as one if its objectives, the increased generation and consumption of renewable energies.

In addition, it compels the formulation of an integrated and sustainable energy plan under principles of optimal use of indigenous and regional resources, balance between supply and demand, economic viability, environmental, health, safety and socio-economic impacts.

2.4.3. The Electricity Regulation Act (4/2006)

The Electricity Regulation Act (4/2006) establishes the framework for electricity supply and development operation of the national electricity supply infrastructure. It defines conditions under which transmission and distribution, trading, import and export of electricity are regulated, and gives authority to the National Energy Regulator to serve as the custodian and enforcer of such framework.

2.4.4. Electricity Regulations on New Generation Capacity (2011)

The Electricity Regulations on New Generation Capacity was gazetted in May 2011 under the Electricity Regulation Act (ERA). The Department of Energy established rules and guidelines applicable to undertaking of an Independent Power Producer (IPP) Bid Programme, and the procurement of an IPP for new generation capacity (Eskom, 2011).

2.4.5. Renewable Energy Independent Power Producers Procurement Programme (REIPPP) (2011)

The Renewable Energy Independent Power Producers Procurement Programme (2011) was launched in August of 2011; it is a procurement program, likewise a bidding process, where renewable projects compete in each window according to rigorous criteria for providing in total 3725MW of electricity. Only energy from onshore wind, solar photovoltaic, concentrated solar power, biomass, biogas, landfill gas and small hydro technologies are considered; the qualifying projects are evaluated 70% on tariff, and 30% on their local economic development plan. Eskom's participation in the program is limited to a buyer of electricity, and to the development of grid connections.

2.4.6. The National Environmental Management Act, NEMA (107/1998)

The National Environmental Management Act (NEMA) (107/1998) provides for co-operative environmental governance by establishing:

- Principles for decision-making on matters affecting the environment,
- institutions that will promote cooperative governance, and
- procedures for co-ordinating environmental functions exercised by organs of state.

It is the NEMA who includes the concept of sustainable development as:

> *"1. Definitions*
> *xix. 'sustainable development" means the integration of social, economic and environmental factors into planning, implementation and decision-making so as to ensure that development serves present and future generations; (xxviii)"*
>
> *(From the National Environmental Management Act, Definitions)*

2.4.7. The White Paper on the Energy Policy of the RSA (1998)

Released by the former Department of Minerals and Energy (DME), it is this White Paper that envisages, on the national agenda, the possibility of satisfying the future energy demand by making use of the various renewable sources available in the country. The document states the importance of energy and electricity to properly address what later was called by Fell (2009) the three key elements of sustainable development: economic progress, environmental sustainability and social justice.

2.4.8. The White Paper on Renewable Energy Policy of the RSA (2004)

In 2004 the DME published the *White Paper on Renewable Energy*; this was the first official document committing the government to the promotion and implementation of renewable energy in South Africa. A goal of 10 000 GWh of energy produced from renewable sources by 2013 was set; and although the target was not accomplished, it initiated the path for the establishment of a renewable energy strategy.

2.4.9. The Integrated Resource Plan for Electricity 2010-2030 (2011)

The IRP provides a long term and cost effective resource plan for meeting the electricity demand. This is consistent with reliable electricity supply, environmental, social and economic policies.

Promulgated in May 2011, it plans a roll out of 8400 MW of new wind generation over the next twenty year

3. CRITERIA FOR WIND FARM SITE SELECTION

In this chapter, a summary of the international best practices for site selection is presented; together with area delimitation approaches and local guidelines developed for the South African context. There is an exposition of worldwide methodologies for optimisation of site selection that integrate technical, environmental and economic concerns. Finally, based on literature review, and mainly on the South African situation, a list of variables considered necessary to be included in macro-siting representation of wind farms is included.

Siting of wind farms is one, if not the most, important decision for the success of a wind energy initiative. Wind resource, wind variability, accessibility to roads and the electrical grid, are dependent on location; this influences the technical and economic feasibility of a project. Environmental disturbance is also expected, as there is associated visual and noise intrusion, electromagnetic interference, possible wildlife collision (e.g. migratory pathways of birds) and other environmental impacts that influence the landscape, the animals and people around it (Kinder, et al., 1996).

Although the environmental impacts of wind energy are considerably more tolerable with respect to those of conventional energy systems (Tsoutsos, et al., 2005), the expansion of renewables and the continuous growth of the sector will inevitably produce planning and environmental conflicts (Douglas & Salinja, 1995). Economic and environmental interests can be addressed through utilisation of appropriate site selection procedures for wind turbine locations.

The following sections present best practice guidelines for wind energy development in different countries, including what has been done in South Africa. A review of worldwide technical methodologies for optimisation of site selection is also presented. Finally, based on literature review, and mainly on the South

African situation, a list of variables considered necessary to be included in macro-siting of wind farms is listed.

3.1. BEST PRACTICE GUIDELINES

Extensive literature regarding best practice guidelines for wind energy development is available. They all are very similar and identify the need for selection of sites that better integrate the technical, environmental and commercial concerns. The differences in the approaches used by each country are based on the importance that each nation gives to their criteria factors and the available information.

3.1.1. United Kingdom

Considered one of the best locations for wind energy in the world, the United Kingdom possesses a total installed capacity above 8 GW, of which approximately 63% is onshore and 37% offshore (UKWED, 2013). In the United Kingdom, 50 MW is used as the threshold for determining the requirements and authorities that decide on wind energy projects. Developments above this threshold are to be attended by the Infrastructure Planning Commission, following a similar process to an Environmental Impact Assessment (EIA). Smaller projects are dealt with by the local authority who also determines if there is merit for an EIA.

The Best Practice Guideline for Wind Energy Development from the British Wind Energy Association (BWEA) addresses the general considerations for site selection from three aspects: technical and commercial, environmental, and dialogue and consultation (BWEA, 1994).

In the initial technical analysis it is recommended to use "desk-based" studies, making provision for wind speeds, local electricity distribution system, road network, and size and site ownership. Environmental considerations should obey dispositions from the Planning Policy Guidance Note 22 (PPG22) that care for inappropriate development in protected areas. It also makes provision for visual effects, proximity to dwellings and ecological designations. Finally, dialogue between developers and local planning authorities is encouraged.

Likewise, the Best Practice Guidelines for the Irish Wind Energy Industry (IWEA, 2012), determines the site selection under a feasibility study with a typical scope that covers:

- Planning,
- environment,
- archaeology and architectural heritage,
- landscape and visual impact,
- wind resource,
- proximity to existing land use constraints,
- grid connection,
- access and transportation,
- market for sale or use of electricity,
- preliminary legal aspects,
- outline wind turbine layout, etc.

This guideline is more detailed in respect to legislation to follow and minimum standards to be applied per criteria compared to the British guideline.

Although the need for an EIA is determined according to the characteristics of the project, regulation orders for a compulsory Environmental Impact Assessment for any development of more than 5 turbines, or total output higher than 5 MW. Projects with wind turbines of a maximum height of 20 m and maximum rotor diameter of 8 m are exempt from planning.

The United Kingdom uses a mix of two methods for identifying areas for wind projects: a landscape sensitivity method and criteria based one. As a result, national areas for wind development are labelled as preferred areas, potential areas or for consultation and sensitive areas to be avoided (PGWC, 2006).

3.1.2. Europe

With 105 GW of installed capacity at 2012, almost half of the total global installed capacity, the European Union is an authority in wind energy matters. The European Wind Energy Association (EWEA) recognizing the importance of projects appropriately sited and sensitively developed, wrote the Best Practice Guidelines (EC, n.d.). Such a document was built on experience gained by the BWEA and the Dutch wind energy industry. It presents therefore technical and commercial considerations, initial environmental considerations and dialogue and consultation similar to the ones described in the British case. They recommend an EIA study to be conducted as part of the initial environmental analysis.

For identification of areas available, Germany uses "negative mapping" based on visual, landscape and criteria analysis. Denmark developed a decision matrix based on environmental considerations and indications of the wind resource. The matrix differentiates four areas of development: free development, controlled development, limited development and no development areas (PGWC, 2006).

3.1.3. United States of America

Wind energy installed capacity is rapidly increasing in the United States. By the end of 2012, it reached 60 GW, 14% of it introduced only in the last year. Due to the federal status of the country, location of wind projects must obey policy according to the state, and it is the federal agencies who review the potential impacts of the construction and operation of the project.

In 2008, after the Department of Energy stated its ambition of 20% of the national energy to be supplied from wind energy by 2030, the American Wind Energy Association released the Wind Energy Siting Handbook (AWEA, 2008). It was designed to assist developers in addressing regulatory and environmental issues associated with commercial scale on-shore wind projects. This document identifies major steps involved in the preliminary site characterisation, as:

- Analysis of the wind source,
- initial site visit,
- establishment of economics of the project,
- critical environmental issues analysis and identify regulatory framework,
- transmission capacity analysis,
- environmental site assessment, and
- assess public acceptability.

3.2. Methodologies for Site Selection

The selection of locations for new wind farms is a multiagent decision-making process with significant geographical characteristics (DTI, 1998). Economic, planning, physical and ecological factors influence the location of wind turbines.

All of these factors are spatially dependent; hence it seems evident that the use of geographic information systems poses benefit for the site selection exercise (van Haaren & Fthenakis, 2011).

The Geographic Information Systems (GIS) are software specialised in spatial data analysis. GIS has a significant contribution as a decision support tool in identifying environmentally feasible locations for wind turbines, which require management and analysis of a wide range of spatial data type sets (Rodriguez-Bachiller & Glasson, 2004). The use of such tools enhances the objectivity in the assessment of information and builds experience; this ultimately increases the acceptance from the public (Krohn & Damborg, 1999).

One of the first attempts for identifying relevant criteria to support the decision-making process in wind farm site selection was done by Baban and Parry (2001) in the UK. The authors developed simple GIS-assisted Wind Farm Location Criteria (WFLC) based on questionnaires to relevant public and private sectors, and published literature.

It consisted of independent maps (layers) for constraining factors, such as land use/cover, population density, access, hydrology, ecology, topography, wind speed and wind direction. The WFLC is grouped into physical, planning, economic, environmental or resource considerations.

Layers were combined to produce a single index of evaluation. The index of evaluation could be obtained by either assigning the same weight to each layer, or by allocating the weight according to its perceived importance. An example of a suitability map based on the second described method is presented in Figure 12.

Note how blank areas where criteria have been identified as not viable are excluded from the analysis. Remaining areas are categorized based on its index of evaluation.

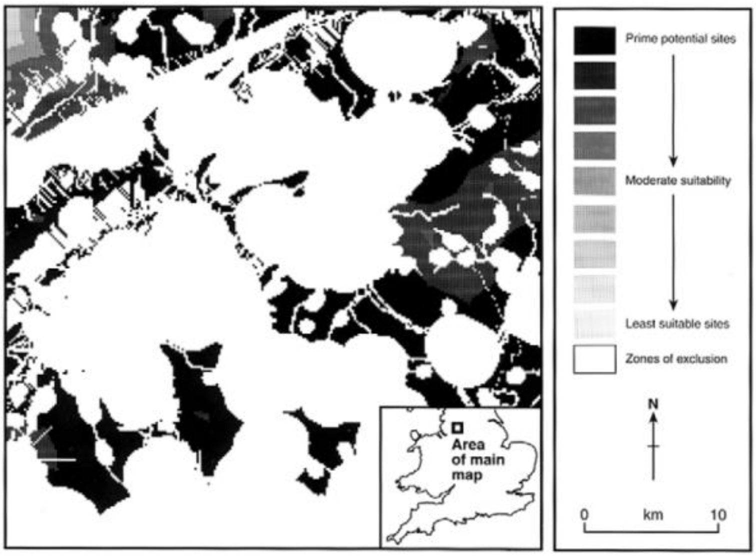


Figure 12: Wind farm site suitability for a 40 by 40 km area in the UK (Baban & Parry, 2001)

In 2003, the US National Renewable Energy Laboratory (NREL) assisted the wind farm analysis and site selection in Sri Lanka (NREL, 2003). Similar to the method proposed by Baban & Parry, a score is assigned to each criterion. The maximum possible score is not the same for all criteria, as it reflects the relative importance of each factor. There is also no overlap of the layers to obtain a unique index; but each criterion is analysed individually. This method includes other variables such as the cost of the energy, or the energy production.

Aydin et al., (2010) proposed another GIS-based method. The environmental impacts of wind energy are evaluated for each 250 m x 250 m block, according to existent legislation and previous studies that have been grouped in environmental objectives. These are then aggregated into an overall satisfaction rating, creating an environmental fitness map (Figure 13), which together with wind potential maps help to identify both technical and environmentally feasible sites.

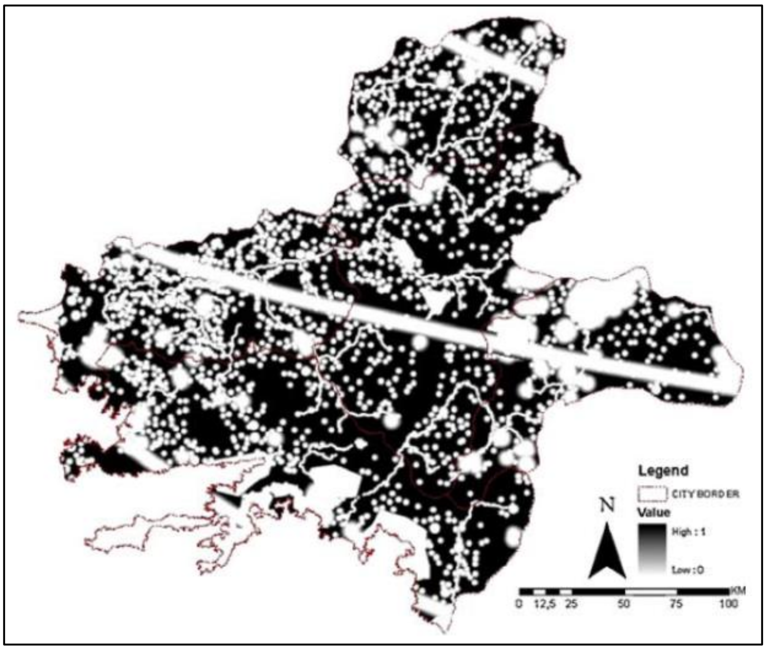


Figure 13: Satisfaction of environmental objectives map for the western part of Turkey, 1 high satisfaction, 0 low satisfaction, blank no feasible area (Aydin, et al., 2010)

A noteworthy aspect from this method is the use of blocks to carry out the analysis. Each block represents the potential location of a wind turbine or a group of wind turbines. A similar method was implemented by NREL as part of the Western Wind and Solar Integration Study, WWSIS (NREL, 2010).

In their study, the NREL team evaluated scenarios in 2 km blocks with a potential energy production of 30 MW that could be aggregated for the "construction" of bigger wind farms. The aim was to understand the economic and operating impacts of higher penetration of wind into the power grid in the Western States of the USA.

Other authors, as Ramírez-Rosado et al. (2007), van Haaren et al (2011), and Grassi et al. (2012) have gone a bit further in the site selection procedures by including strong economic analysis. Ramírez-Rosado et al. use economic profit maps based on the Levelised Electricity Cost (LEC) (Euro/kWh) to include the location preferences of the economic groups. Van Haaren et al. integrated the net present value (NPV) of the major costs of the project that depend on location (e.g. foundations, roads and grid connection). Finally, Grassi et al., (2012) in addition to the levelised cost, included the cash flow of the project in the selection criteria: furthermore a sensitivity analysis of profitability of exploitable land is carried out based on the impact of the Power Purchase Agreement (PPA) price.

The current study operates likewise in the utilisation of optimisation techniques supported on geographical information systems; however, the main criteria to evaluate are the differences in the generation profiles from wind energy and demand profiles from electricity required.

3.3. National guidelines for site selection

The formal process for identifying the potential environmental impacts of a renewable initiative is the Environmental Impact Assessment (EIA).

The EIA process is based on Section 24 of the NEMA (1998). In 2006, regulations R386 and R387 were provided by means of the Government Gazette 28753 Notice to address the assessment process. This contains the list of activities that require a screening and scoping report to determine whether a basic assessment or a full scoping report is required.

A wind energy development may require any of these, according to the characteristics and magnitude of the project as described in Table 3 below.

Table 3: Project criteria that identifies the need for a basic assessment or full scoping and EIA (after (Editha, 2009))

Basic Assessment (R386)		Full scoping and EIA (R387)	
The construction of facilities or infrastructure (including associated structures and infrastructure) for the generation of electricity, where the output is >10 MW but <20 MW	Clause 1(a)	Construction of facilities or infrastructure (including associated structures and infrastructure) for the generation of electricity, where the output is >= 20 MW, or the facility covers more than 1 hectare	Clause 1(a)
Transmission and distribution of electricity above ground with a capacity of >33 kV but <120 kV	Clause 1 (l)	Transmission and distribution of electricity above ground with a capacity of >= 120 kV	Clause 1(l)
The removal or damaging of indigenous vegetation of >10 m2, within a distance of 100m inland the high water mark of the sea	Clause 5	Any development activity where the total developed areas exceeds 20 hectares	Clause 2
The transformation or removal of indigenous vegetation of 3 hectares or more or of any size within a critically endangered or endangered ecosystem	Clause 12		
The construction of mast of more than 15 m	Clause 14		
The construction of access roads wider than 4m	Clause 15		
The subdivision of land exceeding 9 hectares in size in portion of 5 hectares or less	Clause 18		
The decommission or recommissioning of existent facilities or infrastructures for electricity generation	Clauses 23 and 24(a)		

The former REFIT program adopted in 2009 recognized the need for Independent Power Producers (IPP) to obtain environmental authorisation for their proposed projects; this has led the Department of Environmental Affairs (DEA) to be inundated with applications for environmental authorisation (Levendal, et al., 2012). Furthermore, the EIA process faces challenges when it is used to evaluate this new and rapidly growing renewable industry; some of these challenges identified by Levendal et al. are:

- Lack of consideration of environmental criteria in the selection of project sites prior to commencing EIAs,

- poor coordination of inputs amongst all relevant stakeholders,
- negative public perceptions,
- minimal baseline environmental monitoring data, and
- lack of consistent guidelines.

Although not of compulsory nature in the South African legislation, the Strategic Environmental Assessment (SEA) may be a valuable tool for sustainable environmental management. Different to the EIA, that limits itself to the study of a physical project, the SEA looks at policies, plans, ideas and programmes to help planners to understand what will happen to an area if there is a different land use; also the short, medium and long term environmental impacts of different actions (Goodstadt , n.d.).

It is the duty of the government to adopt a framework to assess the renewable projects from a national perspective, a set of guidelines to assist in the rapid and efficient assessment of the DEA to the over-supply of proposals; however, little conscious work has been done in this respect.

Only recently, in 2011, the DEA released the *Strategic Environmental Framework for the Optimal Location of Wind Farms in Coastal Provinces of South Africa (PHASE 1 FOR REFIT 1)*, hereafter SEF, (DEA & GIZ, 2011), of which Levendal et al. argue it is vague, provides a fairly weak framework based on limited information and it only applies to the coastal provinces. Renewable developments are fairly new in the country and hence, they find themselves excluded from most of the current local and regional planning initiatives. Nevertheless there is a good example of guidelines as the *Strategic Initiative to Introduce Commercial Land Based Wind Energy Development to the Western Cape* (PGWC, 2006).

Due to limited information available in South Africa, and budget constraints for the definition of a national landscape policy for wind projects, the Provincial Government of the Western Cape (PGWC) developed the *Strategic Initiative to Introduce Commercial Land Based Wind Energy Developments to the Western Cape* in 2006, with the aim of establishing a methodology to be used for the identification of areas suitable for the siting of wind energy developments in the province.

The proposed methodology started from a complete review of the European case. They compared two methods, a criteria-based one and a landscape assessment approach. The first method involved the GIS plotting of threshold maps for guiding criteria, or so called negative mapping. The second method comprised a landscape assessment based on its character, value, sensitivity and capacity.

While the first method identifies where the wind turbines should not be located in terms of safety, conservation or environmental or planning concerns; the second method answers if the proposed development will cause changes to the characteristics in the landscape. The work undertaken by the PGWC resulted in a combined methodology that used the criteria based method for the delineation of areas appropriate for wind development; but incorporating methodologies for landscape and visual assessment studies.

Other types of guidelines such as the *Best Practice Guideline for Avian Monitoring and Impact Mitigation at Proposed Wind Energy Development Sites in Southern Africa* (Jenkis, et al., 2011), and the *South African Good Practice Guidelines for Surveying Bats in Wind Farm Developments* (Sowler & Stoffberg,

2011) are examples of what is being done for building a baseline for site selection decisions.

At the moment of writing this document (2014), the selection of most of the preferred bidders to provide the 1850 MW of offshore wind energy by 2016 has been completed; however there are still challenges to address, as the industry grows, the land availability becomes scarce and the cumulative impacts of today's decisions show up with time.

For the purpose of this study, Table 4 presents a summary of the current national criteria for wind farm site selection, as well as other selected values and criteria. National guidelines are first candidates, and if not available then international best practices are considered. Some variables would be identified but due to the lack of available information, some of them won't be included in the current study, like bird paths, magnetism or shadow flicker.

Table 4: Comparison of national and international criteria for site selection of areas for wind farm development

Criteria					Baban & Parry (2000) United Kingdom	Hansen *et al.* (2002) Denmark	Aydin *et al.* (2009) Western Turkey	van Haaren & Fthenakis (2011) New York St.	PGWC (2011) Method 1 Cape West Coast	DEA (2011) SEF Coastal provinces	Proposed for this study
Planning	**Visual**	**Noise**	**Flicker**	**Safety**							
Distance to single dwelling and rural areas	x	x	x	x	500 m	500- 1500 m	-	-	400 m	-	500 m
Distance to towns	x	x	x	x	2000 m	500- 1500 m	2000 m	1000 m	800 m	1 000 m	2000 m
Distance to cities	x	x	x	x				2000 m			
Distance to national roads	x		X	x	500 m	150 -450 m		500 m	3000 m	-	3000 m
Distance to local roads	x		X	x					500 m	-	500 m
Distance to provincial tourist route	x		X	x					4000 m	-	4000 m
Distance to local tourist route	x		X	x					2500 m	-	2500 m
Railway line	x			x	-				250 m	-	250 m
Distance to major power lines				x	-				250 m	-	250 m
Communication Towers				x	Omitted	1000 - 2500 m (radio mast)	Omitted	-	500 m	-	500 m
Radio and navigation beacons				x					250 m	-	250 m
Airport with primary radar				x	-	5000-7500 m	3000 - 6000 m	-	25 000 m	-	5000 m
Local Airfield				x	-			-	2 500 m	-	3000 m
Military zone, national security sites				x	-	-	-	-	15 000 m	-	15 000 m
Historic sits, heritage and cultural sites, national trust property	x				1000 m	-	-	-	500 m	-	500 m
Technical											
Slope and elevation	x			x	< 10%			< 10%	1:4 slope	< 8 degrees	<18% or <10°
Distance from ridge lines	x								500 m		500 m
Economical											
Wind resource					> 5 ms^{-1} (7-15 ms^{-1})[a]	250-650 W/m2 [b]	200-400 W/m2 [b]	Uses AEP		WS Ann ave.>8 ms^{-1} [a]	WS Ann ave. >5 ms^{-1} [C]
Distance to national roads					< 10000 m			Use cost/km to national road			<10 000 m
Distance to national grid					< 10000 m					Eskom tier appr: 17 500 Level 1 35 000 Level 2 70 000 Level 3	<10 000 m

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Table 4 (cont.): Comparison of national and international criteria for site selection of areas for wind farm development (cont.)

