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# Performance Analysis of Wind Turbines at Sites in KwaZulu-Natal Province, South Africa

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**Abstract**

Wind energy, like others renewable energies is environmentally friendly and if use would contribute significantly to greenhouse gas effects reduce and improvement of the ecosystem and climate change. Currently wind energy is more and more interesting source of renewable energy attracting researchers and investors. South Africa being identified as one of the countries with higher expectation of wind in Sub-Saharan Africa, this paper targeted the production of electricity using the new generation of wind turbines at two sites where the wind speed data are collected since October 2015 in KwaZulu-Natal Province. The Vestas V90-1.8 wind turbine and the Vestas V90-2.0 wind turbine are used to assess the wind energy conversion into electric energy for the two sites. With little details known about the wind regime at WM12 and the WM13 sites, the Rayleigh probability density function (pdf) is used to determine the statistics of wind speeds at those sites.

The simulation results show that the V90-1.8 perform much better in both sites than the V90-2.0 dispute the difference in rated power. The economic analysis is not considered in this present article.

**Keyword:** Wind speed, wind turbine, Rayleigh statistics, energy delivered, productivity, capacity factor.

## 1. INTRODUCTION

South Africa being identified as one of the countries with higher expectation of wind in Sub-Saharan Africa, has a wind speed from 7.29 m/s to 9.70 m/s recorded in Cape Alguhas through Cape Point. There are no records of the mean wind speed through the country, perhaps it's due to the wind speed variations, the general use of wind turbines in many parts of the country for water pumping using wind potential power to generate electricity [1]. South Africa's wind energy potential is large and the Eastern Cape and Western Cape provinces have the country's best wind resources [2]. Even if studies have shown that South Africa had a potential in wind energy between a minimum of 500 MW and a maximum of 56,000 MW, only 0.05 % were generated by the experimental station of Eskom Kliphenwel and Darling wind farm. A number of stations of small turbines were also built, but they are not connected to the national grid. [3] [4]. The power rate of the wind system depends on the turbine size and wind's speed.

Currently wind energy is more and more interesting source of renewable energy attracting researchers and investors. The advanced knowledge in the design and manufacturing of wind turbines and the development in the assessment of wind energy potential to determine the higher potential areas to install wind farms have made this technology more interesting and bring down the investment cost. Wind energy, like others renewable energies is environmental friendly and if use would contribute significantly to greenhouse gas effects reduce and improvement of the ecosystem and climate change.

This paper presents the performance evaluation of new technology wind turbines at KwaZulu-Natal sites for wind energy conversion into electric energy. Two specific sites were chosen any their measured wind speed data used to determine the performance of the V90-1.8 and V90-2.0 Vestas wind turbines base on the Rayleigh statistics wind speed. The simulation was than performed in Matlab and the results show that the V90-1.8 perform much better in both sites than the V90-2.0 dispute the difference in rated power. Economic analysis is not considered in this present article.

## 2. SITE LOCATIONS AND DATA HARVESTING

The different sites where the wind data are recorded are given in Figure 1 for KwaZulu-Natal Province, South Africa. The sites targeted are the WM12 closed to Eston and the WM13 closed to Jozini. Wind data have been recorded since 2015 as part of wind atlas for South Africa (WASA) project using the measurement instruments given in Table 1. The type of wind station used at the site WM12 and the site WM13 is shown in Figure 2.