Criteria						Baban & Parry (2000) United Kingdom	Hansen *et al.* (2002) Denmark	Aydin *et al.* (2009) Western Turkey	van Haaren & Fthenakis (2011) New York State	PGWC (2011) Method 1 Cape West Coast	DEA (2011) SEF Coastal provinces	Proposed for this study
Enviromental												
National parks and natural reserves	x					1000 m		500 m		2000 m	10 000 m	2000 m
Protected natural environment, area of ecological value/special scientist interest								1000 m		2000 m	1 000 m	2000 m
Private nature reserves						1000 m		1000 m		500 m		1000 m
Ecologically sensitive area								250 m				1000 m
Wildlife conservation area								500 m				500 m
Mountain catchments										500 m	> 8 degrees	500 m
Distance to coastlines of undisturbed scenic value							1000- 4000 m			4000 m	1 000 m	4000 m
Distance to streams, lakes and rivers						400 m (water bodies)	150 - 650 m	400 m	3000 m	500 m		500 m
Distance to flood line									400 m	200 m		200 m
Distance to major wetlands (Ramsar sites)							2500-5000 m			2000 m		500 m
Distance to local wetlands								2500 - 5000 m		500 m		2000 m
Distance to bird habitats or avian flight paths where known							2500-5000 m	2500 - 5000 m		1000 m		500 m
Distance to important vegetation/remnant vegetation, forest and wood lands						500 m (woodlands)	300 - 800 m	by national regulation				1000 m

a. Wind speed annual average (m/s)
b. Wind power density (W/m^2)

3.4. Criteria for Site Selection

3.4.1. Planning

Beyond the provision of clean energy, wind farms can really leverage positive socio-economic benefits for local communities, especially the rural and low income communities (Conservation South Africa, Endangered Wildlife Trust, 2013). Planning criteria involves the location of wind sites where they are not a threatening aspect for the health, aesthetics or discomfort of inhabitants.

Noise

Noise is produced as a result of the mechanical interactions in the gearbox and generator, and from the aerodynamic interaction of the wind with the turbine blades. Noise impact can also occur from the construction and maintenance tasks. In South Africa, the South Africa National Standard SANS 10103:2008 (SANS, 2008) addresses ambient noise standard. For rural areas these are: 45 dBA during the day and 35 dBA during the night. Noise perception may vary amongst communities, and although manufacturers assure that modern turbines operate below the noise threshold, developers usually keep 500 m from the receptor to assure sound levels are met (Baban & Parry, 2001; Aydin, et al., 2010; Hansen, 2005).

A simple relation between the sound level at the source (turbine) and its propagation with the distance can be described by Equation 7 below:

$$L_p = L_w - [10log_{10}(2\pi R^2)] - \alpha R \qquad \textbf{Equation 7}$$

Where, $R^2 = H^2 + X^2$

L_w is the sound power level at the source and L_p the sound pressure level at a location, both measured in dB. H is the tower hub height, X is the horizontal distance of the receptor to the tower and $\propto$ the atmospheric absorption constant of 0.005 dB/m (van Haaren & Fthenakis, 2011).

Visual impact

Any landscape modification has a potential visual impact associated with it. Some areas may be more visually sensitive than others due to different factors such as number of viewers, viewer expectation, and cultural, ecological and scenic values. There is not a unique formula to address visual impact. A unique visual impact assessment must be undertaken for each project; therefore its inclusion in an initial site selection study is limited to minimum standards that avoid the selection of areas with the following: important topographical features, steep slopes, are less than 1 km from coastal zones, less than 2 km from large settlements and far from tourist routes and areas of high scenic value (2 to 4 km).

Turbine size, wind farm layout and distance between wind farms also have a significant impact in aesthetics; such factors are to be considered in more detail in a micro siting study.

Shadow flicker

In sunny conditions, there are alternating changes in light intensity from the moving shadows on the ground caused by the rotating blades. This shadow flicker may be a nuisance to nearby humans and even harmful if the frequency is high enough. It can also be a distraction to drivers if the turbines are located close to roads.

Shadow flicker is a function of the location of the receptor, wind speed and wind direction, diurnal variation of sunlight, local topography, latitude of the site and the presence of any obstructions (Nielsen, 2003). Mapping of this criterion is not available, but a safety buffer of 500 m is used to prevent effects on residents and drivers.

Roads and scenic routes

Traffic roads, rails or even hiking trails are a means of transport for people that will be exposed to the visual impacts of nearby wind farms. The type of road, its importance, carrying capacity and scenic tourist value are variables that affect the impact from wind farms.

Delivery infrastructure

Wind turbines rarely fail, but if they do, this may affect buried pipelines in the vicinity. Jackson et al. (2012) considered it appropriate to define an exclusion zone around transmission pipelines of approximately 1.5 times the mast height.

Adequate spacing between structures and overhead power lines is also recommended for general safety reasons. Turbines represent a risk to the conductivity of the transmission lines because of turbulence and vibrations. Effects on earth wires or just the falling of any of the generator pieces are also to be considered when selecting a site.

The UK National Grid Company recommends a spacing no less that 5 rotor diameters to the towel lines (Warein, 2008). As a general constraint, 250 m around delivery infrastructure has been chosen as a security buffer.

Electromagnetic interference

Either by being a physical obstruction that distorts communication signals, or by electromagnetic emissions produced, electromagnetic interference of the turbines can have a negative impact on signals important to human activities (NRC, 2007; AWEA, 2008). Although television and radio signals may be affected by wind turbines which are located in a 2-3 km zone around the largest installations, today, cable networks or line-of-sight microwave satellite transmissions are eliminating the electromagnetic interference of wind energy (IEA, 1987).

Aviation constraints

The Airspace and Safety Initiative Windfarm Working Group (ASIWWG, 2013) has indicated how wind turbine operations carry potential risk of collision, interference with accuracy of navigation aids, creation of turbulence that affects slower or lighter aircrafts, and modification of the flight paths due to the restrictions in the height of overflowing earthly obstacles.

With blades of 100 to 150 m tip height, a wind turbine offers a significant radar cross section to primary radar systems, returning a signal similar to the one produced by a medium aircraft such a Boeing 737 (Kirkland, 2010). Although authors Aydin et al. and Hansen initially considered a radius of between 3 to 7 km around airports safe, in the *Wind farm safety analysis for Port Elizabeth Airport in relation with potential wind farm developers in the region*, Kirkland strongly recommend avoiding any type of wind development within less than 10 km from a Secondary Surveillance Radar. In the case of Primary Surveillance Radars that may have a larger range, the location may be conditional to direct negotiation with the air controlling agencies.

National Security Sites

Not only due to possible electromagnetic interference, but for national security reasons, areas in this category are to be kept at minimum interaction with any other development. These may include, but not be limited to, military areas, defence sites and nuclear facilities. The PGWC makes provision for 15 km radius around it to be excluded for wind farm setting.

Heritage sites

Those locations designated by the governing body as important to the cultural heritage of a community. Concern over these sites is mainly related to visual contamination and safety reasons; the PGWC suggested a 500m radius of non-interference to this areas. Designation and management of heritage sites in the country follow the statutes from the *National Heritage Resource Act, 25 of 1999.*

3.4.2. Technical

Topography plays an important role not only in the wind resource but also in the technical feasibility of the project. Baban & Perry found in their surveys with stakeholders that the desired slope of the terrain should be smaller than 10%. Terrains with greater slopes are excluded simply because cranes to erect wind turbines and boring machines to construct foundations cannot operate safely on such slopes (van Haaren & Fthenakis, 2011; Grassi, et al., 2012).

Van Haaren and Fthenakis included another factor usually ignored in siting studies, i.e. the presence of porous soils and caves. Porous soils may double the cost of foundations. The destruction of caves not only possesses a structural risk; they may also modify the habitat of some fauna. They recommended avoiding zones with caves at least 100 m from surface.

The speed-up effect over ridges and tops of hills made them preferred areas for location; however it may also increase visibility. On the other hand, positioned aside from ridgelines and hilltops, turbines can be partially or totally hidden by hills and mountains. The SEF determined 500 m from the ridge lines as a good practice.

3.4.3. Economical

Wind energy projects have the advantage of using free fuel; but they are capital intensive. Initial investments include the cost of the wind turbine generators (WTG), transmission line interconnection, civil works, permits and studies (Grassi, et al., 2012) and (Wagner & Mathur, 2009). Project costs related to site location may account up to 20% of the total construction cost. These are: foundations, roads and grid connection (van Haaren & Fthenakis, 2011).

Wind resource

With no doubt, the most important factor for selection of a site is the wind resource. Wind varies over time, horizontal space and height. These variations are represented by vertical profiles of wind speed and direction, where the wind speed at ground level is 0 ms-1 (see Equation 2). Diurnal, seasonal and annual variations are also experienced (Manwell, et al., 2002; MacKinnon , et al., 2004; Grassi, et al., 2012).

The recommended value of average wind speed for coastal provinces in South Africa is a minimum of 8 ms^{-1} given the good resource of the country;

however, speeds of 5 ms^{-1} are good enough to maintain the rotation of the blades. Wind turbines are designed with a cut-in speed at which they begin to produce power, this value is usually in the range of 3-4.5 ms^{-1}. A cut-off speed is also set to prevent failure, which can be as high as 25 ms^{-1} (Grassi, et al., 2012).

As stated earlier, wind power is proportional to the third power of the wind speed, and to the blade swept area (sees Equation 4 for power density). Sites with higher power density than 200 W/m^2 are considered fairly good to start a project (Hansen, 2005; Aydin, et al., 2010).

Table 5 lists the wind resource classes as used by the NREL wind atlas, their corresponding average wind speed and wind power densities at 50 m height above ground level. Parvin (2010) presents the same information for wind values at 10 m height.

Table 5: NREL Wind power classification (NREL, 2003)

Class	Resource Potential (utility Scale)	Wind Power Density (W/m^2) @ 50m agl*	Wind Speed (ms^{-1}) @ 50 m agl
1	Poor	0-200	0.0-5.6
2	Marginal	200-300	5.6-6.4
3	Moderate	300-400	6.4-7.0
4	Good	400-500	7.0-7.5
5	Excellent	500-600	7.5-8.0
6	Excellent	600-800	8.0-8.8
7	Excellent	>800	>8.8

*agl: Above ground level

If the wind resource is good, as is the case of the South African coastline, the selection of sites with average speeds higher than 7 ms^{-1} is promising. The challenge of this study is to evaluate whether sites with lower annual average power density may be better candidates if their temporal variation profile resembles closer the energy consumption temporal profile of the population.

Distance to national roads

Installation of roads for the access of cranes, turbines and construction machinery implies high cost; these roads require at least 12 to 15 m width and a minimum radius of 45 m (Morgan & Ntambakwa, 2008). The recommended threshold for distance of generators to roads is usually applied for minimal safety concerns. Nevertheless, distance to major roads carries an important part of the economics of the project. Some authors (Ramirez-Rosado, et al., 2007; Grassi, et al., 2012; van Haaren & Fthenakis, 2011) include this component in their cost calculations proportionally to the number of kilometres of road that must be built to meet any of the major national roads. Baban & Perry suggested that sites in a range of less than 10 km from major national roads are desirable sites.

Distance to national grid

Surveys in the UK concluded that ideal locations are to be in a radius of 10km from major transmission lines (Baban & Parry, 2001). For South African initiatives, proximity to the national grid is a key consideration in the IPP first stage because extensions of the existing grid are unlikely to happen in the immediate future. Eskom, who plays the role of the buyer of electricity and manager of the transmission lines, has designed a three tier approach for connection of renewables:

- Tier 1: Connection of points that do not require power transmission reinforcement in the short term (2013), buffer of 17.5 km applied around substations.

- Tier 2: Medium term projects (2014 – 2020) for extensions to the grid that do not require reinforcements. Buffer of 30 km around substations.
- Tier 3: Long term strategy for the creation of transmission hubs and corridors. Buffer of 70 km around substations.

3.4.4. Environmental

In general, effects from wind energy on the environment are positive; energy produced is considered clean as it reduces contaminating mining activities and greenhouse and air pollutant emissions. However, there is evidence of the influence of wind farms on ecosystems by direct impacts on organism, or through impacts on their habitats by alteration or displacement of landscape (NRC, 2007).

The SEF determined as good practice to keep areas in 1 km radius around sites of environmental concern undeveloped, and 10 km around national parks with the possibility of being reduced accordingly by independent analysis of each case. Most of the decisions for land use are to be in agreement with the *National Environmental Management: Biodiversity Act, 10 of 2004*.

Natural Reserves

National parks, natural reserves and private game reserves are to be excluded and protected from wind farm development. This is not only for aesthetic alterations, but as protective measures taken to reduce the negative impacts on terrestrial animals.

Protected areas

Either because they are representative areas of South Africa's biological diversity, natural landscapes or seascapes; protected areas are unquestionably to be excluded from any renewable energy development. *The National Environmental Management: Protected Areas Act, 57 of 2004* describes these areas and gives guidance for their management.

Surface waters, wetlands and coasts

Streams, rivers, lakes and coasts are special features of the landscape, home of avian species and sites of recreation that should be excluded. Security measures also apply in order to prevent them from flood damage.

Likewise, wetlands and Ramsar sites are ecologically important areas, as they are crucial in protection, collection and purification of water. As South Africa is a water scarce nation, strong preservation measures must be put in place, where minimum distances of 150-500 m from wetlands have been proposed (Baban & Parry, 2001) but if land availability is not a constraint, bigger buffers (approximately 2000 m) are recommended by the PGWC.

Avian flight paths

One of the most common rejections to wind projects is that they may be detrimental to birds and bats through the destruction of habitat, the displacement of populations from preferred habitat, and collision mortality; however very little about the topic is known in South Africa.

The rotating blades of wind turbines cause blur image on bird's eyes; therefore, birds construe that image as safe to go through, which leads to bird collision (Morrison & Sinclair, 2004). Studies have estimated a mortality rate of 2.5 birds and 12.2 bats per year per turbine (Miller, 2008).

Impacts on bats may vary depending on site selection, species and season. According to Sowler & Stoffberg (2011), bats fatalities outnumber bird fatalities by a ratio of 10 to 1. Negative impacts are the result of direct collision, lung damage produced by sudden change in air pressure close to the turning blade, loss of habitat, barrier effect of commuting and migrating routes, and some emissions of ultrasounds from the turbines (Sowler & Stoffberg, 2011).

To mitigate or eliminate the risk of bird and bat collision and prevent disturbance of their habitat, generators should be placed at a safe distance of bird flyways and breeding grounds, specifically wetlands and wildlife refuge forest (van Haaren & Fthenakis, 2011). The proposed setback ranges from 300 m to 500 m (Clarke, 1991).

After site selection, the *Best practice guidelines for avian monitoring and impact mitigation at proposed wind energy development sites in Southern Africa* and the *South African Good Practice Guidelines for Surveying Bats in Wind Farm Developments*, propose the implementation of pre- and post- construction monitoring projects and surveys at the proposed site, starting at a minimum of 12 months before the initiation of the construction works.

Agricultural land

Uncultivated land with a high potential for cultivation should also be dealt with carefully to ensure that the potential to cultivate the land sometime in the future is not foreclosed (DEA & GIZ, 2011). For the case of agricultural land, it is ruled by the *Conservation of Agricultural Resources Act, 43 of 1983*.

4. GIS METHOD FOR SITE SELECTION

This chapter describes the methodology followed in the assessment of environmental and technical related criteria from the Site Identification Group; and the discussion of sources, methods and evaluation of the wind resource and its expected power output. Results are then combined to estimate the overall fitness of a site in terms of environmental feasibility, wind potential and adjustment to electricity demand. The whole process is developed and documented in a GIS environment.

A Geographic Information System is the combination of technical and human resources to efficiently capture, store, manipulate, analyse, manage and display all forms of geographically referenced information (Redlands, 1990).

These informatics systems allow for arrangement of real world and projected information in a given region as a set of maps. Each map -also referred to as layer- displays specific information of one characteristic in the region. Each layer is carefully overlaid with others, so the location matches precisely with the location of other maps in a common reference system.

GIS provides powerful tools for decision making when identifying feasible wind turbine locations that reduce environmental impacts. It has been successfully implemented around the world since early 2000's (Baban & Parry, 2001). Some examples were presented earlier in Section 3.2: Methodologies for Site Selection. Its functionality lies in the fact that multiple data sources can be included in the analysis, and be adjusted for user preferences. This leads a highly efficient and tailored process. The methodology becomes easy to track and reproduce, facilitating the sharing of the results (Aydin, et al., 2010).

4.1. PROPOSED GIS BASED METHOD FOR SITE SELECTION

The installation of a wind farm has multiple stages where GIS can be useful, such as: The initial suitability assessment, project planning, micro-siting, wind farm layout, land management, etc. The aim of this study is to propose a GIS customized tool for the earlier stage in the project development, the initial suitability assessment.

The herein proposed methodology was developed using GIS software from the Environmental System Research Institute, ESRI, in its ArcGIS Desktop version 9.3 (ESRI, 2009). The ArcGIS 9.3 includes a set of interactive geoprocessing tools (i.e. clipping, merging and overlays) that can be linked in a sequence of workflows in order to build models. Although any scripting language that supports Component Object Model (COM) can be used for creating the models; the ModelBuilder application includes a visual programing environment to graphically link the geoprocessing tools (ESRI, 2008).

The analysis is done on geographically referenced datasets, with user-specified criteria. Once the programming is concluded, the model becomes an accurate documentation of the methodology used, which can also be easily reproduced in any other area.

Datasets are a combination of vector or raster data representations of geospatial characteristics. Vector data models refer to discrete representation of the world by using points, lines or polygons. Raster data models refer to a continuous representation of a surface divided into a regular grid or cells (ESRI, n.d.). Figure 14 exemplifies the difference between vector and raster information. For the proposed methodology, the resolution of the raster data will be determined by the output resolution of the wind model.

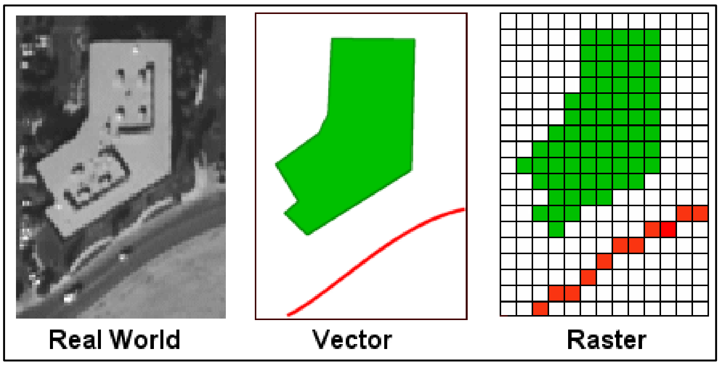

Figure 14: Representation of vector and raster data models (geography.hunter.cuny.edu)

As discussed earlier in section 3.4, there are different criteria that affect the planning and the technical, economic and environmental feasibility of a wind farm. For the proposed method, such criteria have been grouped into two main categories: The Site Identification group, and the Resource & Energy Generation group. The Site Identification group incorporates technical, environmental and restricted criteria within a spatial frame; while the Resource & Energy Generation group accounts for the wind resource, estimated energy generation and fitting to energy demand profiles under a spatial-temporal frame.

Finally, by using a weighted overlay, the layers are combined assigning each one a percentage according to the influence of each factor, the result is an individual Site Identification Score. The proposed weights were assigned empirically and are not exempt of being improved by an expert's opinions.

On the other side, wind resource data is used to estimate the energy potential. The energy potential is compared against electricity consumption and the results are used to assign an individual Resource & Energy Generation score for each site.

Output from the Site Identification group is combined with the output from the Resource & Energy Generation group. This combination ends up with a final suitability output score that may help decision makers and wind developers in addressing the starting point for site selection. The suggested sites are expected to perform better according to the energy consumption profile, and to have a less harmful impact on the environment.

A schematic of the proposed methodology is given in Figure 15 below, and will be described in more detail in the subsequent sections.

For the site selection exercise, different layers of information must be collected and geo-processed. The study area is divided into a regular grid of determined resolution where each cell represents a potential site for location of a cluster of wind turbines. The criteria associated to the technical and environmental objectives are then resampled to fit the created grid.

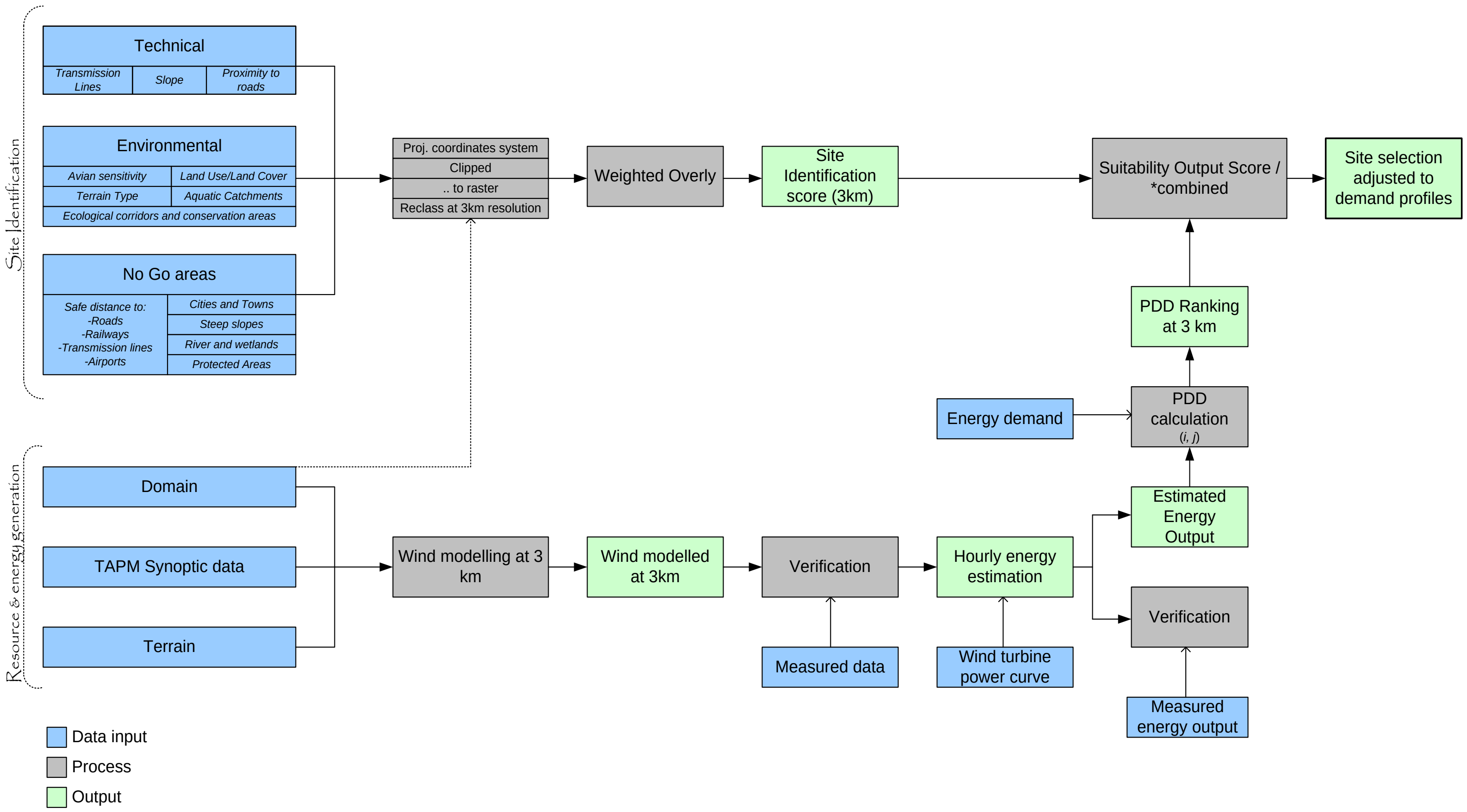

Figure 15: Representation of the proposed methodology for initial site suitability assessment

4.1.1 The Site Identification Group

The Site identification group evaluates all characteristics that make a site suitable for wind farming in terms of economics, technical feasibility and environmental and planning restrictions.