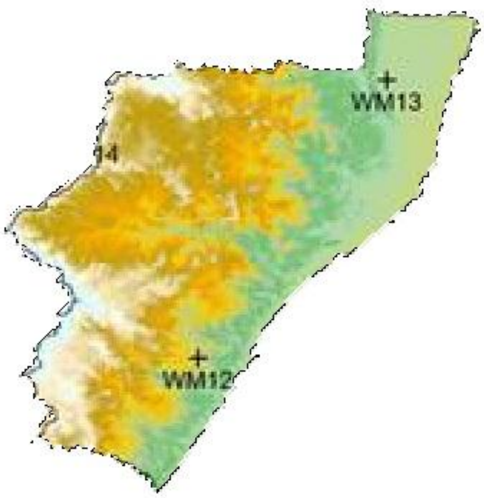


**Figure 1:** Wind data collection sites in KwaZulu-Natal Province, South Africa [5]

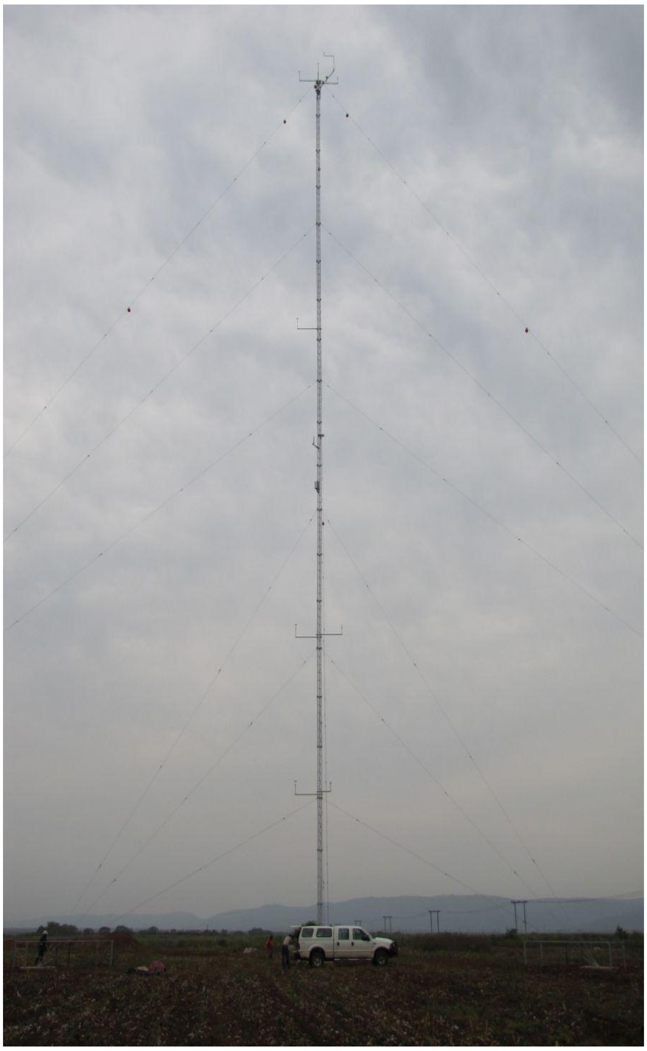

**Figure 2:** Wind turbine data collection station used at the WM12 and the WM13 sites [6]

**Table 1:** Measurement instruments used for the collection of wind speed data at WM12 site and WM13 site for in KwaZulu-Natal Province, South Africa

| Device | Model | Manufacturer |
|---|---|---|
| Cup anemeter | P2546A | WindSensor, Denemark |
| Potentiometer wind vanes | W200P | Vector Instruments, United Kingdom |
| Temperature and relative humidity probes | HMP155 | Vaisala Oyj, Finland |
| Temperature difference sensors | P2642A01 Pt500 | WindSensor, Denemark |
| Barometers | PTB110 | Vaisala Oyj, Finland |
| Data loggers / Compact flash module | CR100 / CFM100 | Campbell Scientific Inc, United Kingdom |

The windspeed data are collected at the heights of 10m, 20m, 40m, 60m and 62m. Details about the data can be found in [7] [6]. Table 2. gives the summary of the average wind speed for data collected from 16$^{th}$ October 2015 to 07$^{th}$ December 2018 at both sites.