Technical

The technical component includes the evaluation of the slope gradient, as well as the distance of the site to the national roads and the transmission grid lines. These factors are believed to strongly impact the capital and construction cost, hence having a significant influence in the total cost of the wind project.

The average wind resource is usually found to be analysed together with these components. However, for this study, a different and independent treatment of the wind resource and its energy generation profile was undertaken. It consists of evaluating the unique wind power profile of each site against the energy consumption profile.

The distance of the potential sites to the national roads and the transmission lines has been set up as desired being less than 10 km (refer to Table 4). In order to categorize the sites, the Euclidean distance tool is used. The Euclidean distance between two points is represented by the length of the line segment connecting them, and is given by the Pythagorean formula. Description of the ranking according to this distance is given in Table 6.

The roads and transmission lines are datasets of vector type. The national roads vector file was obtained from the Chief Surveyor-General office, which includes national, secondary and arterial roads. Regarding the transmission lines, only lines of high voltage were considered as capable of handling the connection of a wind turbine project (>132kV chosen for this case); although this will depend on the size and number of turbines.

On terrains with slopes greater than 20%, cranes cannot be safely operated to erect wind turbines, nor the machinery to construct the foundations. Transport of equipment on such slopes becomes complicated, and the requirement of construction of access roads of 12-15m wide and a minimum radius of 45m for the transit of cranes, makes the project exorbitantly expensive (Morgan & Ntambakwa, 2008). A slope of 18% (or 10°) or less has been identified as suitable for wind development. The proposed ranking according to the slope value is also presented in Table 6 below.

Table 6: Suitability ranking criteria proposed for the technical component

	Criteria		Ranking	Description
Distance to Transmission line	<10		5	Preferred – Immediate availability
	10-17.5 km		4	Eskom Level 1 – Immediate availability
	17.5 – 35 km		3	Eskom Level 2 - Medium term availability
	35 km – 70 km		2	Eskom Level 3 – Long term availability
	>70 km		1	Unsuitable
Distance to national roads	<10 km		5	Preferred
	10-15 km		4	Adequate
	15-20 km		3	Tolerable
	20-25 km		2	Not recommended
	>25 km		1	Unsuitable
Slope	0°-5°	0-8%	5	Preferred
	5°-7°	8-12%	4	Adequate
	7°-8°	12-14%	3	Potentially Sensitive
	8°-10°	14-18%	2	Highly Sensitive
	>10°	>18%	1	Unsuitable

The slope values are derived from the global elevation data collected by the Shuttle Radar Topography Mission (SRTM) from the NASA. It recorded elevation data for almost the whole earth at a resolution of 3 arc-seconds, or approx. 90 m

(NASA, n.d.) (VTP, n.d.). Data for Africa is freely available from the University of Free State mirror website at *http://mirror.ufs.ac.za/datasets/SRTM3/Africa/.*

The slope is calculated as the rate of maximum change in the elevation over the distance between each cell and its neighbours, and it can be given in percentage or degrees. The lower the slope value the flatter the terrain (ESRI, 2008).

Environmental

The environmental component includes the evaluation of sites in terms of their environmental sensitivity; this includes avian sensitivity, ecological corridors and conservation areas, aquatic biodiversity sub catchments, terrestrial biodiversity and land use.

An indication of the South African areas where the establishment of wind farms may have a negative impact on birds, has been given in the *Avian Wind Farm Sensitivity Map for South Africa* (Retief , et al., 2012).

The map estimates the sensitivity of each 5′x 5′ block (approx. 8 x 8 km) by taking into account the bird species and the sensitivity of the area. The bird species evaluation includes the presence of most vulnerable species to be killed by wind turbines, which is based on research undertaken in other countries (for complete list of studies see Retief, et al., 2012; pg. 9-12), the species of conservation concern, and the species not likely to be found in areas of wind farm settlement. The area sensitivity takes into account whether the block falls in a protected area, Ramsar site or a site with congregatory birds.

As this map is in its first version, it still has a high uncertainty in the data. Uncertainties are mostly from the information regarding bird species likely to be found in a given area. Therefore, together with the final sensitivity score of each block, a confidence factor (CF) ranging from 1 to 10 is given, where 1 indicates low CF and 10 the highest. There is an additional CF denominated SB1; it indicates the lowest CF as data for it was obtained from the Southern Africa Bird Atlas Project 1 and may be outdated.

The CF value is proportional to the number of submitted lists recording species in a determined area (block). Namely a CF of 4 means that for that specific block 4 field visits have been carried out. In each visit, information regarding the types of birds and conditions found in that specific area are recorded and submitted. It has been concluded that after about 7 visits/lists, the number of new species identified in the area is not significant.

As input criteria of the proposed tool, the avian sensitivity is required to have a unique numerical value attached to each cell; hence a transformation of the data was undertaken. The transformation of the data implied a new confidence factor estimated as follows: if the original CF is SB1 or ranges from 1 to 3 is now classified as ‘low’, if the CF value ranges from 4 to 6 is classified as ‘medium’ and if it ranges from 7 to 10 is classified as ‘high’.

If the new confidence factor is low, it is expected that the species of birds present in that area are being underestimated; hence the new sensitivity factor corresponds to the original sensitivity factor multiplied by 1.2. If the new confidence factor is medium, it is expected that the bird species inventory slightly underestimates, and then the original sensitivity factor is multiplied by 1.1. If the confidence factor if high, the sensitivity value remains as the original.

This new Total Sensitivity Factor ranges from 0 to 1000, which is reclassified for a scale suitable to the required ranking system as detailed in Table 7 below.

Table 7: Suitability ranking criteria proposed for the avian sensitivity of the environmental component

	Criteria	Ranking	Description
Avian sensitivity	0-200	5	Preferred
	200-400	4	Adequate
	400-600	3	Tolerable
	600-800	2	Potentially Sensitive
	800-1000	1	Highly Sensitive

Ecological corridors are biodiversity areas that act as a link for wildlife and plant migration that once was separated by human activities or structures. As areas of such importance for preservation of the biodiversity, it is preferred to avoid them. Conservancy areas and proposed conservancies areas, although not yet under a firmer conservation commitment (Mpumalanga Parks Board, 2006) still indicate areas of high biodiversity that should be of concern. Proposed ranking for the ecological corridors and conservancies is presented in Table 8.

Shape files of the ecological corridors, conservancies and proposed conservancies were obtained from the Mpumalanga Parks Board, as part of the Mpumalanga Biodiversity plan.

Land use/Land cover data is useful to indicate the changes and impacts on biodiversity, and are often a reference for applications for monitoring, planning, biodiversity, climate change, etc. For this reason, the South African National Biodiversity Institute (SANBI) compiles the national land information in its Land use/Land cover product (SANBI, 2009). The version used in this study corresponds to the 2009 one; a raster file that identifies seven classes of land covers for the whole country. Each class has been ranked according to its suitability to be used for the construction of wind farms. It is presented together with other environmental factors in Table 8 below.

Table 8: Suitability ranking criteria proposed for environmental component

	Criteria	Ranking	Description
Ecological corridors and conservancies	N/A	5	Preferred
	Proposed Conservancy	3	Area to be negotiated
	Conservancy	2	Potentially sensitive
	Ecological corridor	1	Preferred to avoid
Aquatic biodiversity sub-catchments	5. Ecosystem maintenance	5	Preferred
	4.Important and necessary	4	Adequate
	3.Highly significant	3	Potentially Sensitive
	2.Irreplaceable	2	Highly Sensitive
	1.Protected	1	Unsuitable
Terrestrial biodiversity	6. No natural habitat remaining	5	Preferred
	5.Least concern	5	Preferred
	4.Important and necessary	4	Adequate
	3. Highly significant	3	Potentially Sensitive
	2. Irreplaceable	2	Highly Sensitive
	1.Protected	1	Unsuitable
Land use / Land cover	7. Mines	4	Adequate
	6. Plantations	3	Potentially Sensitive
	5. Water bodies	1	Unsuitable
	4. Urban Built-up	1	Unsuitable
	3. Degraded	5	Preferred
	2. Cultivation	3	Potentially Sensitive
	1. Natural	4	Adequate

No-Go Areas

Besides the criteria mentioned above, wind energy projects are not likely to be allowed in land serving a specific purpose like national parks, historic sites, protected areas, military zones, etc. There are also safety restrictions of minimum distance required around roads, power lines, railways, airports, etc.

The restricted zones are formed by applying an inclusive buffer of a given dimension according to the criteria mentioned earlier and summarised in Table 9 below. The No-Go areas component is then formed by simply merging all the independent sets of restricted zones.

Table 9: Restricted areas and buffers applied for definition of the No-Go areas

Criteria	Buffer applied
Local airfield	2500 km
Railway lines	250 m
Roads – Highways	2000 m
Roads – Provincial roads	500 m
Rivers – FEPA	500 m
Rivers – Third and Fourth order	250 m
Ramsar sites	2000 m
Large wetlands	500 m
Transmission lines	250 m
Urban areas	2000 m
Protected areas	1000 m
Sloped > 10°/18%	Restricted
National Parks and natural reserves	2000 m
Historic sites	500 m
Military zones	15000 m
Communication towers	250 m

The identification of No-Go areas simply uses criteria to determine where wind turbines cannot be located for safety, conservancy or environmental issues. By itself, it is just a negative mapping without much information; but when combined with other datasets it becomes relevant for decision making.

The information regarding airports was obtained from The Air Transport dataset, 1:50 000 accuracy vector maps from the Chief Surveyor-General office (*http://csg.dla.gov.za/struc.htm*). Data seemed to include old and non-operational airfields; therefore it was compared and updated with the airport records in Google Earth® and open access data from *www.ourairports.com*.

Railway lines and national roads information was also obtained from the Chief Surveyor-General office. Only national and arterial – so called provincial-roads were included. The buffer around arterial roads was set as 500m for security concerns, and a 2 km buffer was applied around the highways. This wider buffer is mainly a subjective decision to account for the beauty of the landscape crossed by the national roads in the study area.

Information regarding rivers and wetlands was obtained from SANBI. The shape file for rivers summarizes the information used to derive the Freshwater Ecosystem Priority Areas (FEPAs) national atlas (SANBI, 2011).

The South African Protected Areas Database (SAPAD) was obtained from the former Department of Environment Affairs and Tourism (DEAT). It includes, amongst other datasets, the shape files of national parks, nature reserves, world heritage sites and protected environments (DEA, n.d.).

Although the land cover dataset mentioned in the environmental component differentiates land used for urban purposes and water bodies, such a product should be used just as a rough indication of major land types. It is suggested by the developers to avoid its use when finer detail is required (SANBI, 2009). For this reason, datasets of higher resolution were used to exclude rivers, wetlands, Ramsar sites and urban areas.

Regarding settlements, the latest Census South Africa undertaken in the year 2011 adjusted the boundaries of the demographic areas to include the extension of towns and cities (Statistics South Africa, 2012). The census data results are grouped into Census Sub-places which are geographic areas smaller than the local municipalities.

The British and European guidelines suggest urban areas should not be candidates for placing turbines, and wind farming should happen as far as possible from the cities. However, other opinions are also available, such as the one from the PGWC (2006) which proposes that bringing turbines closer to the urban areas also brings energy generation closer to the bulk of energy consumption. In this case, the first approach is used with the possibility of updating the method later for inclusion of urban settlements and surroundings, although this may require updated high resolution of urban areas data. In order to determine with accuracy what census sub-places can be designated as urban or rural, the household density was used. Census sub-places with a household density bigger than 100 houses per square kilometre have been designated as urban areas, and a 2 km buffer around them was applied.

In rural areas, as a safety measure, wind turbines should be located 500 m from any household. In order to identify the location of the households in the rural areas, the 2006/07 Spot Building Count (SBC) product from Eskom was used. The SBC is a satellite product that places a point (spot) on each detected roof and represented it in a vector format (SANBI, 2009). Each point is assumed to be a household, and a 500 m buffer around was applied.

Site Performance Index

In order to rank the sites, a GIS-based multi-criteria decision making tool is used. An overall Site Performance Index (SPI) is obtained for individual alternative locations by using a weighted overlay (Eastman, 1995).

The weight of each layer has a direct influence on the results obtained, therefore two scenarios were evaluated. Scenario one assumes that all the layers are equally important therefore the same weight is assigned. Scenario two allocates weights according to a perceived importance (order), which is always susceptible of being changed from experts' evaluation. The applied weights for scenario two are summarised in Table 10 below.

Table 10: Weights applied to each characteristic

Site identification characteristics	Order	Weight
Distance to Transmission line	1st	20%
Distance to national roads	1st	20%
Slope	2nd	15%
Ecological corridors and conservancies	2nd	15%
Avian sensitivity	3rd	10%
Terrestrial biodiversity	3rd	10%
Land use / Land cover	4th	5%
Aquatic biodiversity sub-catchments	4th	5%
No-Go areas		Restricted/Excluded
Total		**100%**

4.1.2 The Resource and Energy Generation Group

The wind resource

Environmental suitability and wind energy potential are to be considered together. A site which does not have sufficient wind energy potential is not an appropriate location for wind turbines no matter how high its environmental performance score is; this makes the information regarding wind resource vital for the analysis.

In the country, the best source of wind resource information is the Wind Atlas for South Africa, WASA. It is a numerical atlas for the national planning of large-scale exploitation of wind power (WASA, n.d.). The description of the methodology used for modelling and verification is freely available in their web site, as well as the results obtained so far (WASA, n.d.).

Figure 16 displays modelled wind speed from WASA at 100 m height. It is of note that the modelling was restricted to 3 provinces along the coast line. Although this modelled wind dataset is currently the most reliable source of information for wind resource evaluation, the fact that it only covers areas in the Northern, Western and Eastern Cape limits its usage for intended developers in other areas in the country (see Figure 16).

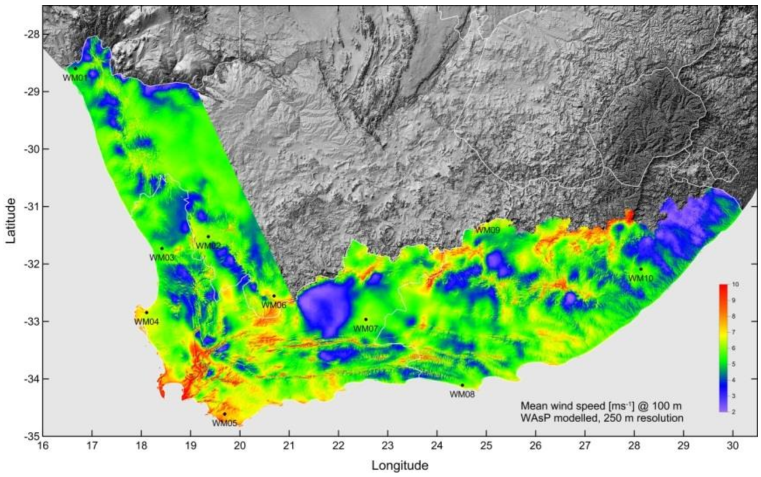

Figure 16: WASA modelled mean wind speed (ms^{-1}) at 100 m height (www.wasaproject.info)

EScience Associates (Pty) Ltd has completed notable work in wind resource identification over the whole country parallel to the WASA project. EScience has kindly provided TAPM modelled hourly wind for the full year 2011 within the area of study.

The Air Pollution Model (TAPM) is a mesoscale prognostic atmospheric model that makes use of observed data to accurately model meteorology over a regular grid. Meteorology is an essential requirement and is the principal factor to the dispersion of pollutants in the atmosphere. Important meteorological factors that directly impact the dispersion of a pollutant include wind speed and direction, atmospheric turbulence which is related to vertical dispersion and vertical temperature profiles associated absolutely stable layers that affect vertical dispersion (Hurley, 2008).

Geophysical data requirements of the model include land use type and terrain elevation. Land use categories and terrain of the surrounding region are discussed in their relevant subsections. These features (land use and terrain) have a strong influence on wind speed and turbulence, which are key components for dispersion.

TAPM synoptic data is provided by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) as input of their dispersion model. A set of synoptic data contains the patterns of all meteorology around the globe for a given year. At the time of running the wind model for this study, the latest available TAPM data was for 2011.

Wind varies with time and also in the horizontal space and height. For a specific location, such variations are characterised in terms of vertical profiles of wind speed and wind direction, as well as diurnal/annual variations. The modelled wind data includes the average and the standard deviation of annual wind speed characterised by the Weibull distribution parameters (refer to section 2.1) (Grassi, et al., 2012). The vertical profile is strongly dependent of the roughness of the terrain (Manwell, et al., 2002; MacKinnon , et al., 2004).

Modelled wind output is obtained at reference heights of 10m, 20m, 50m, 100m, 150m, etc. above ground level. In case the wind speed needs to be extrapolated to the hub height of the generator, the logarithmic approximation (Equation 2) is used. Spacing between the modelled grid points is 3 km, which is the reason why this analysis for site selection is limited to such resolution.

Wind resource verification

WASA modelled wind output has already been verified against measurements taken on tall masts (60 m height) distributed along their domain. TAPM or any other modelled wind data may be verified against the WASA tall mast information if the location matches. Otherwise, wind speed and wind direction records from the meteorological stations of the South African Weather Services (SAWS) across the country can be used. Herein, measured wind data at 10 m height for verification, was kindly provided for by SAWS.

Verification includes visual inspection of time series, calculation of index of agreement, correlation coefficient, comparison of Weibull distribution parameters, wind roses, etc.

Estimated energy generation

Traditional wind resource assessment uses Annual Energy Production (AEP) as a means of evaluation of the energy potential of the sites (refer to section 2.4.6). The value of the AEP is affected by the wind over the eligible area, the technical parameters of the wind generator and the losses as a result of the array of the turbines (Grassi, et al., 2012). In order to select a site according to its energy generation profile rather than its AEP, estimations of the expected energy produced are done for smaller time periods, hourly in this case.

The power output of a Wind Turbine Generator (WTG) is represented by a power generation curve. Each turbine is built with specific dimensions and efficiency rates to accommodate the conditions (i.e. strong intermittent winds, or soft continuous winds, etc.), hence different WTG have different power curves.

This calculated power output is usually provided by the manufacturer of the turbine, or it can also be found in databases of wind farming modelling software. A Vestas V90 (2 MW) generator of 90 m diameter and 100 m hub height was chosen for the energy estimations. This turbine performs better in light but constant winds, as the ones present in the study area. Its power curve was obtained from the Wind Atlas Analysis and Application Program (WAsP) WTG database, and is presented below in Figure 17.

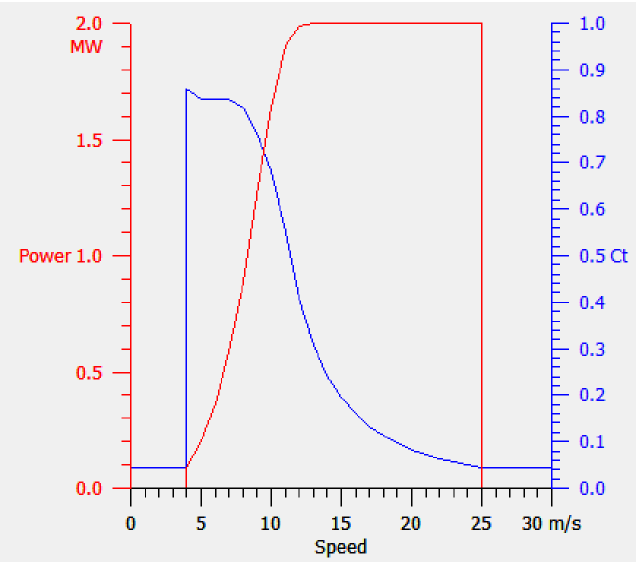

Figure 17: Power curve for a Vestas V90 2MWof 100m hub height and 90m rotor diameter (sourced from WAsP - WTG database).

Vestas is a Danish manufacturer currently producing about 40% of the new wind turbines to be installed in South Africa under the window 1 to 3 of the REIPPP program.

The turbines need a minimum wind speed to produce the torque necessary to make the blades move. The speed at which turbines start to rotate is known as cut-in speed, 4 ms^{-1} in this case. Likewise, a cut-off speed is set to break the system and prevent the damage by tension and torsion; usually at 25 ms^{-1}.

As the wind speed increases, the electrical output also increases rapidly by almost a factor of three. However there is a point known as the rated output wind speed; from this point, the power output stops increasing as it has reached the limit that the generator is capable of (Wind Power Program, n.d.). Calculated energy output in power curves are in accordance to the already mentioned Betz limit and other energy losses (refer to section 2.1)

To calculate the hourly energy output of each cell, power curve values are applied to hourly wind data. An assumption is made that each 3km block cell represents a wind farm, and can accommodate 3 turbines. A typical wind farm would consist of 10 to 20 turbines; however in this case we are comparing the results against the electricity demand profile of a small section of a town where the maximum requirement is about 9 kWh.

Other factors such as the air density and the wake effect from the distribution of the turbines are known to affect the final energy output. In this case the standard air density of 1.225 kg/m^3 was used (at sea level and 15 C°); but calculations can be modified to include different air densities according to the altitude of the site.

Wake effects from the arrangement of the turbines are expected to reduce the possible electricity obtained from a wind farm. In reality one will have to determine the exact location of the turbines within the 3 km block, and the layout, in order to estimate these losses accurately. However, for the aim of this study, assuming a reduction of 30% is sufficient. 30% is the average of wake losses found in literature (Breakey & Halberg, 2013).

Energy generation verification

The output from the above proposed method for estimation of energy generation requires some verification. For it, calculations were undertaken for the already existing Klipheuwel wind farm in the Western Cape, and results then compared against the recorded hourly energy output.

Verification includes visual inspection of time series, calculation of index of agreement and correlation coefficient.

4.1.3 Demand Analysis

Besides different strategies in place to smooth the variations in the electricity demand, there are always significant variations produced by the mass number of consumers and their power needs; for instance the morning and evening peak hours. Figure 18 presents the demand fluctuations at an energy distribution point in Volksrust during the 7th of August 2012, the day with the highest peak consumption during the year. Off-peak time, standard time and peak time are marked as recorded by Eskom in their billing system.

Demand rose rapidly at around 5 am and decreased significantly during the night. The half hour changes in demand are shown in the right-hand figure. Between

5:30 and 6:00 in the morning, the maximum change between two consecutive half hours was 424 kW; and during the evening 254 kW between 7:30 and 8:00 pm. Negative changes are usually recorded from 9:00 pm onwards.

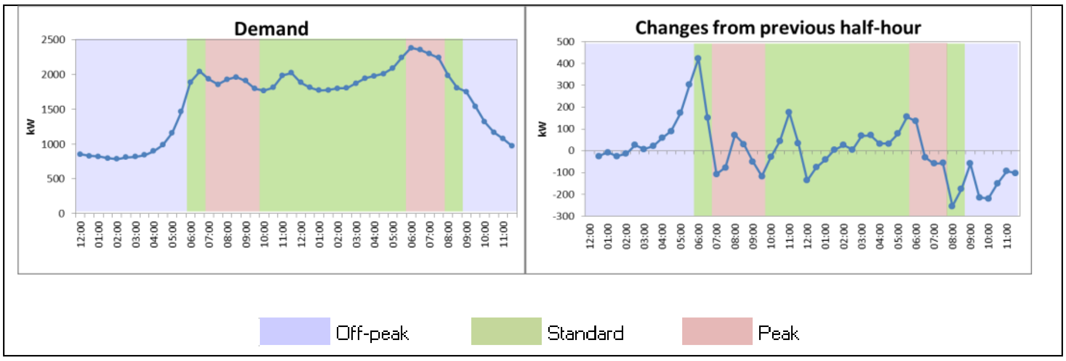

Figure 18: Demand fluctuation at energy consumption point on 7th August 2012

The need is for selecting places with the smallest variation between the electricity produced and the electricity demand. The Production to Demand Difference (PDD) has been selected as the indicator of such variations, so that the new purpose is to identify spots where PDD becomes smaller with time. The Mean Difference (MD) is also taken into account to obtain further information regarding the trends of the differences. For instance, if the MD is negative, it may suggest that the electricity generated from the wind is not sufficient to supply the demand most of the time.

Figure 19 presents two days of hourly energy demand of a consumption point in Volksrust (blue dot line). The diurnal profile is obvious, as the reader could observe peaks at around 7 am and 8 pm. The green solid line on the other hand, indicates the expected energy output produced in a generation block for the same period; it is based on the wind speed which is represented by the red dot line.

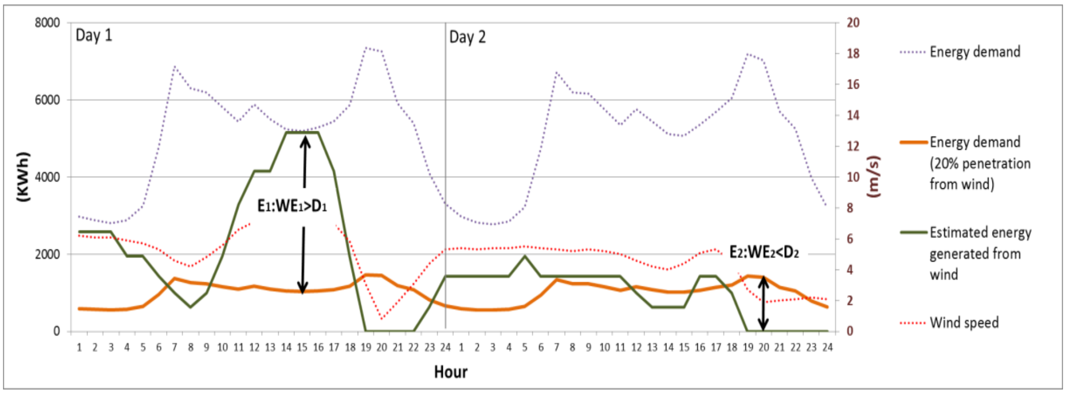

Figure 19: Hourly energy demand vs. estimated wind energy production at the study areas, considering the 20% penetration scenario.

The penetration of wind electricity into the national system is considered safe until around 20%. As explained earlier (refer to Section 2.4.4), this percentage is calculated from the total annual energy required; but not on an hourly basis as required for our study. Therefore it was decided to compare the wind generated electricity against a fraction of the total hourly electricity demand. Two scenarios of this fraction are evaluated, the 10% and 20%. In the graph it is represented by the orange solid line which becomes the new target. E1 and E2 denote the differences incurred when the wind electricity generated (WE) is higher or lower than the electricity required (demand, D).

Thus, the PDD and MD calculations over a period of one year are given by:

$$PDDannual = \frac{\sum_{i}^{8760}(WE_i - D_i)^2}{8760} \quad \textbf{Equation 8}$$

$$MDannual = \frac{\sum_{i}^{8760}(WE_i - D_i)}{8760} \quad \textbf{Equation 9}$$

Where i indicates the hour of the year, with a typical year having 8760 hours.

When evaluating variation, the differences have the same importance as if they are the result of over or under production; however, small variations are expected to receive a smaller penalty and this is achieved by the use of the square in the PDD formula - although applying that square also means that the final PDD values are usually large numbers. In order to facilitate the calculations, when combining it with the SPI, the PDD values have been scaled down by dividing them into 1 000 000.

Hourly energy demand data for a consumption point in Volksrust was obtained from Eskom for the year 2012, which then defined the study area. As mentioned earlier, only 2011 wind data was available, therefore the energy demand profile for 2011 was assumed to be the same as in 2012.

A comparison graph of the electricity consumption for the week number 10 of the years 2012 and 2013 is presented in Figure 20, where it can be demonstrated that electricity consumption in general remains very similar from one year to another. Differences are expected if there are stronger winters or any other external factor such a big sports event.

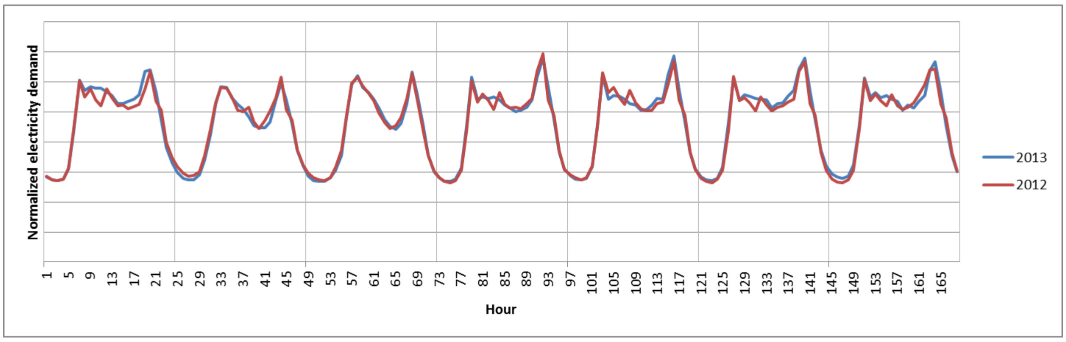

Figure 20: Normalized hourly electricity demand of week number 10 of two different years, 2012 and 2013, for a consumption point in Volksrust, MP – Sunday to Saturday-

Proper care was taken when assigning the 2012 values to 2011, to align the same day of the week, subsequently the first Monday in 2012 is also the first Monday in 2011; this is because the electricity demand presents a strong weekly profile.

4.1.3 Combined score

The individual score of the SPI of each cell is then multiplied by the PDD of that same cell, giving a result which is the *Combined Suitability Output Score*, also referred to as *combined score*. The blocks with a lower combined score will then indicate potential sites for location of wind farms that are environmentally suitable and with a smaller variability. Notice that the SPI scale was previously in the range of 1 to 5, with 5 being the most desired site. To be consistent to the PDD approach, the SPI scale has been inverted before doing the combined score. Consequently 1 now indicates the most desired site and 5 the least desired one.

A display of the complete built model is presented in Appendix A. This itself can become the full documentation of the method applied and can easily be reproducible for different areas, and implemented by other users.

5. STUDY CASE

This chapter presents the results and analysis of results after applying the methodology described earlier in a 160 km by 160 km domain covering mainly Mpumalanga. Different scenarios are evaluated to present the flexibility of the tool. Finally, the combined modelled results are displayed in a map with a scale that suggests site development according to criteria discussed in this document.

The selected energy consumption point for the study corresponds to one of the biggest distributors of electricity within the Pixley ka Seme Local Municipality, in the Gert Sibande District Municipality, Mpumalanga, South Africa.

This point is located in proximity to the Volksrust town, with coordinates latitude: -27.375 and longitude: 29.879 (see Figure 21). It works as a re-distribution centre from the Municipality, dispensing electricity from the national electricity producer, Eskom, to the final users. In 2012 the amount of electricity re-distributed by it counted for about 45% of the total electricity provided by Eskom to the Municipality and surroundings (Aucamp, 2013).

For the site identification and wind resource analysis, a domain of 160 by 160 km, including the study point, was chosen. The domain contains the Pixley ka Seme Local Municipality, as well as parts of Lekwa, Msukaligwa, Mkhondo and Govan Mbeki municipalities from the Mpumalanga province, Newcastle and Emadlangeni municipalities from the KuaZulu-Natal Province, and Phumela Municipality from the Free State Province.

The dimension of the domain was decided in order to include a large enough area for the site identification analysis and the wind modelling. It also contains the SAWS meteorological stations used for modelled wind verification.

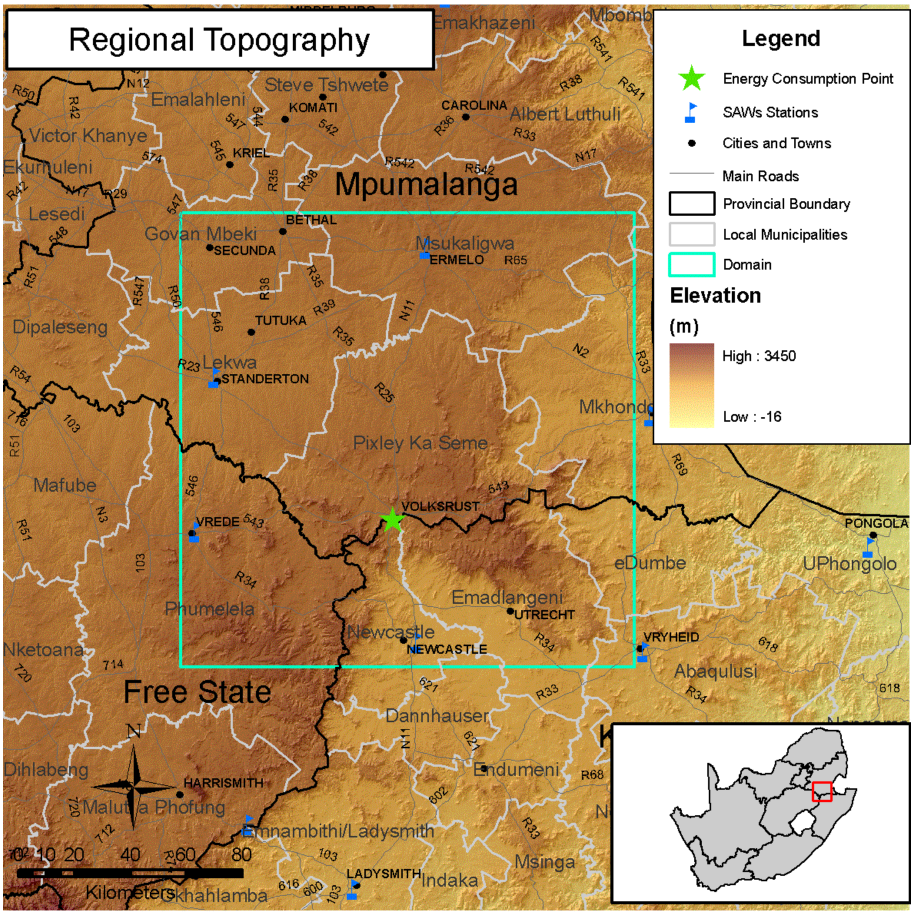

Figure 21: Representation of the study area

The study area is located on the Eastern escarpment of South Africa. It includes the Highveld region, characterised by Grasslands and undulating landscape; and the greener low lying areas of KwaZulu-Natal. The change in elevation over the escarpment is from 1900m at Volksrust to 1200m at Newcastle, with the highest wind speeds occurring at the crest of the escarpment.

Climate during the winter is generally cold with possible presence of frost or snow in higher altitudes. In summer, the climate becomes temperate to hot, especially in the areas below the escarpment.

5.1. Site identification

5.1.1. Technical Assessment

Due to the presence of the Witbank coalfields, the Mpumalanga region is home to the largest electricity generation cluster in the country. The generated electricity is transported across the country through a high voltage transmission network (see Figure 22). The display of the reclassification of the 3km blocks according to its proximity to the transmission lines is shown in Figure 23, where 5 indicates the most adequate place for wind farming according to its proximity to the electrical grid and 1 indicates the least adequate place. The format 5 to 1 of the score is kept the same for all criteria within the Site Identification group.

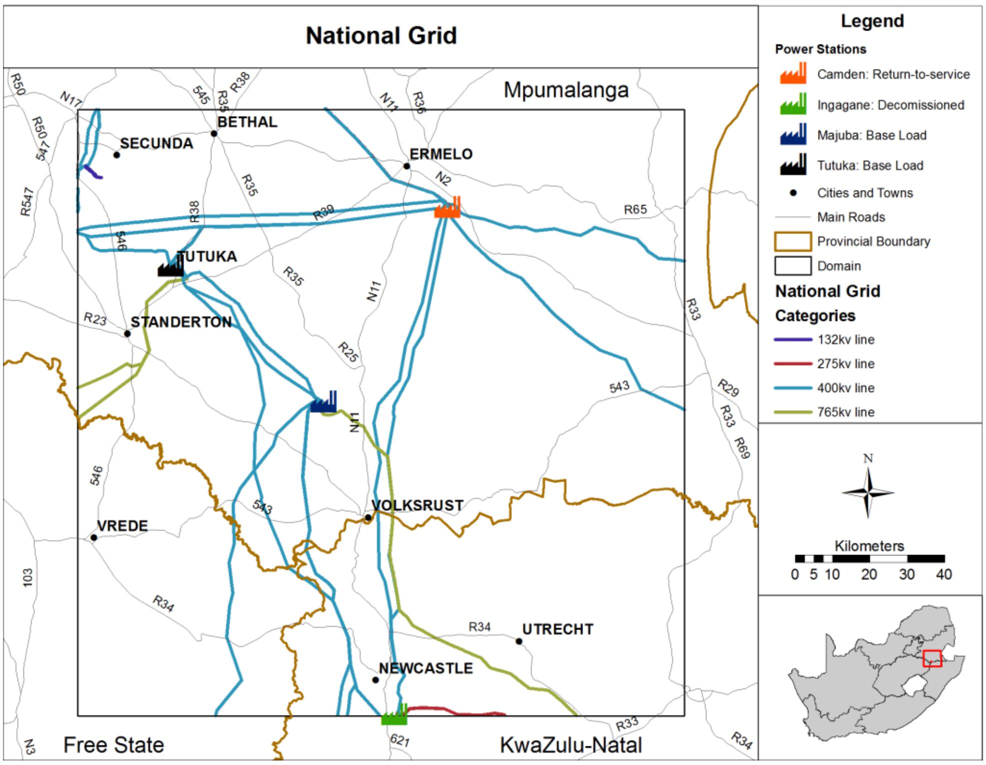

Figure 22: Display of the national transmission grid and power stations within the area of study.

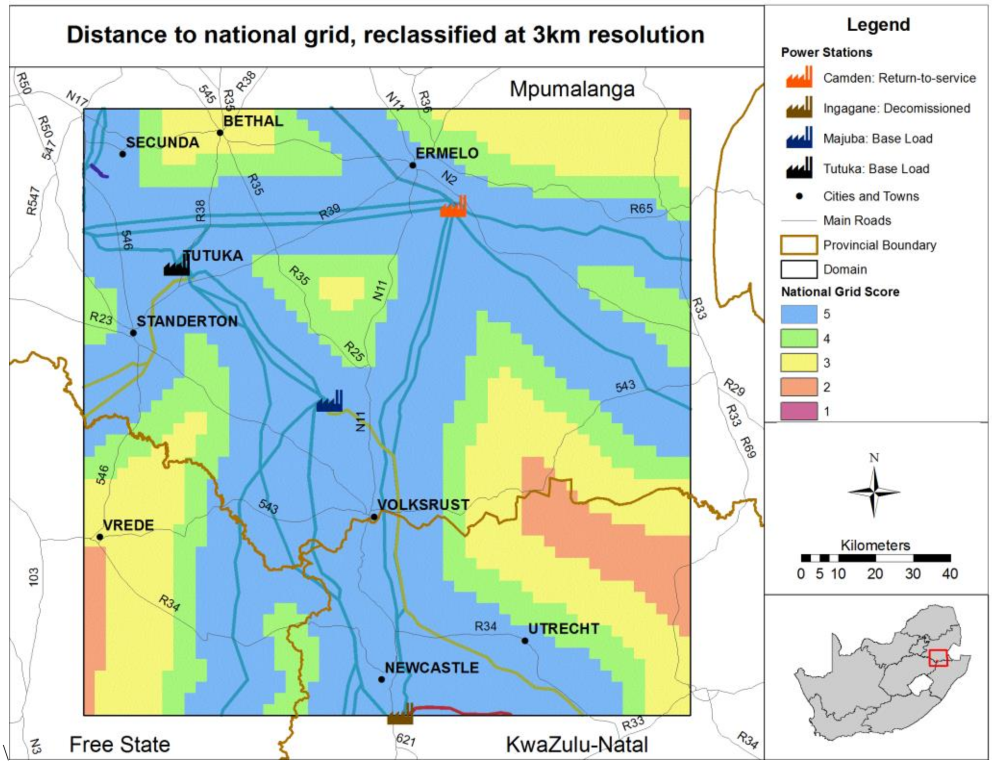

Figure 23: Distance to the national transmission grid reclassified at 3km resolution

It is observed that in the selected domain there are no areas located further than 70km to the transmission lines; in fact, a large part of the land is within the desired 10km that assures short term availability to connection.

The exact distance to the transmission grid has a proportional effect on the connection cost. That could easily be included in a further study that considers connection costs as a variable affected by the kilometres required to meet the national transmission infrastructure.

Concerning roads, the national highway N2 connects the area to the Indian Ocean. The N11 national road is an alternate route between Gauteng and KwaZulu-Natal to the N3 freeway as carriers try to avoid the N3 toll fees.

In general, the area is highly accessible in terms of road infrastructure, which is required for the transport of equipment and parts. The sites between the N11 and N2 seem to be connected only through minor roads. A depiction of the main roads is found in Figure 24 and the display of the 3km blocks according to its proximity is shown Figure 25.

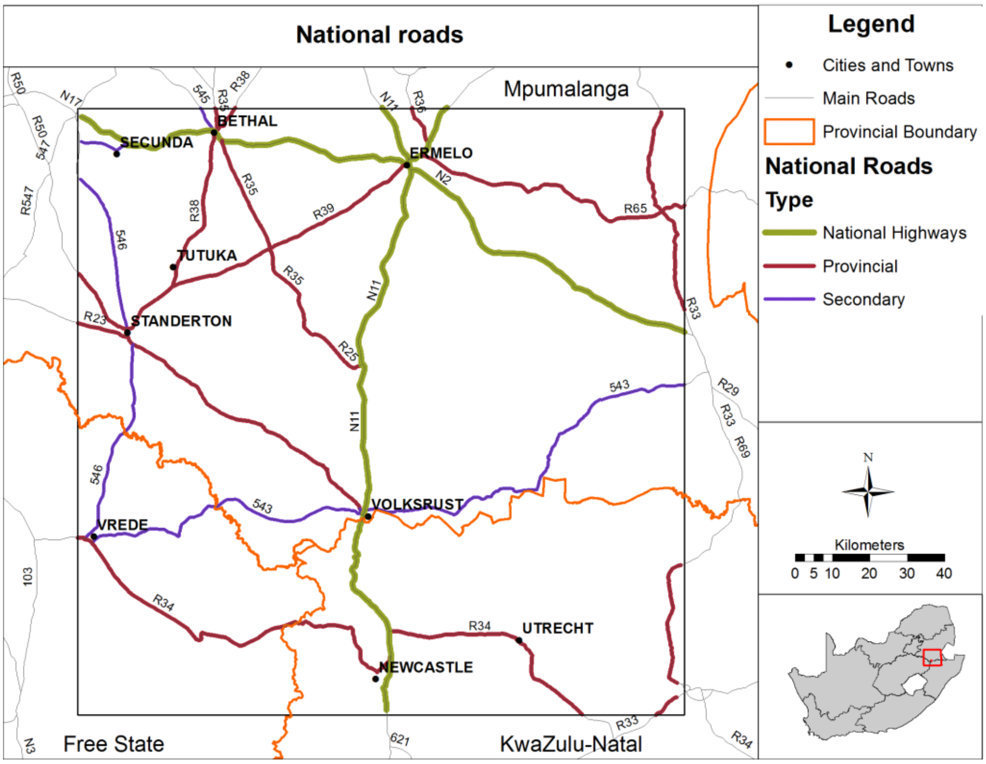

Figure 24: Display of national, provincial and secondary roads within the study area

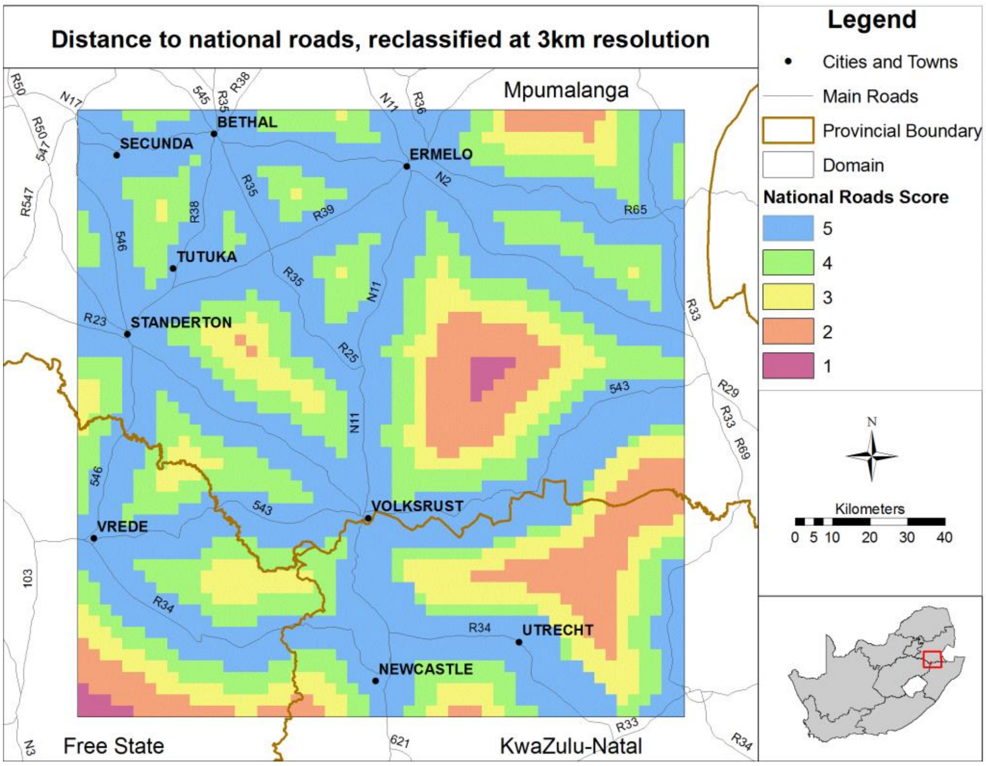

Figure 25: Distance to national roads reclassified at 3km resolution

Regarding the slope, the values were calculated from 90m blocks as it is the original resolution of the SRTM data (Figure 26). To match all the other Site Identification criteria, it had to be resampled at 3 km and scored from 1 to 5 (Figure 27).

As expected, much of the information gets diluted or lost; thus for the determination of No-Go areas the original resolution is used, and all blocks of 18% (10°) or higher slopes were removed.