**Table 2:** The summary of the average wind speed for data collected from 16th October 2015 to 07th December 2018 at the WM12 and WM13 sites at KwaZulu-Natal Province, South Africa

| Sites | Closest town | Longitude [$^0$] | Latitude [$^0$] | Measured windspeed [m/s] | | | | Calculated windspeed [m/s] |
|---|---|---|---|---|---|---|---|---|
| | | | | @ 10 m | @ 20 m | @ 40 m | @ 60 m | @ 80 m |
| **WM 12** | **Eston** | **30.52872** | **-29.8503** | **6.29** | **6.69** | **6.75** | **6.66** | **6.72 (α = 0.0319)** |
| **WM13** | **Jozini** | **32.16645** | **-27.426** | **6.14** | **7.2** | **8.63** | **9.19** | **9.81 α = 0.2254)** |

## 3. WIND TURBINE CHARACTERISTICS

The market of industrial wind turbines is mostly dominated by the following manufacturers: Vestas, Gamesa, and General electrics (GE) [8]. The manufacturers offer different ranges of hub height relates to the frequencies of 50 Hz and 60 Hz specified in the technical data sheet of different turbines.


**Figure 3:** Typical Vestas V90-1.8 / V90-2.0 wind turbine [9]

In this study Vestas made wind turbines are used for the evaluability of detailed data. Two turbines both with the diameter of 90 m and the rated power of 1,8 MW and 2,0 MW respectively were used, the Vestas V90-1.8 wind turbine and the Vestas V90-2.0 wind turbine. Those turbines are upwind horizontal axis wind turbines (HAWT). The turbine choice is made based on South African electric network frequency of 50Hz. Figure 4 shows the power curves for those particular wind turbines obtained from manufacturer data sheets. More details about those turbines can be found in [9].

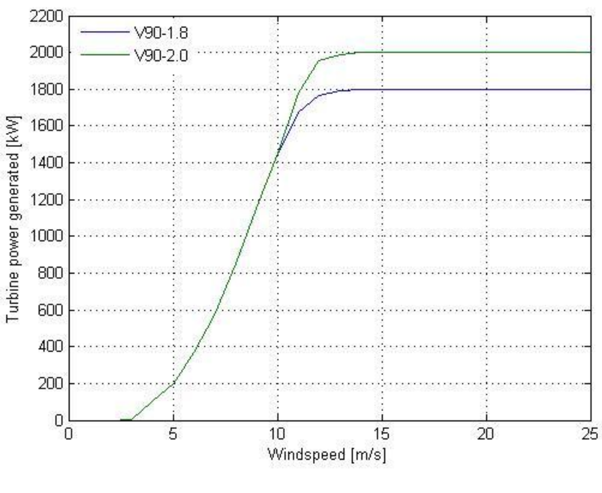


**Figure 4:** Power curves for the Vestas V90-1.8 wind turbine and Vestas V90-2.0 wind turbine (extracted from the manufacturer datasheet) generated with Matlab

It can be observed that both turbines have the cut in windspeed of 4 m/s, the rated wind speed of 12 m/s and the cut- out or furting windspeed of 25 m/s. Table 3 gives details related to the two turbines for this particular study conditions.

**Table 3:** Wind turbines specifications

| **Wind turbine** | **Rated power [kw]** | **Cut in windspeed [m/s]** | **Rated windspeed [m/s]** | **Furting windspeed [m/s]** | **Diameter [m]** | **Hub height [m]** |
|---|---|---|---|---|---|---|
| V90-1.8 | 1800 | 4 | 12 | 25 | 90 | 80 |
| V90-2.0 | 2000 | 4 | 12 | 25 | 90 | 80 |

## 4. STATISTICS OF WIND SPEEDS AND ENERGY DELIVERED

To determine the energy delivered by a wind turbine at a specific site, the statistics of the wind at the site and the power in the wind must be determined first. The power in a wind blowing at a specific wind speed at a site is a cubic function of the wind speed and it is given by the Equation (1).

$$P = \frac{1}{2}\rho\, A\, v^3 \qquad (1)$$

Where ρ is the wind density [= 1.225 kg/m$^3$], A is the swept area of the rotor [m$^2$], and v is the wind speed at the site [m/s].

As wind flow at the site is a transient phenomenon accompanied with uncontrolled changes in wind speed, the statistics of wind speeds at the specific site is characterised by the use of Weibull probability density function (pdf) which represent the starting point. This function is given in Equation (2).