There are limitations when moving from high resolution to low resolution data, in the case of the slope calculation it implies that the average value does not represent accurately the rapid changes in terrain. By excluding all areas of 18% and higher slope in the No-Go areas assessment, it is expected to reduce the impact of such dilution of the information. However, it is recommended to keep high resolution data when refining the study or doing micro-siting planning.

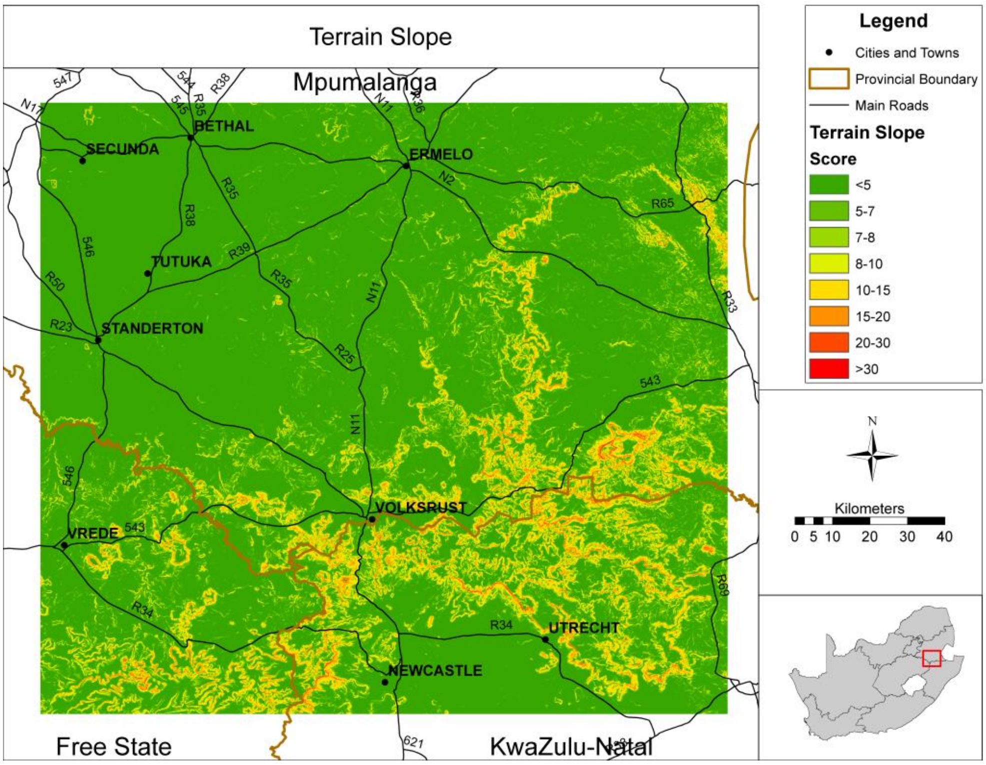

Figure 26: Terrain slope calculated from SRTM data, and categorized per degree of inclination (90 m resolution).

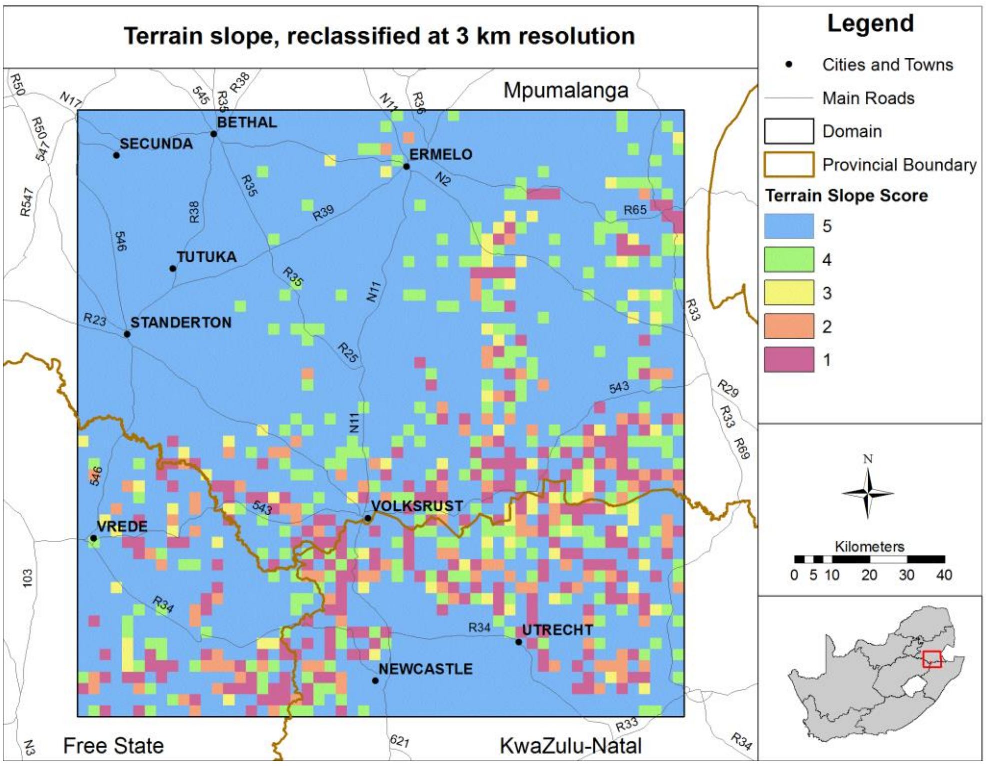

Figure 27: Terrain slope score - reclassified at 3km resolution

As expected, more dramatic changes in height occur along the Drakensberg Escarpment in the boundary between KZN and Free State, and KZN and Mpumalanga. Flatter areas are located along the Highveld.

Environmental

Avian sensitivity is usually a focus of attention when implementing wind energy facilities, and as a result this lead to the publication of an avian sensitivity map. The map presents 8 km cells correspondent to the area division for the submission of lists.

Figure 28 is a representation of the 8 km sensitivity map after applying the data treatment described in Section 4.1.1 - *Environmental*, and the resampling at 3 km in Figure 29. The Wakkerstroom area in south Mpumalanga, and the Seekoeivlei Nature Reserve in the east of the Free State are prime birding sites in the country. It is not a good practice to move from low to high resolution; however, the need of data at 3 km resolution motivated this action. Although it is important to remember that the avian sensitivity per se cannot be interpreted as a No-Go area it is rather used as an indicator for initial sensitivity assessment.

Bat studies were also not available; furthermore, pre- and post- construction monitoring and surveys of birds and bats at the proposed site are required.

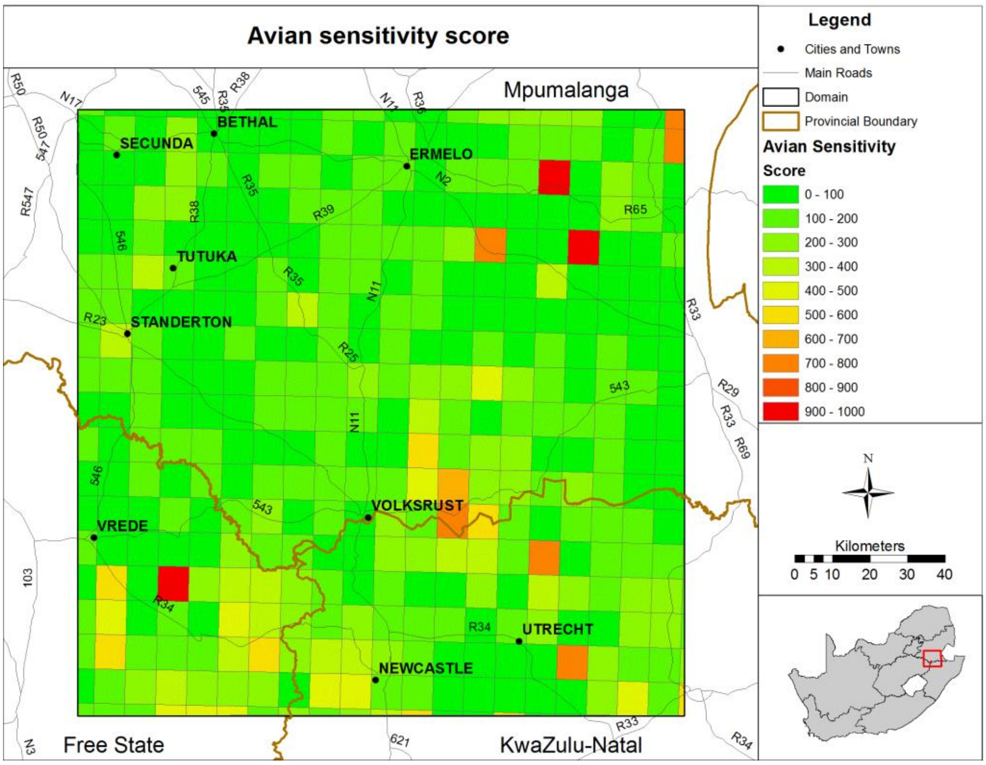

Figure 28: Avian sensitivity score at 8 km resolution (after data treatment described in section 4.1.1)

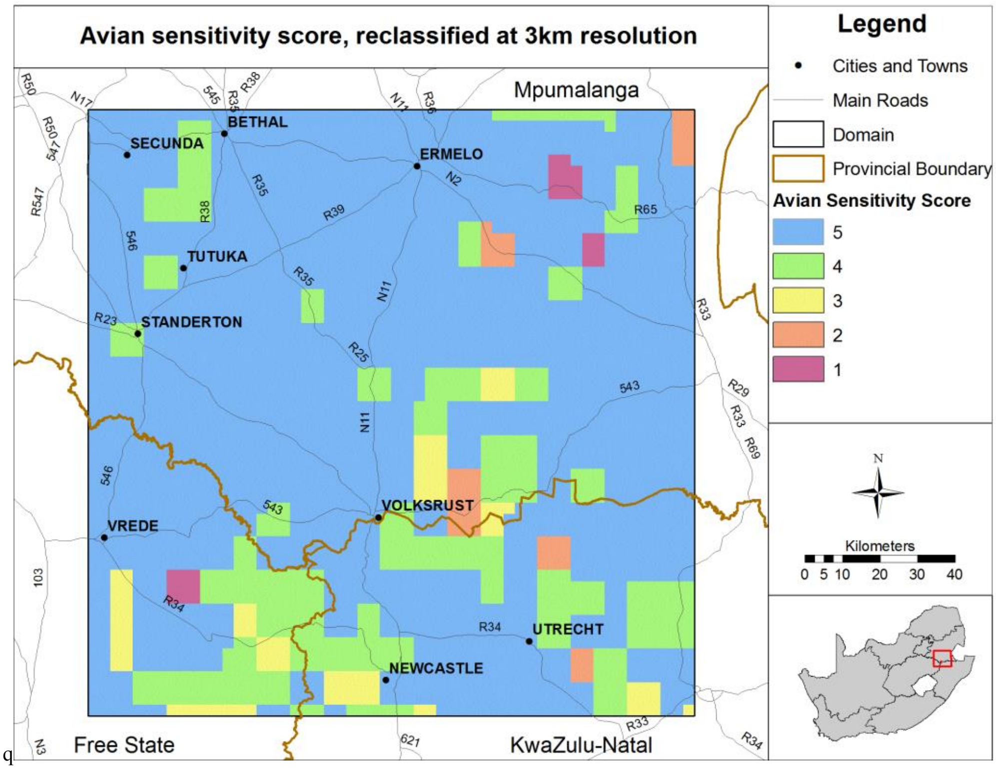

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Figure 29: Avian sensitivity score - reclassified at 3km resolution

Ecological corridors are mainly delineated along the river line and altitudinal gradient. This to make provision for the movement of animals and plant species, in response to environmental change. Corridors and conservancies of the study area cover a portion of the Vaal River from Standerton, the Chrissiesmeer area left of Ermelo, and parts of the Wakkerstroom at the south (Figure 30). Unfortunately, such data was only available for the Mpumalanga province; therefore all areas within the domain besides Mpumalanga were disregarded during the resampling (Figure 31).

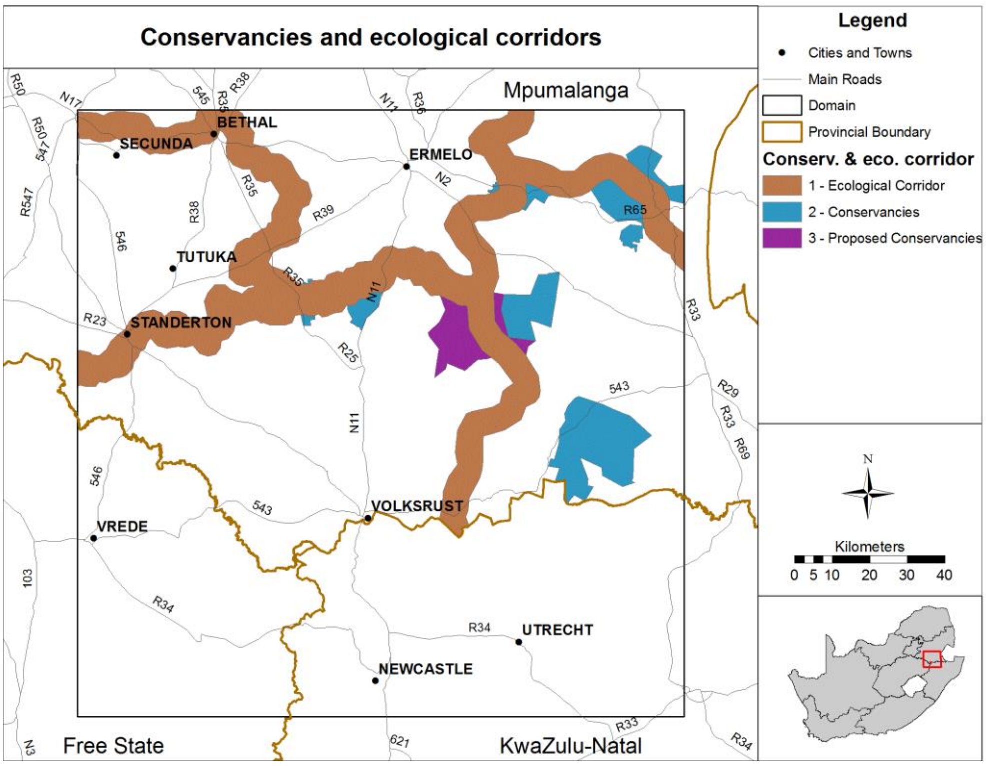

Figure 30: Display of conservancies and ecological corridors within the study area

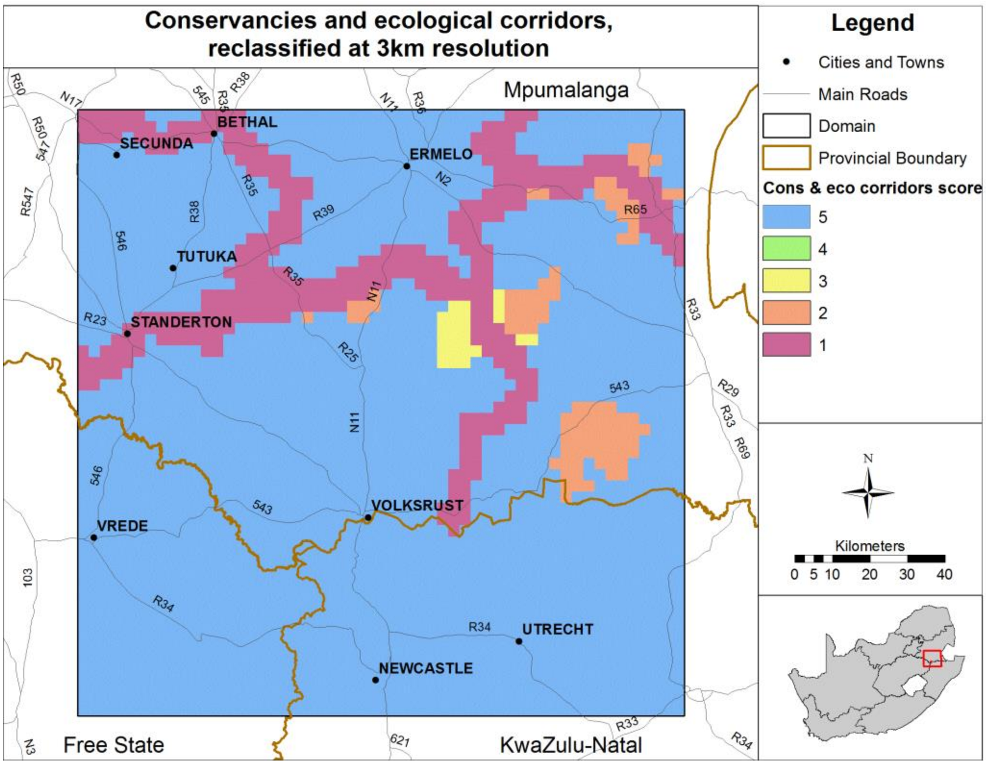

Figure 31: Conservancies and ecological corridors score reclassified at 3km resolution

Aquatic sub-catchments and terrestrial assessment are important for biodiversity and water production features. As the conservancies and ecological corridors, these datasets were only available for the Mpumalanga province. Figure 32 and Figure 34 present respectively the classes from the aquatic and terrestrial biodiversity values; while Figure 33 and Figure 35 exemplifies the resampling of such features.

Again, special attention is brought to the ecological value of the Wakkerstroom wetlands and the Paardeplaats Nature Reserve, as well as adjacent areas to rivers (i.e. Pongola River).

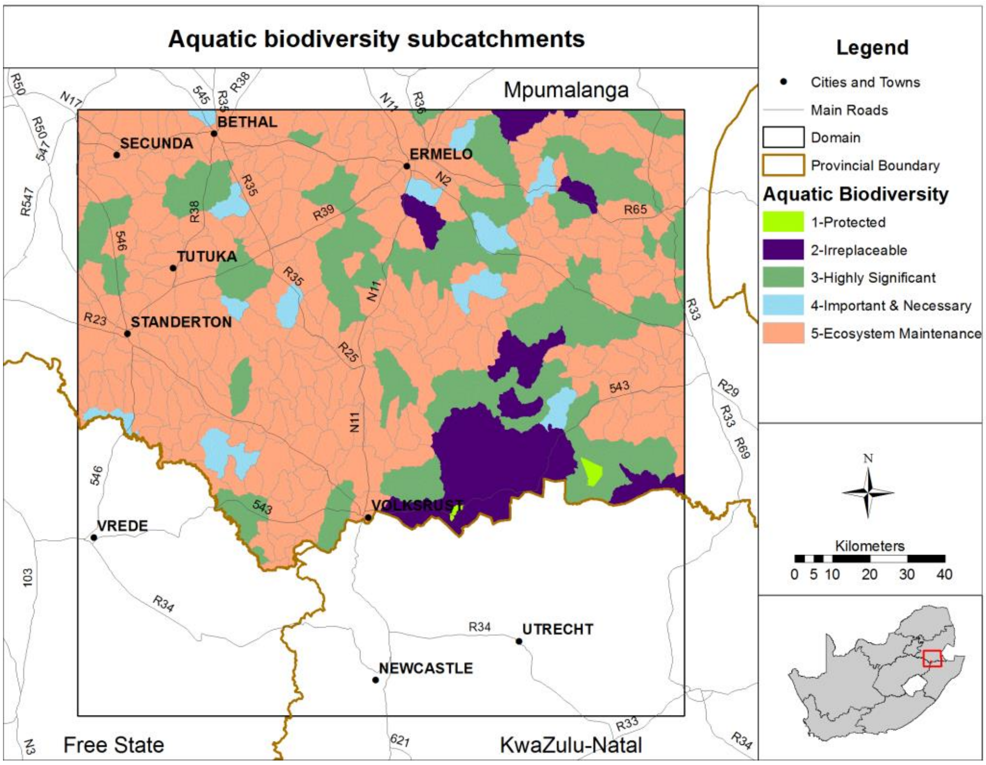

Figure 32: Display of aquatic biodiversity sub catchments within the study area

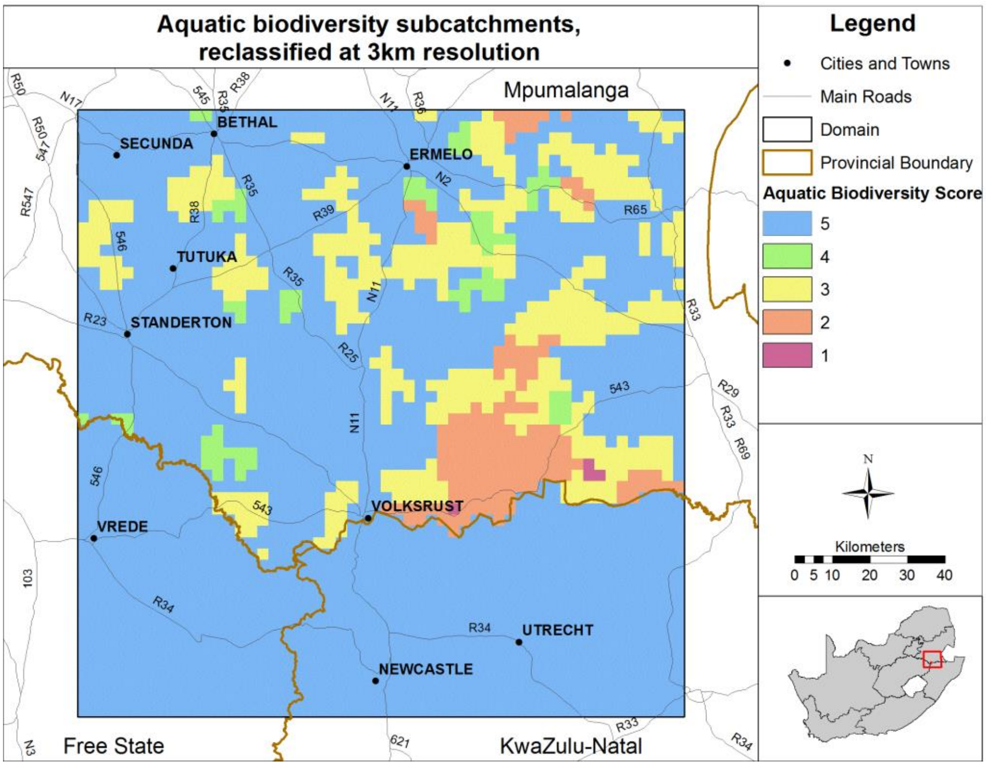

Figure 33: Aquatic biodiversity sub catchments score - reclassified at 3km resolution

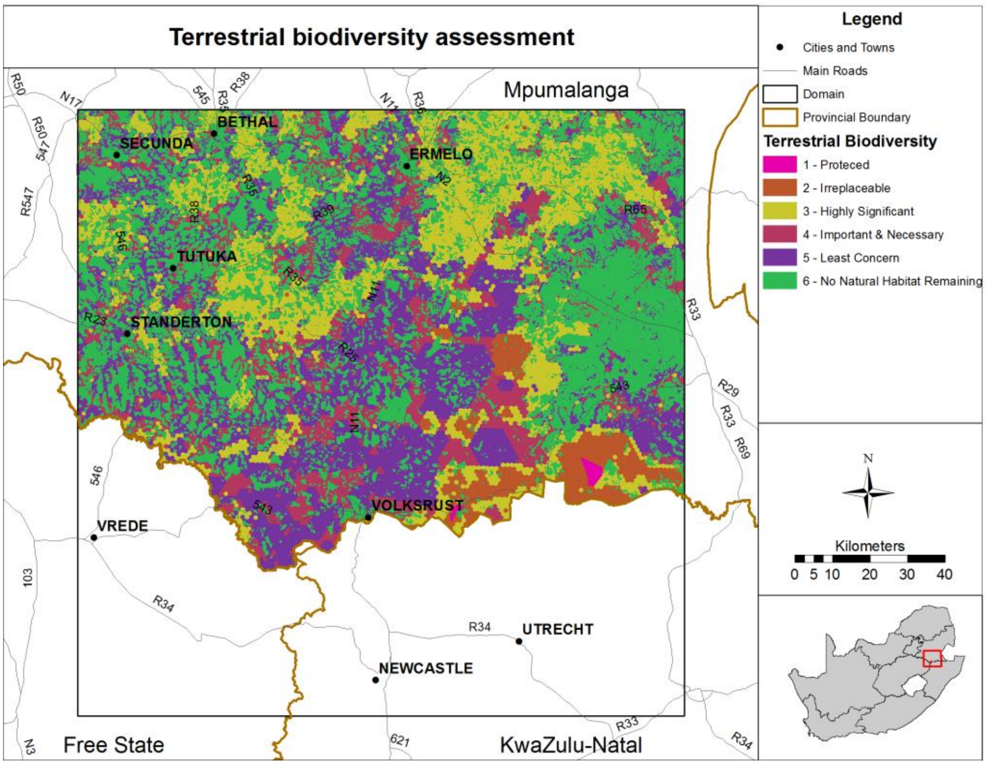

Figure 34: Display of the terrestrial biodiversity assessment within the study area

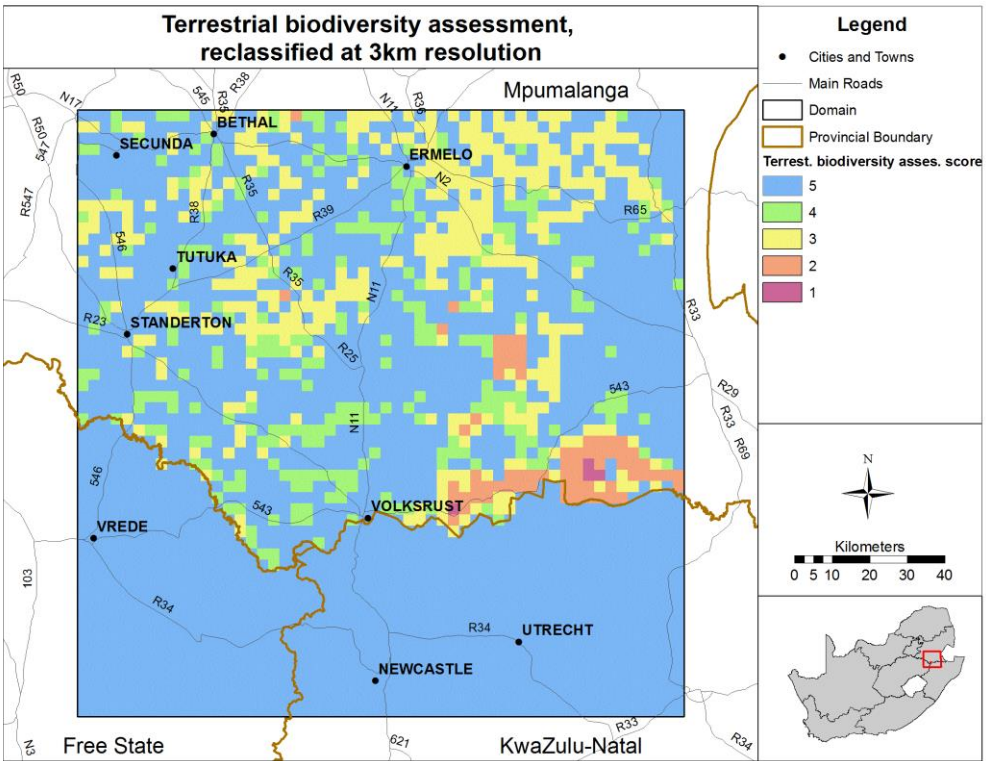

Figure 35: Terrestrial biodiversity score - reclassified at 3km resolution

Finally, the land use/cover information offers an indication of the main use of the land (see

Figure 36). The categories are very general, but enough for an initial screening of the sites. It should also be noted that some of this detailed information is lost due to the resampling (Figure 37).

Areas classified as natural may indicate open wild land as well as protected forest; hence a more detailed treatment for location of turbines is required over the feasible sites. In the case of urban areas, they have been given the lowest score in order to be avoided; but they are also included in the No-Go areas criteria.

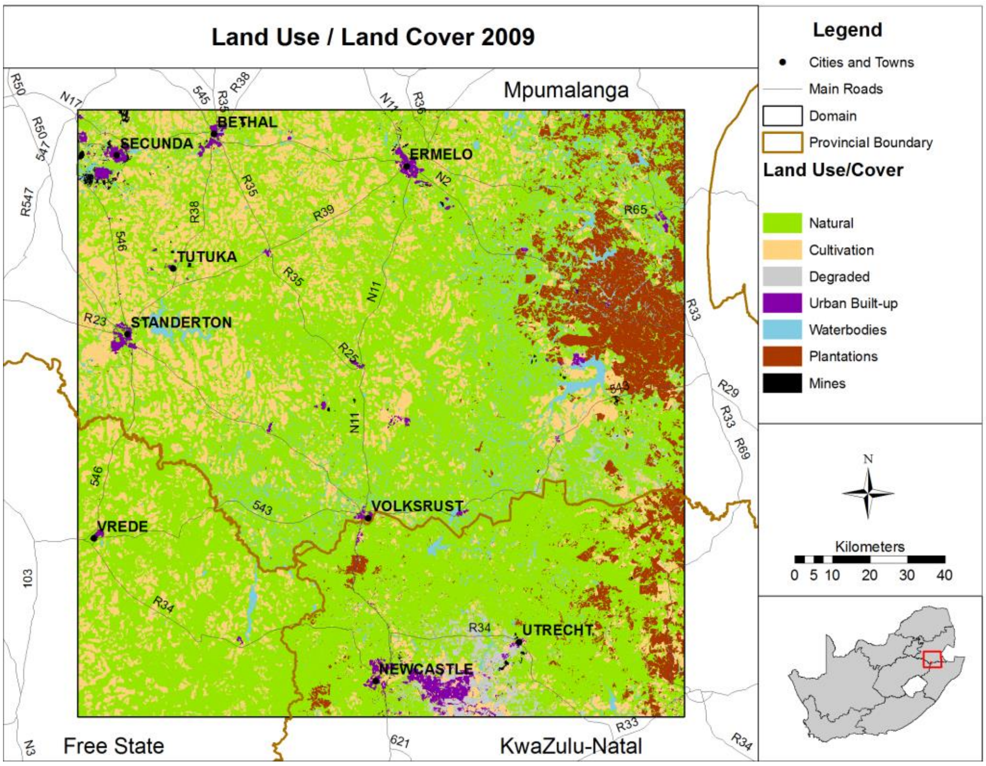

Figure 36: Display of land use/land cover terrain classification for the study area

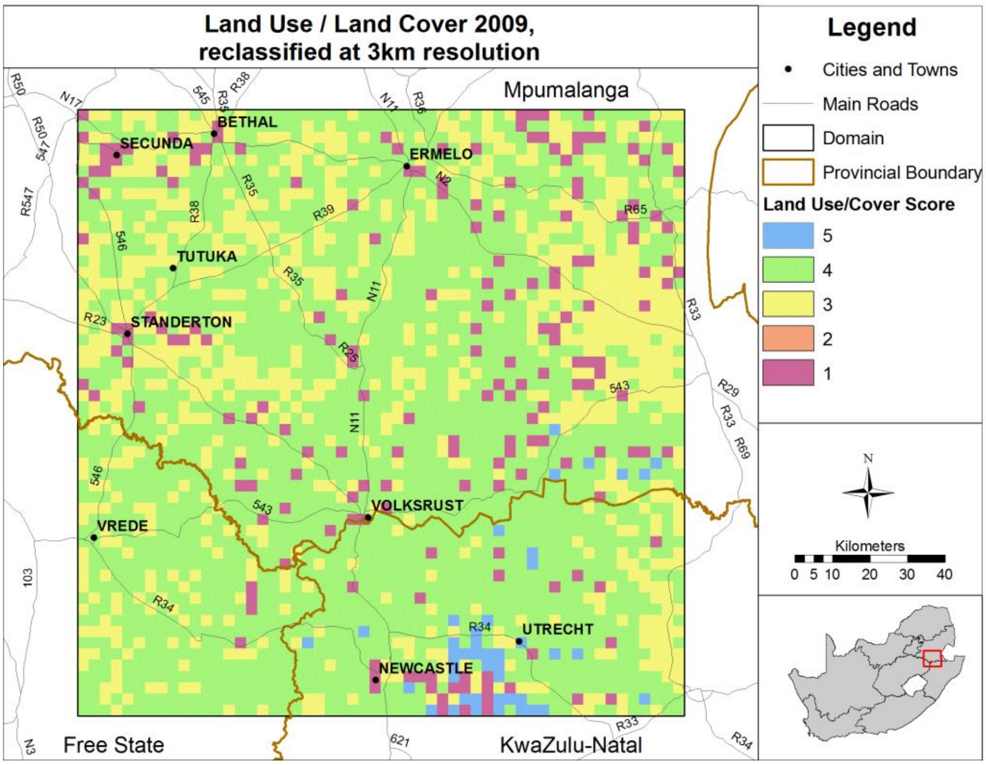

Figure 37: Land use/land cover score reclassified at 3km resolution

No-Go Areas

As discussed earlier, No-Go areas are made from the union of restricted areas identified according to the criteria. Some of the criteria presented in Table 9 were not available during the time of this study, such as the location of communication towers, military zones or tourist routes. Others, such as historic sites, heritage sites, national parks and botanical gardens, are available but there were not locations of this type within the study area

It is to be mentioned that the selection of rivers to be taken into account was done according to their order. The order of a river is an indication of the size of the perennial or recurring stream; it ranges from first order to the largest which is 12th

(Briney, 2013). The largest South African water body, the Orange River, is classified as of 7th order.

When zooming into the study area, streams of order 1 to 4 were found; it was decided to apply a 250m buffer around categories 3 and 4. Other rivers denominated by the FEPA as "freshwater ecosystem priority area" were also excluded for potential locations of wind farms in an area of 500m radius around them. Regarding wetlands, only the ones categorized as "large" - and the surrounding area within a 500m buffer of them - were excluded, mainly for animal biodiversity concerns.

These exclusions are applied in terms of the initial site selection; however, a more detailed assessment of all water bodies present in the area and their condition must be carried out when completing the Wind Atlas Analysis and Application Program, as wind turbines could be considered in proximity of smaller streams.

Regarding the 500m security buffer around rural settlements, it was decided to ignore these criteria from the feasibility stage, and include it perhaps in subsequent phases of refining site selection or micro siting of wind farms. This is because, after plotting the security buffer, the remaining available land for wind farming is significantly reduced.

The complete set of No-Go areas is presented in Figure 38 and Figure 39.

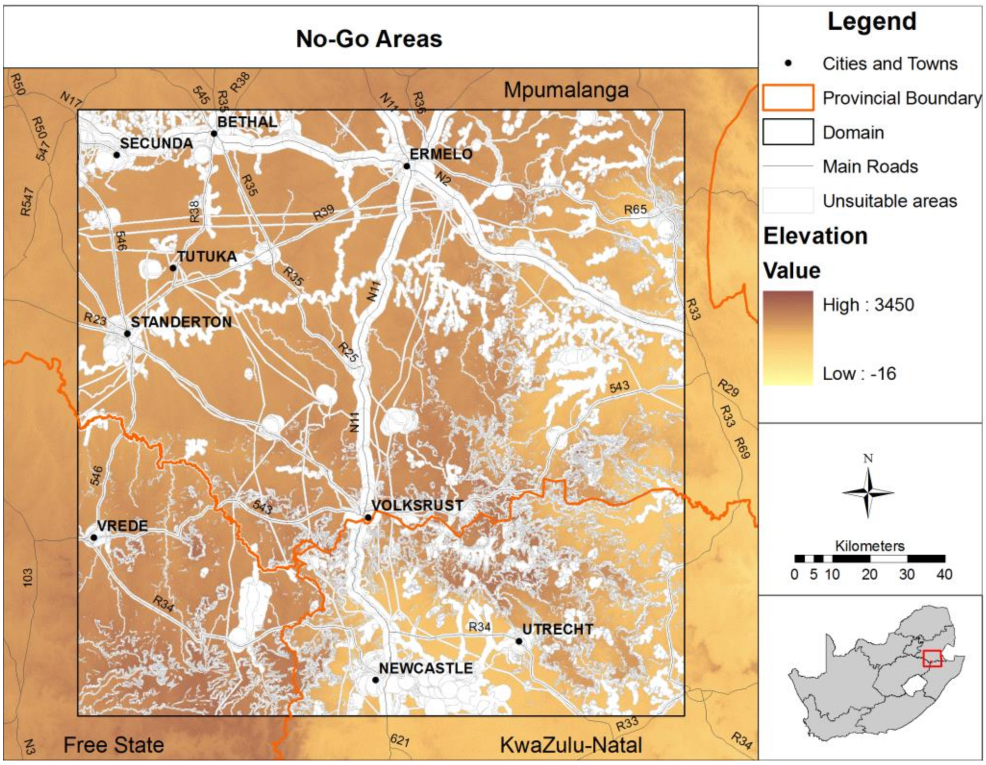

Figure 38: Map indicating the combined No-Go areas, as determined by application of criteria in this study

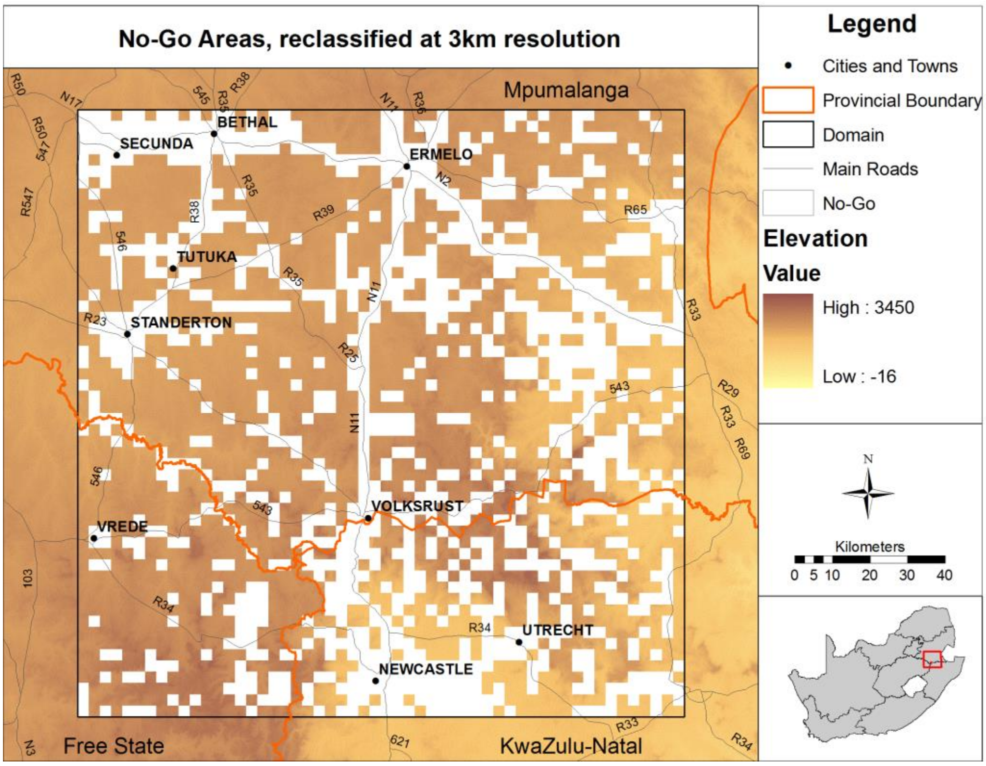

Figure 39: No-Go areas reclassified at 3km resolution

Notice that the mapping of negative criteria, representing a No-Go area, does not necessarily mean that the positive areas are suitable for development. No-Go areas are simply used as criteria to determine where wind turbines cannot be located for safety, conservancy and environmental issues. To obtain a coherent result, other data sets and the wind resource should all be analysed together with the positive areas (PGWC, 2006).

Site Performance Index

The result of data geoprocessing on the Site Identification group factors is a Site Performance Index (SPI) that enlightens the suitability of a specific block, given its technical and environmental aspects.

Figure 40 presents the output when using the same score for all layers, and Figure 41 demonstrates the changes in results when different weights are allocated to the constraint layers according to its perceived importance.

Different to all the previous site identification criteria, the suitability scale of the SPI ranges from 5 to 0, where 5 indicates a preferred site and 0 indicates a restricted area. The scale has been inverted in this step just to make it coherent for the further mathematical operations that include the PDD. The patterns of the restricted area reflect the influence of the buffers from roads, rivers and wetlands and urban areas. In total, the restricted area corresponds to 37% of the total study area.

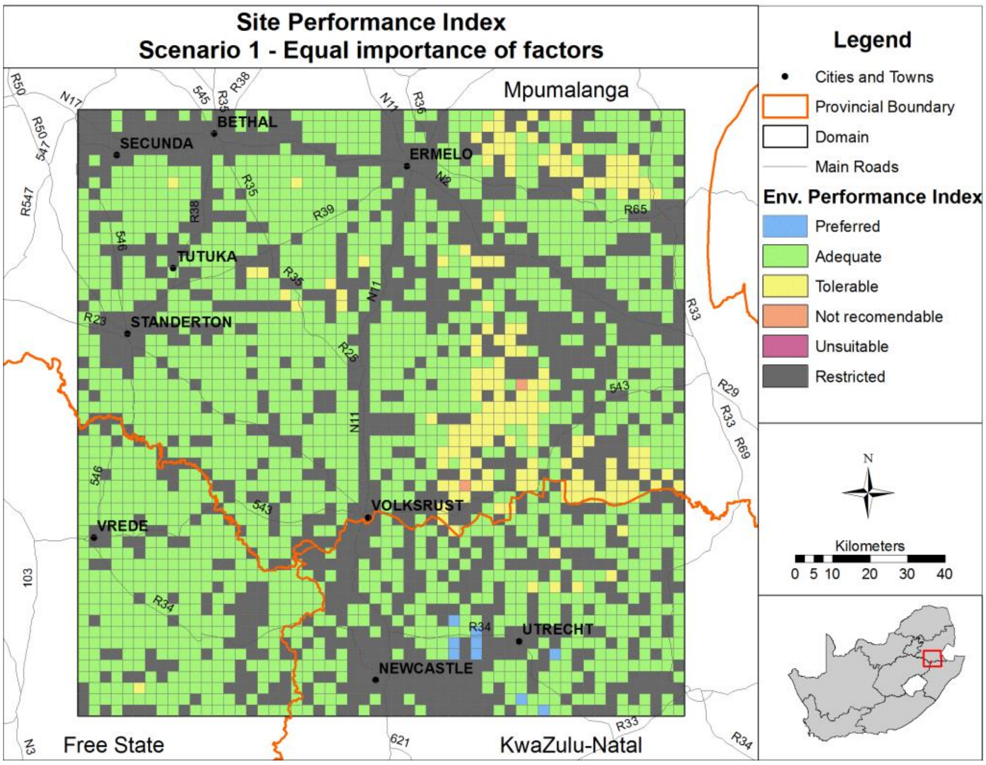

Figure 40: Site Performance Index for Scenario 1 using equal weights in the factors to overlay, at 3 km resolution

Under the scenario 1 approach, the preferred area for development represents less than 1% of the total domain size, while the land categorized as adequate represents 56%. This highlights the importance on including the wind regime when selecting a site. However, the preferred areas in the south of the domain may display a good rank as a result of the lack of environmental restriction in that area, as some of the input data only contained data for the Mpumalanga province.

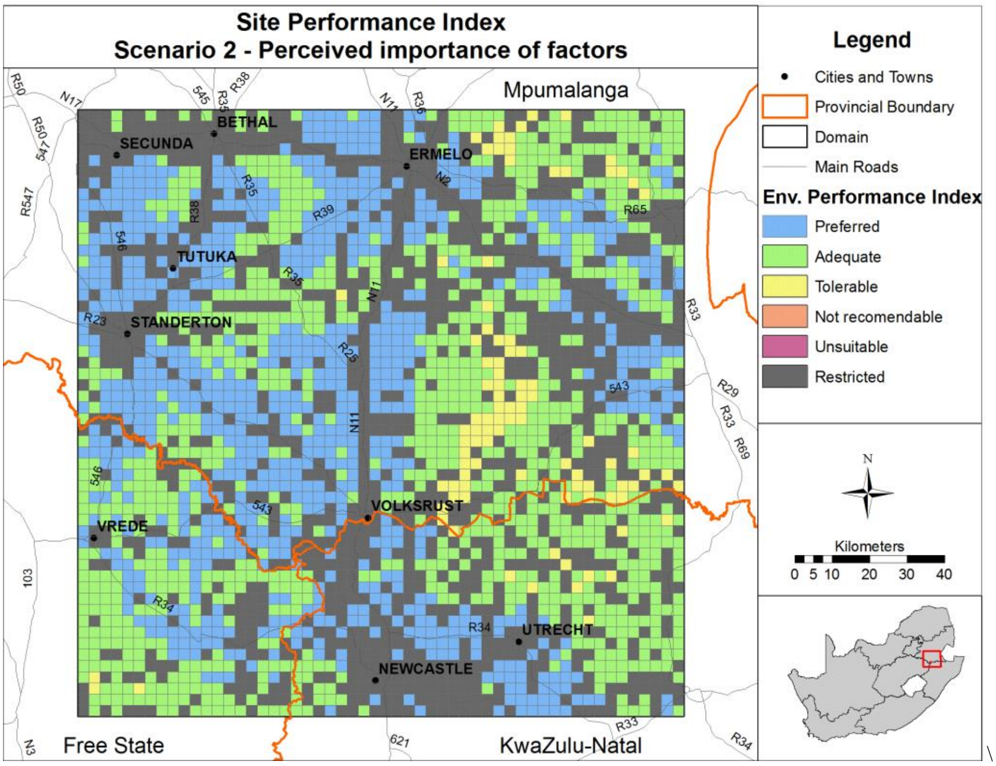

Figure 41: Site Performance Index. Scenario 2, using arbitrary factors in the weighted overlay (3 km resolution).

On the other hand, when a different weight is applied to each factor during the overlay, it significantly affects the results obtained. For instance, by giving more importance to the technical characteristics (roads and electrical grid) the preferred area corresponds now to 28% of the study area, mainly in proximity to the main roads and transmission lines. Allocated weights are merely empirical; a thorough study assessing weighting factors would be a serious undertaking involving stakeholders' participation

5.2. RESOURCE AND ENERGY GENERATION

From TAPM, hourly wind modelled output for every 3km blocks is obtained. There are 2915 blocks in total. Figure 42 shows the modelled annual average wind speed for the study area.