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \qquad (2)$$

Where k is the shape parameter and c is the scale parameter.

When little detail is known about the wind regime at the site, k is assuming to be equal to 2 and c obtained from Equation (3).

$$c = \frac{2}{\sqrt{\pi}}\bar{v} \qquad (3)$$

Where $\bar{v}$ is the average wind speed at the site [m/s].

The Weibull pdf becomes the Rayleigh pdf given in Equation (4).

$$f(v) = \frac{\pi v}{2\bar{v}^2} exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2\right] \qquad (4)$$

The energy delivered by the wind turbine at a specific location is obtained by summing different energy delivered by the turbine of each wind speed at the site. This energy is given by the Equation (*5*).

$$E_g = 8760 \sum_{i=1}^{n} f_{v_i} P_{v_i} \quad (5)$$

Where $P_{v_i}$ is the power rated of the turbine at $i^{th}$ wind speed $v_i$ given by the manufacturer [kW].

The turbine efficiency is defined as the ratio of the energy delivered by the wind turbine and the energy in the wind and it is obtained from the Equation (6).

$$\eta_{avg} = \frac{E_g}{E_w} \quad (6)$$

With $E_w$ define as the energy in the wind and it is given by the Equation (7)

$$E_w = 8760\, \bar{P} \quad (7)$$

In which $\bar{P}$ given by the Equation (8) is the fraction of wind power converted into electricity by the wind turbine at the site.

$$\bar{P} = \frac{1}{2} \frac{6}{\pi} \rho\, A\, \bar{v}^3 \quad (8)$$

Where $\bar{v}$ is the average wind speed at the site [m/s].

The productivity of the turbine is given by the Equation (9). It is the ratio of the wind turbine energy delivered by the swept area of the wind turbine rotor.

$$prod = \frac{E_g}{A} \quad (9)$$

Any electric power system is mostly evaluated on base of the power delivered continuously at full power basis. Since the wind turbine power delivered is transient over the year, the capacity factor (CF) as the ratio of the actual power delivered by the rated power of the wind turbine, obtained from the Equation (10), can be used to evaluate the performance of the wind turbine at a specific site. As high the CF as high the power delivered for the turbine at the specific site.

$$CF = \frac{E_g}{8760\, P_R} \quad (10)$$

## 5. PERFORMANCE ANALYSIS AND DISCUSSIONS

The simulation of the wind turbines V90-1.8 and the wind turbine V90-2.0 is performed with Matlab software package using the wind data collected at WM12 and WM13 sites. Figure 5 shows the Rayleigh wind statistics as function of windspeed for measured site WM12 and measured site WM13. It can be noticed that the higher probability is reached for the wind speed of 5 m/s for WM12 and 8 m/s for WM13.

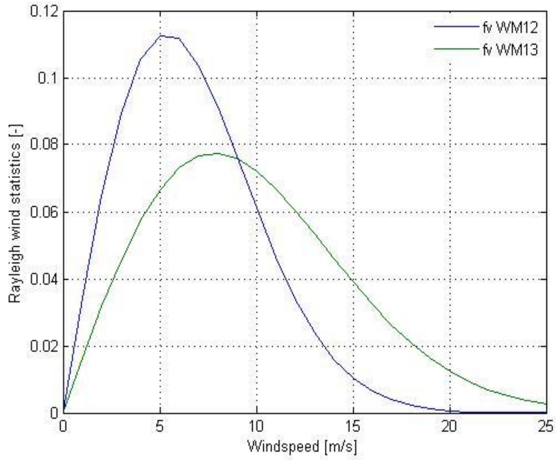


**Figure 5:** Rayleigh wind statistics as function of winds peed for KwaZulu-Natal measured site WM12 and measured site WM13

This is materialized by higher number of winds blowing over a year for both sites as seen in Figure 6.