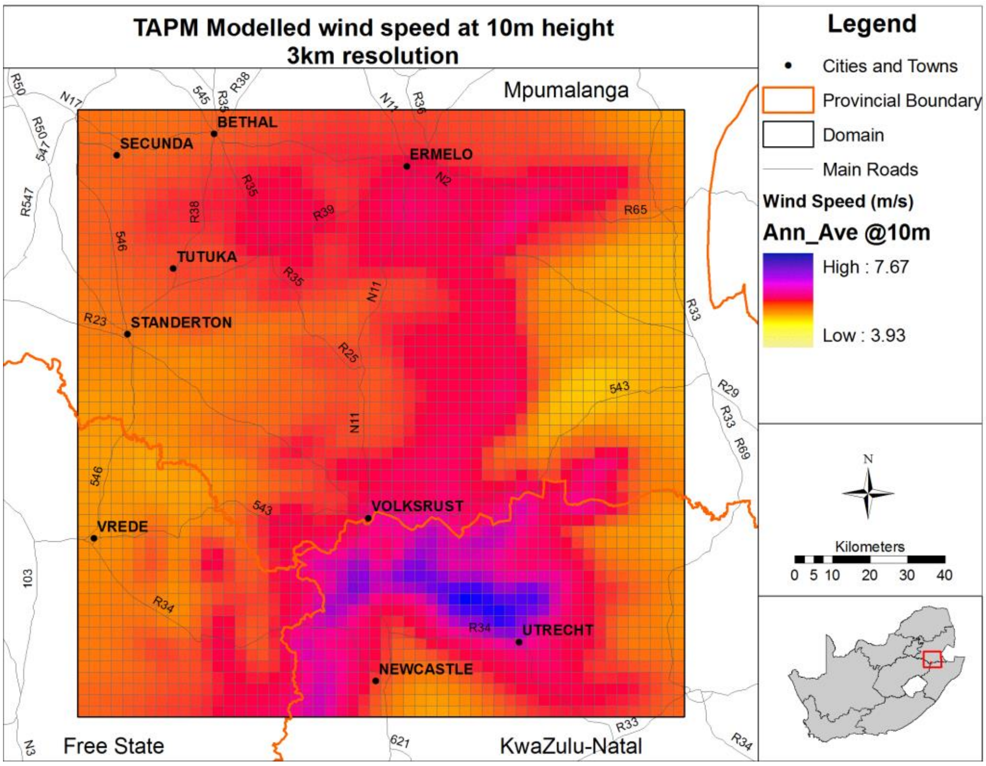

Figure 42: TAPM modelled annual average wind speed at 10m and 3 km resolution, 2011.

Wind patterns vary across the domain due to a combination of driving forces. Typically, predominant wind direction on the Highveld is determined by the prevailing synoptic condition, while stations in mountainous areas are further affected by locally induced flow. The predominant wind direction at Ermelo is North Easterly with most wind speeds between 4 and 8 ms^{-1}. A south westerly component is also present and was found to occur in May and June. Vrede wind data reveals no dominant wind direction and wind speeds are much lower than

Ermelo, with most speeds less than 6ms^{-1} and a large percentage below 4ms^{-1}. Newcastle shows dominant East-West components due to mountain-plain winds caused by proximity to the Drakensberg and the low lying areas of KwaZulu-Natal. Wind speeds in Newcastle are typically low and seldom exceed 6ms^{-1} (Weston, 2014).

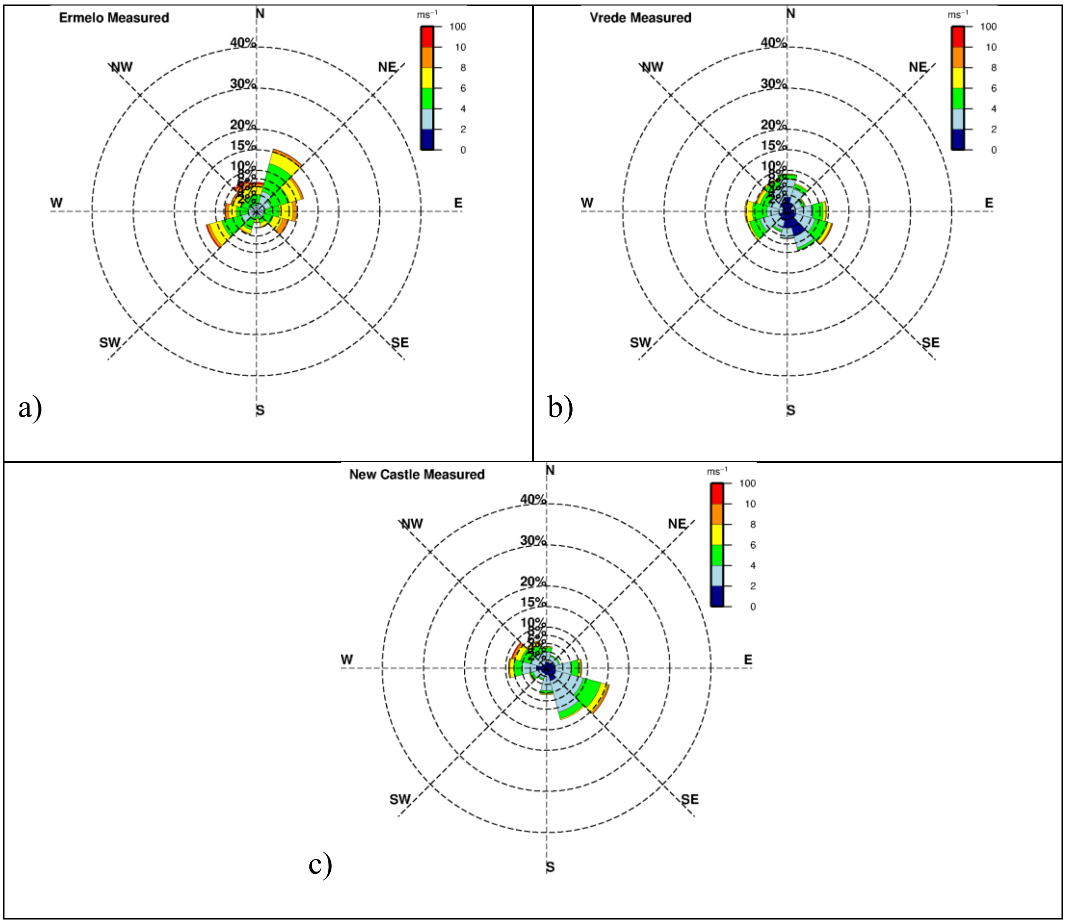

Figure 43: Annual wind roses for measured wind at 3 different stations: a)Ermelo; b)Vrede; c) Newcastle

Figure 43 contains the annual wind roses for each SAWS station within the study domain. The percentage of valid recorded data for each station in 2011 was: 76%, 81% and 88% for Ermelo, Vrede and Newcastle respectively.

5.2.1. Verification

Modelled wind is verified against SAWS wind measurements. Figure 44 presents a sample of the time series comparison for the three stations during the month of September 2011. The Index of Agreement of the annual comparison was: 0.87 for Ermelo, 0.84 for Newcastle and 0.88 for Vrede, and the correlation coefficient: 0.56 for Ermelo, 0.46 for Newcastle and 0.60 for Vrede. It suggests a good performance of the model in reproducing the temporal patterns and magnitude of the wind vector. A slightly underestimation of the wind is observed, especially in the Ermelo station.

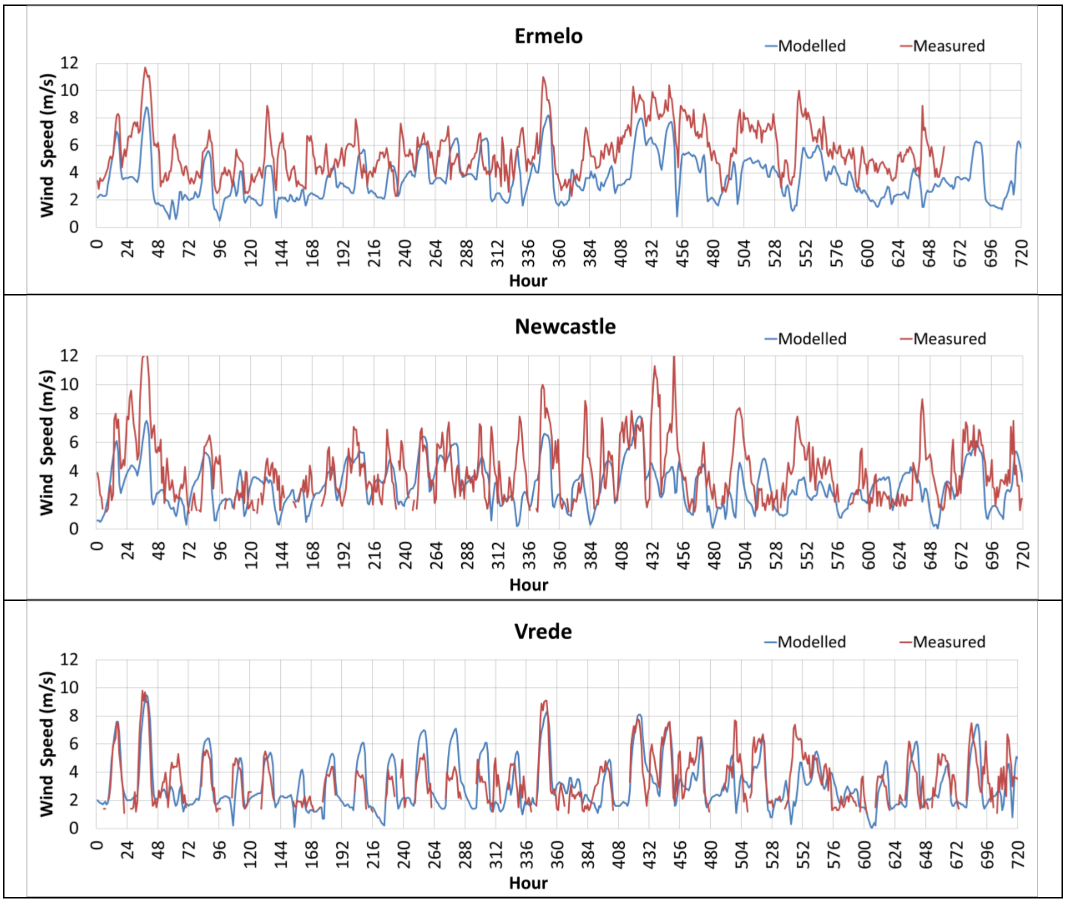

Figure 44: Time series of hourly wind speed at 10m, modelled vs. measured data, at 3 SAWS stations. September 2011.

5.3. Wind Energy Generation

The details of the wind energy generation have already been explained in Section 4.1.2 - Estimated Energy Generation. In this section we will present the results obtained by applying the same methodology at the Klipheuwel experimental wind farm and comparing it with recorded output. Klipheuwel was chosen as there is no current wind farm operating in the proximity of the study area.

5.3.1. Verification

Klipheuwel wind farm is an Eskom demonstration facility located north of Cape Town. It consists of three generators (Vestas V47, Vestas V66 and Jeumont J480) with a total capacity of 3.2 MW and capacity factors calculated between 20 and 30% (DOE, 2014).

TAPM modelled wind for the site was combined with the individual power curves of each generator following the procedure described in Section 4.1.2. A sample of results obtained against real energy output for the first quarter of the year is presented in Figure 45.

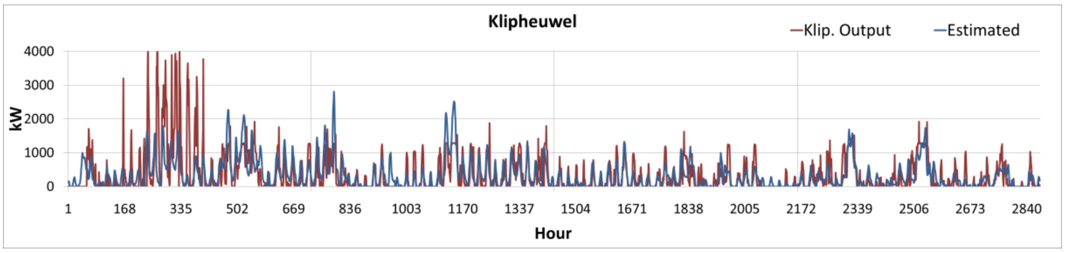

Figure 45 : Time series of hourly electricity output, estimated vs. measured, at Klipheuwel wind farm (3 generators). January to April 2011.

With an index of agreement of 0.84, correlation coefficient of 0.6 and accurate resemblance of the temporal profiles; the results validate the proposed method especially when taking into account that the periods when one of the turbines stopped working is unknown. It can be concluded that the output from the electricity estimation is trustworthy and may be replicated for the estimation of power generation at the study site.

5.4. Demand analysis

Annual results of the MD and PDD calculations are presented in Figure 46 below. Significant differences are found between the demand profile and the energy output for the sites along the escarpment where the wind resource is higher. PDD values are lower further away from the escarpment and extremely high on top of the escarpment in the 10% penetration scenario (see Figure 46-a). The 20% penetration scenario (b) reflects the same pattern; but values are slightly higher in the valleys and slightly lower on the escarpment.

To identify how the differences relate to the energy production levels, the MD is used. A quick look at the colour scale suggests that the electricity output in the valley areas is mostly below the requirement (c). However, in the mountainous areas there is an opposite behaviour, with energy produced above the requirements especially for the 10% case. Such results seems to point to the fact that wind energy produced presents peaks in different times of the consumption peaks, especially in the high wind resource sites.

The PDD value is desired to be closer to zero, while the MD could be above zero. A positive value of the MD would indicate that the minimum requirement of energy is being supplied most of the time.

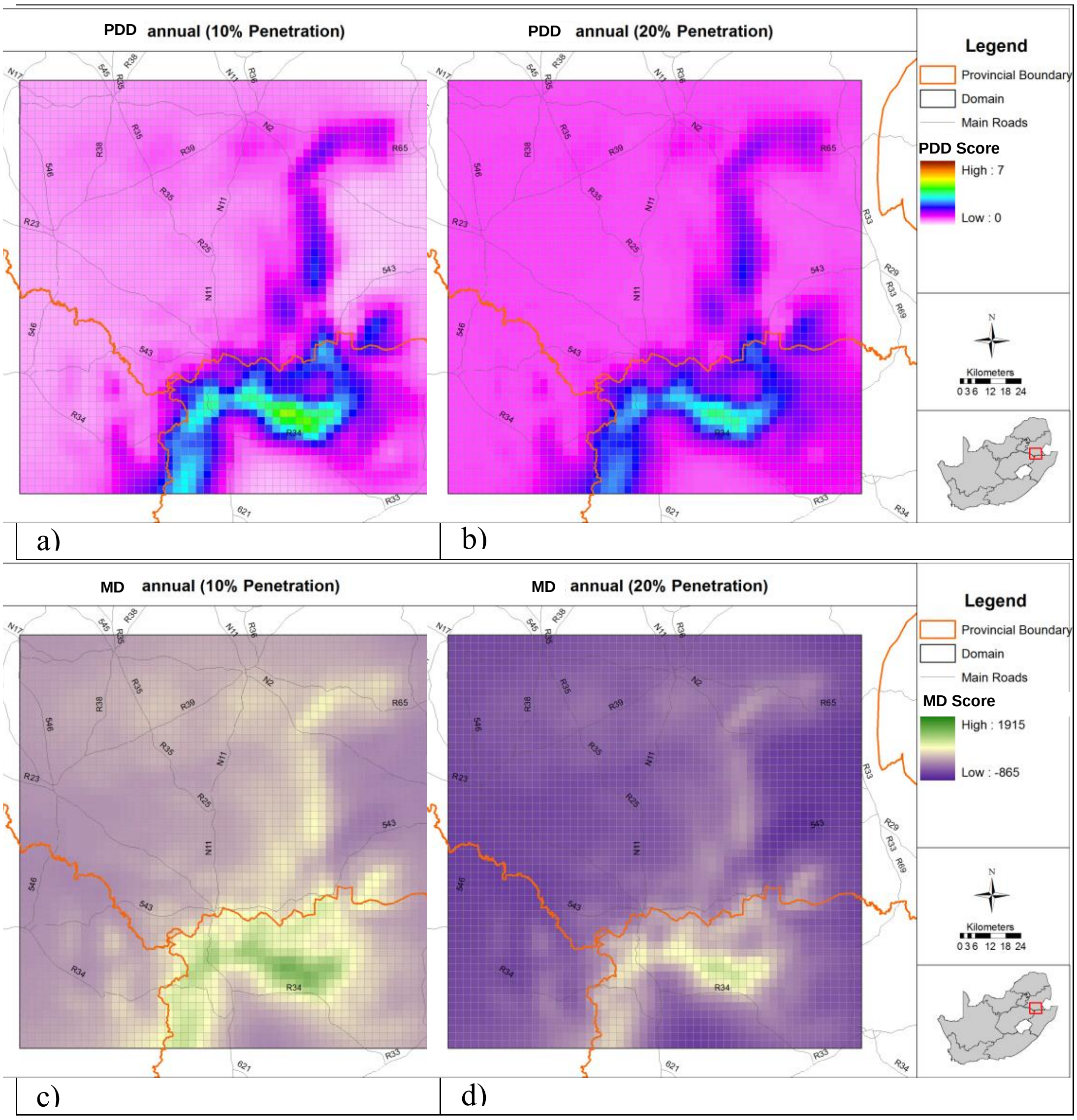

Figure 46: Annual estimation of PDD and MD for two penetration scenarios a) PDD - 10% scenario; b) PDD - 20% scenario; c) MD - 10% scenario; and d) PD - 20% scenario.

When looking at winter months (Figure 47) the PDD values for the 10% case are even lower across the domain when compared to annual values (see (a) in

Figure 47); however, for the 20% case (b) the PDD increases on the left side towards Swaziland and around Standerton.

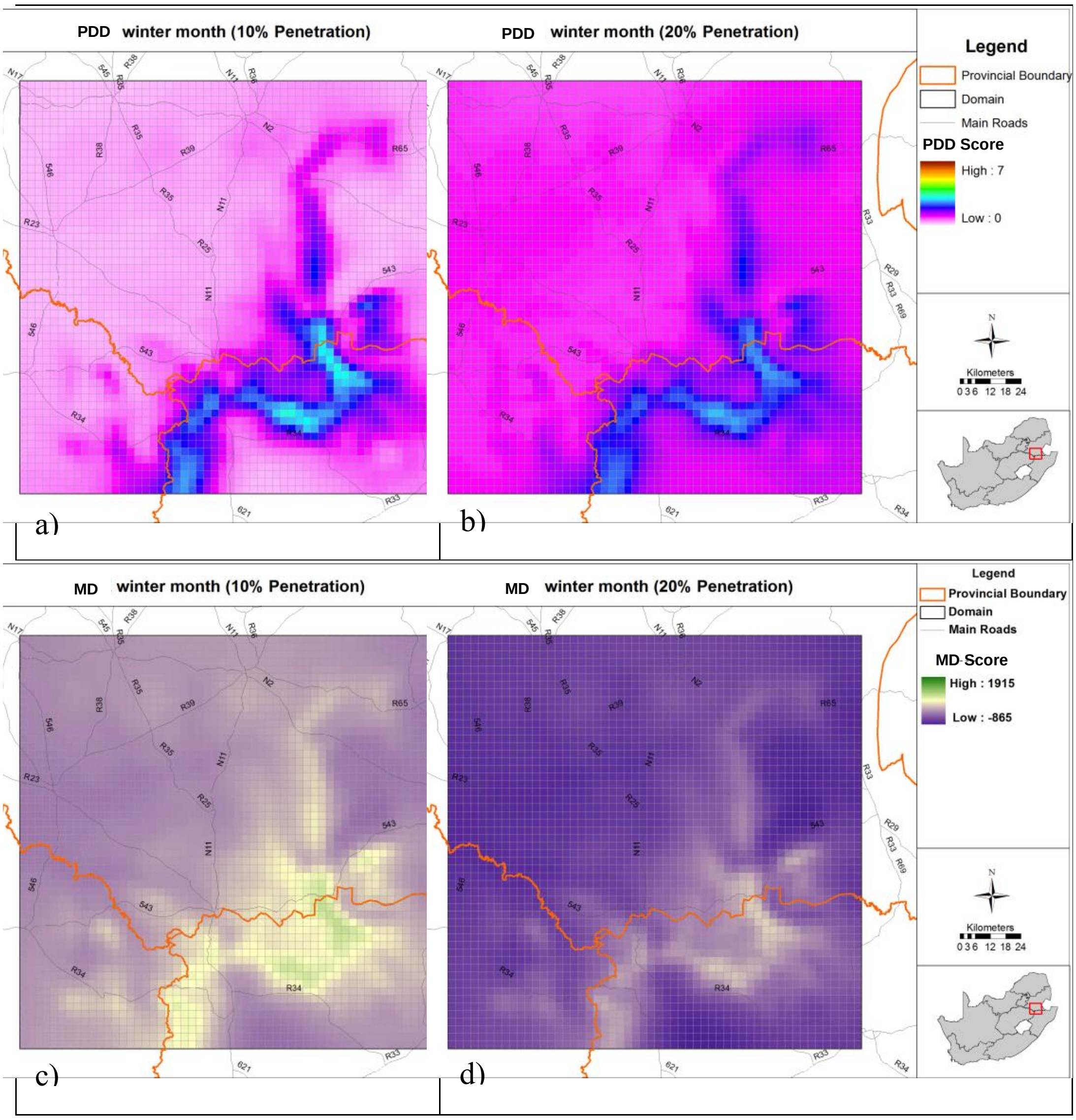

Figure 47: Monthly estimation of PDD and MD for two penetration scenarios a) PDD-10% scenario; b) PDD-20% scenario; c) MD-10% scenario; and d) MD-20% scenario for a winter month (July)

The MD (c) and (d) indicates that the differences between production and consumption of energy are smaller in winter months across the domain. It is known that the electricity demand in winter is higher. All purple areas indicate shortages to meet even the 10% case of electricity demand; this does not happen at the higher altitude areas.

Summer months (Figure 48) follow a different pattern given by the changes in the wind resource. PDD values for the 10% case (a) seem to increase across the whole domain with exception of the area between the R65 and 543.

For the 20% case (b), the increases of PDD values happen over the same areas that showed a reduction in winter, left from the escarpment and close to Ermelo and Tutuka. The MD results make it clear that such differences are the result of higher winds with higher energy production, combined with the fact that the electricity consumption tends to decline in summer months.

The PDD and MD maps reflect the same pattern of the wind resource. This is explained because PDD and MD are in fact functions of the wind resource.

So far the results suggest that areas of high wind resource do not necessarily perform better, as they may be over producing electricity at unnecessary times. For lower electricity requirements, wind energy produced in the valley may suffice. The possibility of having a hybrid arrangement or other storage system in place, and the flexibility to modify the demand profile, are factors that will affect the ultimate choice for site selection.

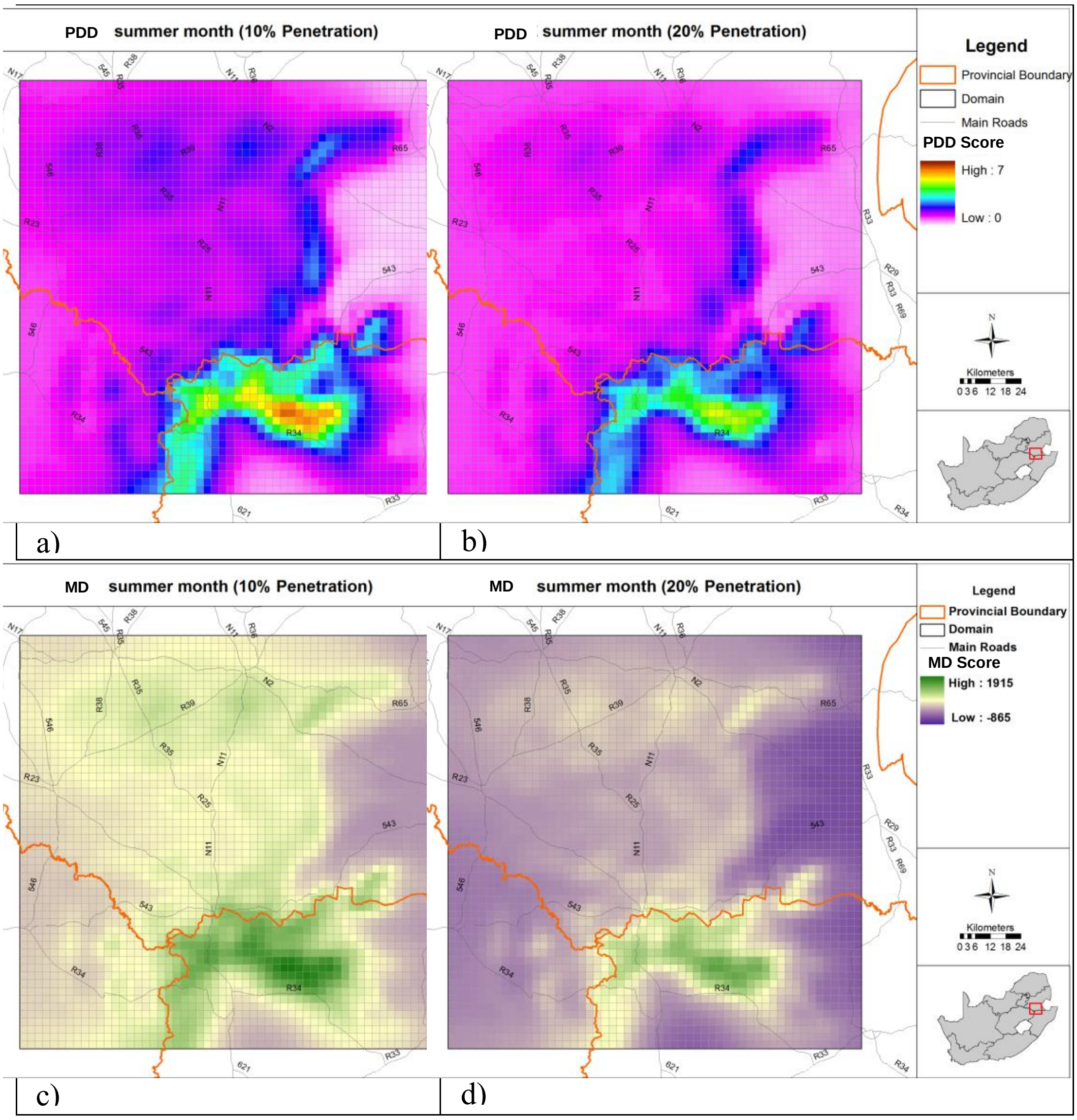

Figure 48: Monthly estimation for 3 turbines and a) PDD-10% case; b) PDD-20% case; c) MD-10% case; and d) MD-20% case for a summer month (November)

5.5. COMBINED MODEL RESULTS

The final output of the proposed model is the *combined score* between the PDD indicator and the SPI for each analysed case; these are presented below in Figure 51 for each scenario of evaluation.

The newly obtained combined score ranges from >0 to <10, recommended to not recommended. Restricted areas for exclusion are left blank. It is interesting to note how places with better wind resource are not necessary ideal for wind farming under this new approach. The following figures will help in the understanding of why and what to expect when assessing a different site.

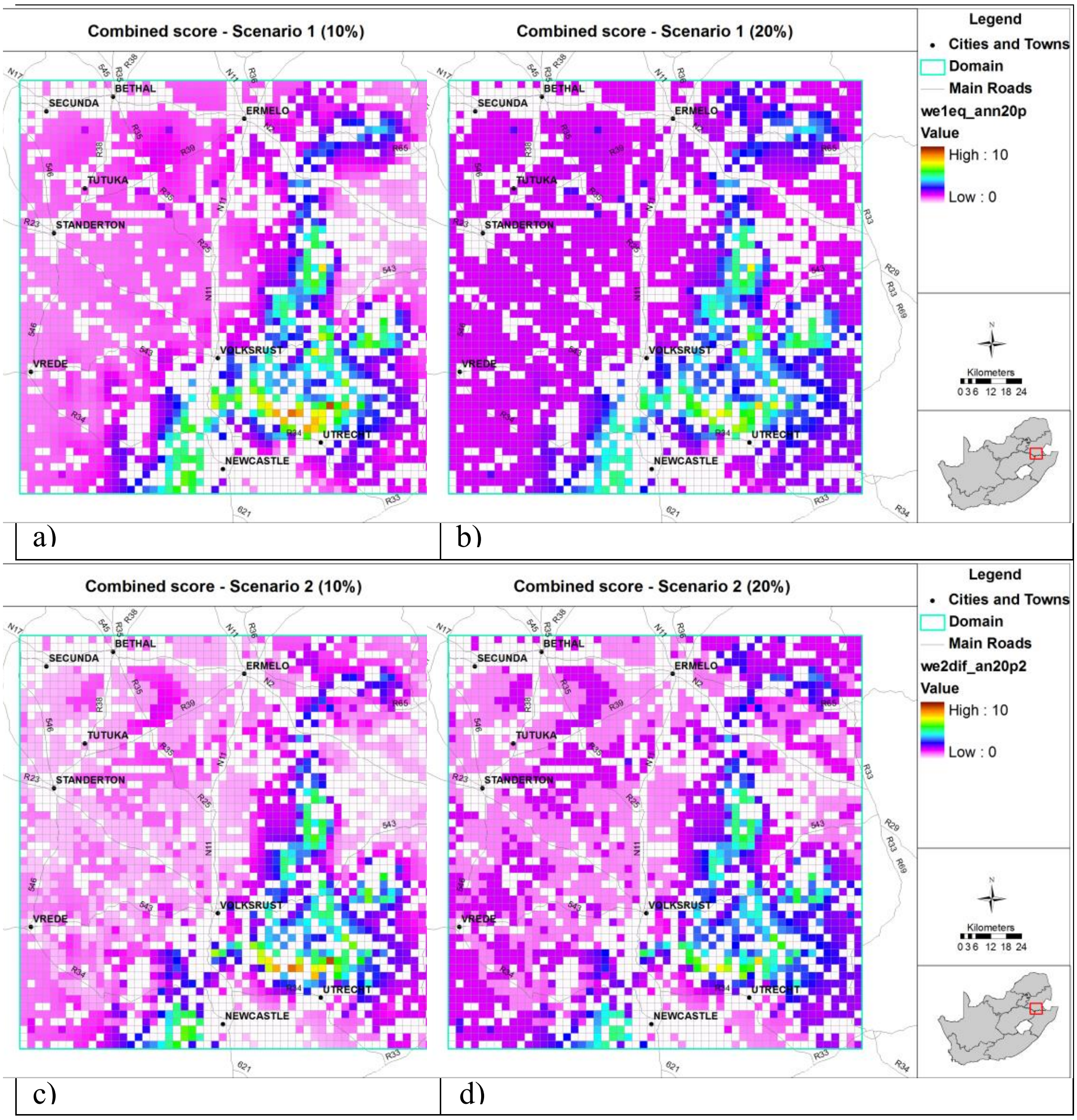

Figure 49: Combined score for a) Scenario 1 & 10% penetration; b) Scenario 1 & 20% penetration; c) Scenario 2 & 10% penetration; d) Scenario 2 & 20% penetration.

A block of high wind resource but low combined score was selected (B1-Figure 50). Hourly energy output was estimated for the case of using one, two or three turbines and the results are compared against the 10 and 20% of total energy demand of the consumption point (Figure 51).

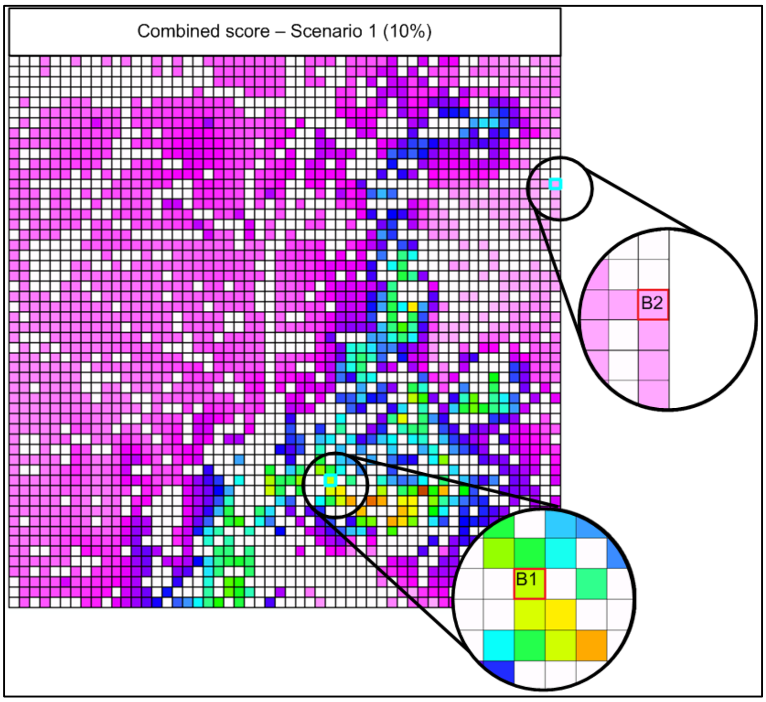

Figure 50: Zoom-in of two blocks, B1 and B2, with opposite combined score for comparison (B1: high wind resource but low CS, and B2: low wind resource but high CS)

The same was done for a low wind resource point (B2) with high combined score (see Figure 52).

Figure 51: Comparison of wind energy output and electricity profile consumption for a Winter month (July 2012). The B1 case: high wind resource but low CS

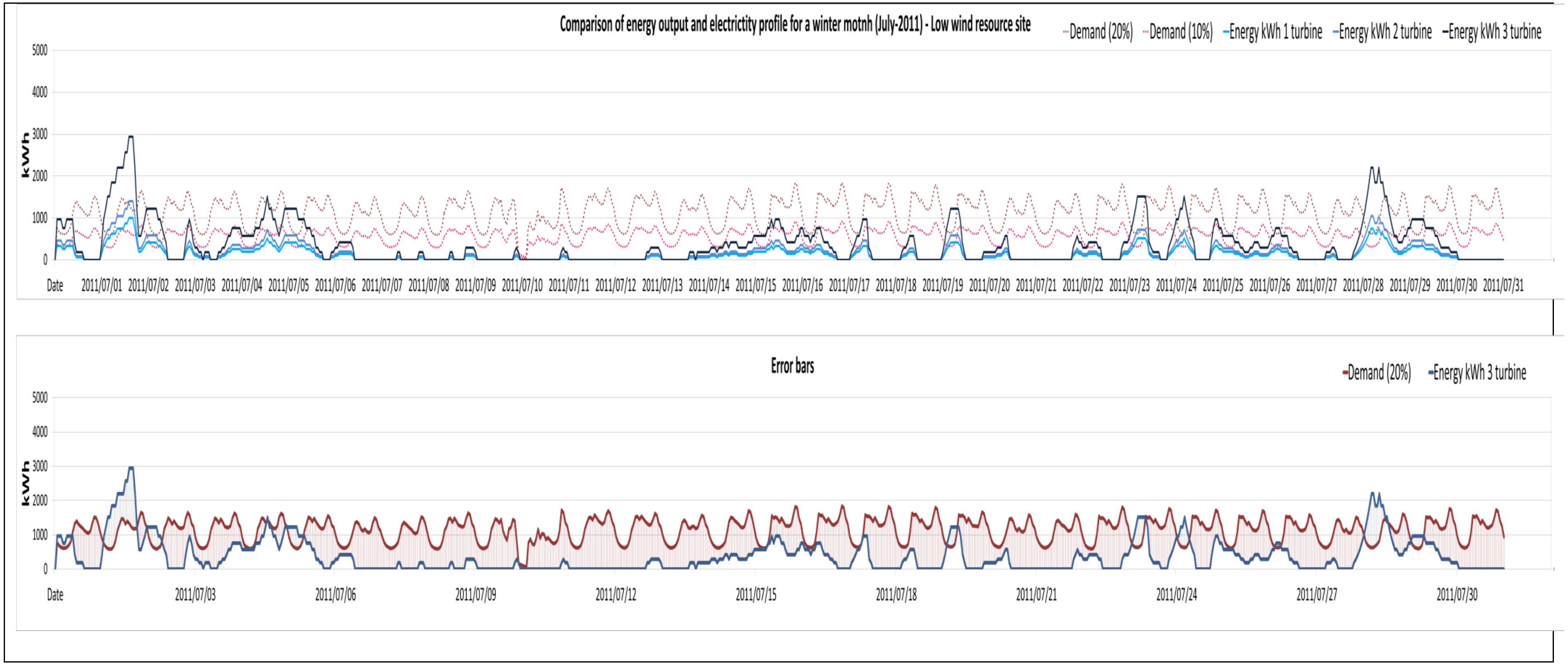

Figure 52: Comparison of wind energy output and electricity profile consumption for a Winter month (July 2012). The B2 case: low wind resource but high CS

Notice how in this particular case, the energy (kWh) required at the assessed demand point is actually very low, therefore the 10 and 20% demand from wind can actually be supplied from fewer turbines.

Table 11 presents the calculated values MD and PDD for the two sample blocks. The high wind resource site has days of impressive wind energy; however, most of the time it is below the requirements and its peaks fail in agreeing with residential consumption peaks. Wind energy peaks are produced during the night when the lowest consumption takes place. On the other hand, the wind profile of low wind resource has a better correlation; although under-producing energy most of the time.

Table 11: Summary of MD and PDD results for the two selected blocks

	10% Scenario		**20% Scenario**	
	MD	**PDD***	**MD**	**PDD***
B1-1turbine	15	0.310954	-485	0.654668
B1-2 turbines	220	0.612778	-280	0.767664
B1-3 turbines	1 012	3.301751	513	2.729649
B2-1turbine	-380	0.199128	-880	0.899172
B2-2 turbines	-333	0.194055	-832	0.847803
B2-3 turbines	-148	0.302811	-648	0.778319

*Divided by 1 000 000

Figure 53 presents the final output for each one of the scenarios evaluated, for the case of installing three turbines. The maps display the top 30 3x3 km blocks for turbine location (in black), and the bottom 30 sites (in red), these besides the ones already defined as No-Go areas (blank).

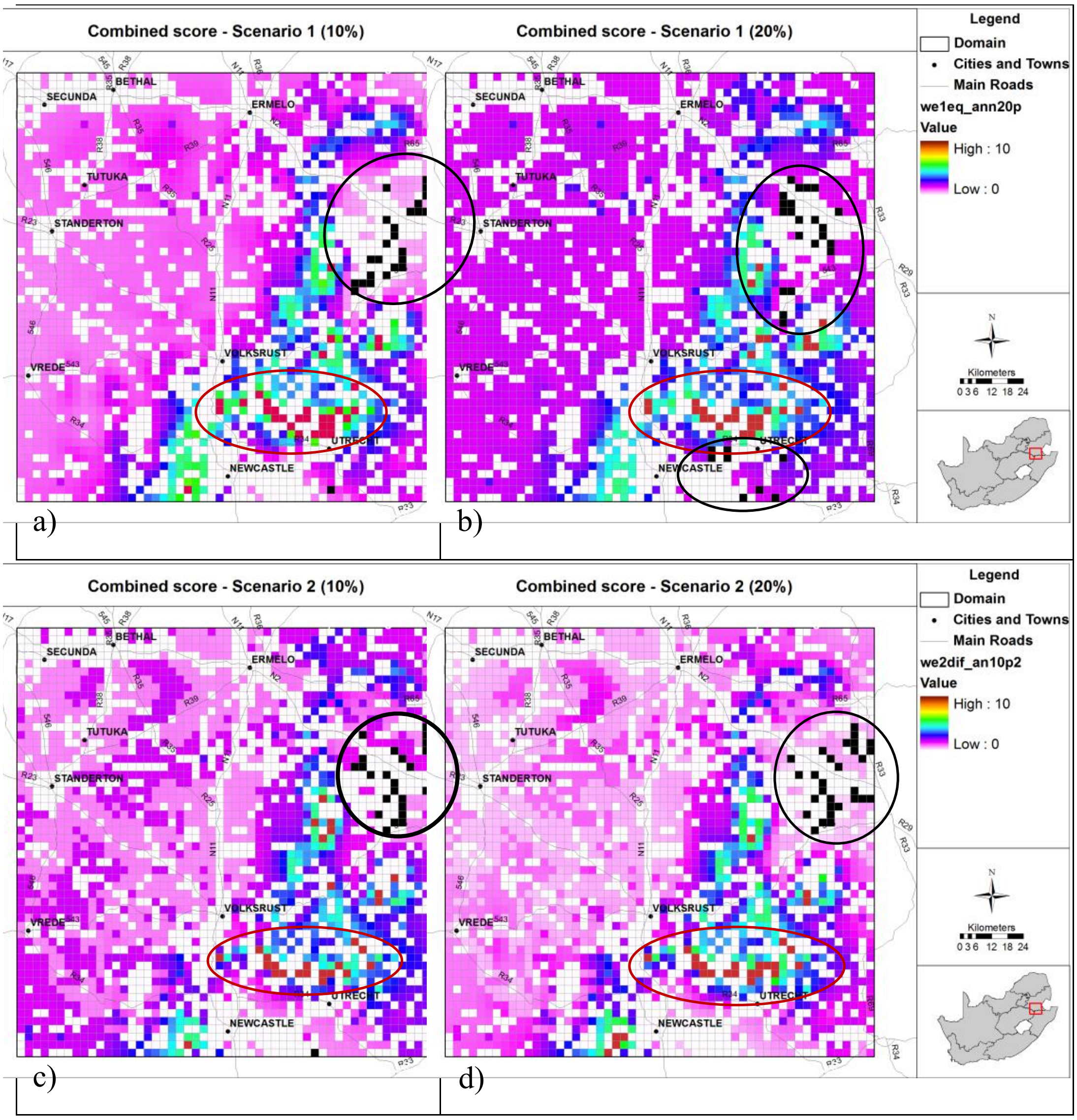

Figure 53: Combined modelled results showing top 30 and bottom 30 sites for a) Scenario 1 & 10%; b) Scenario 1 & 20%; c) Scenario 2 & 10%; d) Scenario 2 & 20%.

Although slight variations are presented between each scenario, for the analysed case, the best area for location of wind farms seems to be in the south east of the Mpumalanga province. Under the defined criteria, the sites located between Driefontein and Piet Retief, in the surroundings of the Heyshope dam rank higher in the obtained results. This area is located in proximity to the N2 and R543 roads, and to a 400 kV transmission line communicating to the Camden-Return to service station. The terrain is mainly flat, and there are very few conservancy areas. Because of agriculture and mining, most of the natural vegetation has already been lost and its biodiversity irreversibly changed to the point of being denoted by the SANBI as virtually dysfunctional.

On the other hand, the results show that areas in the surroundings of Wakkerstroom and Chrissiesmeer shouldn't be taken into account for wind farm development. Although the area has an extremely promising wind potential, the strong winds during the night when the energy demand is low, the complexity of terrain and the presence of important sub-catchments, forest vegetation, and threatened species of plants and animals, makes this area an important one for the environmental conservancy of the region and of the country.

The obtained results may change according to the variables used in the scenarios definition, i.e. amount of energy required, level of penetration, type and number of turbines, etc. However, in general terms and for an initial assessment of the site location, the proposed tool brings coherent and valuable input for further activities of site selection.

6. CONCLUSIONS

This study has presented the challenges that wind developers face when defining the location of the wind farms. It provided a set of criteria to consider and a GIS tool for the efficient treatment of the information. The highlight of the proposal consists on the evaluation of the profiles for energy generation and demand. The factors that have a strong effect on the output have been identified and mentioned in this chapter, as well as some of the advantages and shortages of the method. Finally, some suggestions for further studies are brought up.

- This study exposes the challenges that developers experience when deciding where to site wind farms. The distinctive component to other similar studies is the addition of an independent treatment of the wind resource and its energy generation profile. It implies the comparison of the unique hourly wind power profile of each site, against the energy consumption profile for the same period.

- In South Africa the only available mechanism for environmental evaluation of wind farms is the EIA. The EIA process only starts after the position of the project has been decided. There are other available guidelines; but these are limited, and focus mainly on the coastal areas.

  Herein, a summary of recommended criteria is presented. This is based on existing literature and includes planning, technical and environmental components. However, the official publication of such factors, or the national delineation of No-Go areas linked to the local land planning programs, will enhance the positive impacts of wind energy and facilitate the evaluation by the authorities.

- Room for improvement is found in a thorough study assessing the weighting factors used for the overlap of the different parameters that result in the SPI. Such a study will require the active involvement of stakeholders, and adapted to the particular South African situation.

- One of the greatest advantages of the proposed method is the simplicity in the calculations, making it relatively quick to compute. The use of GIS facilitates significantly the management and treatment of information. Changes, updates and additions of information can be easily implemented; and the ModelBuilder tool makes the programming task user friendly even for non-experienced users.

- Modelled TAPM wind shows an overall good performance and an appropriate alternative for areas where WASA wind data is not yet available. However, the extension of the WASA project to the rest of the country is essential for the spreading of the wind generation facilities. The dispersed location of wind farms will smooth the variations from the wind, and reduce the negative impacts on the electrical grid.

- The accuracy of the wind model and the capacity of replicating the wind behaviour at smaller time steps are key factors to improve the results of the site selection model.

- The use of PDD and MD indicators of profile fitting allow the evaluation of the differences between supply and electricity demand. The magnitude of the target electricity demand is influenced by the wind energy penetration level, as well as the number and type of users. The magnitude of the available electricity varies depending of the wind resource and the type and the number of turbines in the cluster.

The truth is that for a facility connected to the grid system, the wind energy produced at point A won't be delivered exclusively to point B; but will be added to the electricity already flowing through the system. Hence the need to combine the wind electricity supply with other sources of energy, hybrid systems or storage devices.

However, given the strong influence of the residential sector in the demand profile, the pattern of the demand is expected to be maintained across the country. Therefore the PDD and MD are still useful for the evaluation of multiple demand points, although adjustments to the model must be incorporated.

- The proposed model requires that all input information is converted into quantitative sets with a score assigned. This potentially implies the exclusion of qualitative issues important for wind farming such as visual impact on the landscape.

The accuracy of the site selection model outcome is determined by the accuracy of the sources. Errors in one original dataset will propagate when combined with other datasets, so that the final map could be less truthful and less accurate than the input data (Baban & Parry, 2001). The following factors have been identified to influence the results: the quality, accuracy and availability of the information, the resolution of the input information (especially for wind data), and the magnitude of the energy consumed at the analysis point. Records from the wind farms, once they are fully operational, will become valuable input for improvement.

- Other improvements can be made by the inclusion of economic factors in the model equations. The biggest investment in a wind energy project is related to capital and construction costs, and those are strongly affected by the location (i.e. access road, connection to the grid). In countries where the price of purchase is set, a more accurate financial modelling can be prepared, increasing the possibility of access to funding. In a free market environment, more competitive prices can be offered.

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APPENDICES

Appendix A: Overview of the model structure in the GIS Model-builder