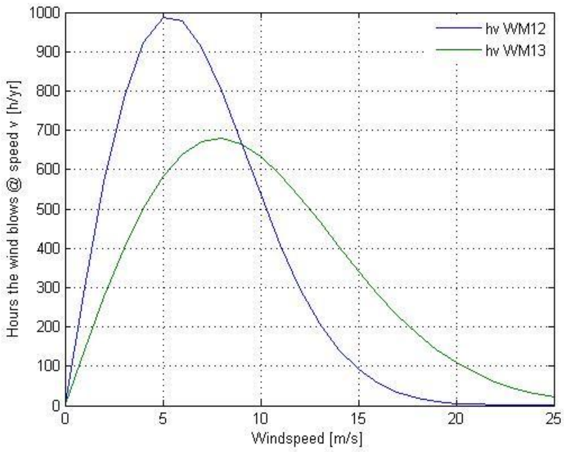


**Figure 6:** Hours per year the wind blows at each wind speed for the Vestas V90-1.8 turbine and the Vestas V90-2.0 at the WM12 site and the WM13 site for 80 m hub height and average wind speed of 6.72 m/s and 9.81 m/s

Both turbines produce almost the same power with the wind blowing at the windspeed below 10 m/s at both sites as represented in Figure 7. The difference in power delivered become more noticeable at the site WM13. This is probably due to the difference in rated power between the two wind turbines as the wind speed is higher compared to the WM12 site.

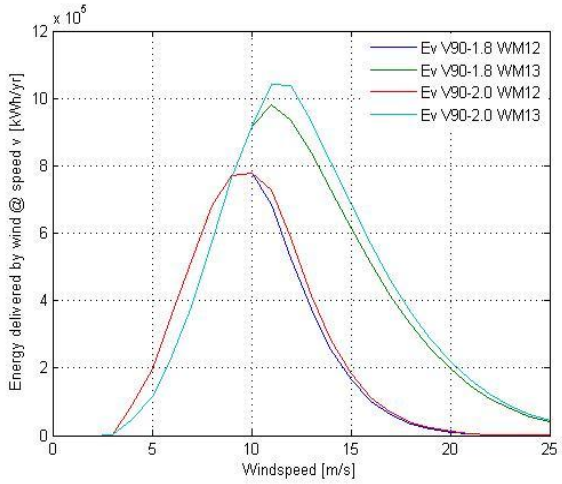


**Figure 7:** Energy delivered by the wind for the wind turbine V90-1.8 and the wind turbine V90-2.0 at WM12 and WM13 sites for 6.72 m/s and 9.81 m/s respectively

The difference between power delivered by the two wind turbines at those sites are given in Figure 8. The difference in energy produced is noticed from wind speed above 10 m/s and the peak power is reached at the wind speed of 12m/s which is equal to the rated windspeed as the individual turbine powers become noticeable. The generator produces as much power as it is designed for [10].

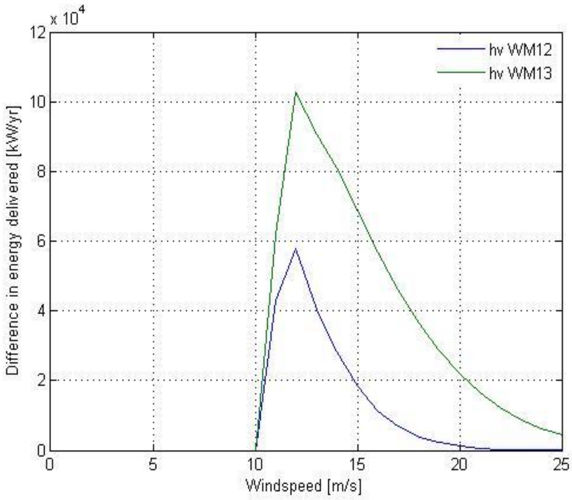


**Figure 8:** Difference between energy delivered by the wind turbine V90-1.8 and the wind turbine V90-2.0 at WM12 and WM13 sites for 6.72 m/s and 9.81 m/s respectively

Figure 9 and Figure 10 show hours per year and energy delivered per year at each speed for Vesta V90-1.8 wind turbine and Vesta V90-2.0 wind turbine respectively at the WM12 site.

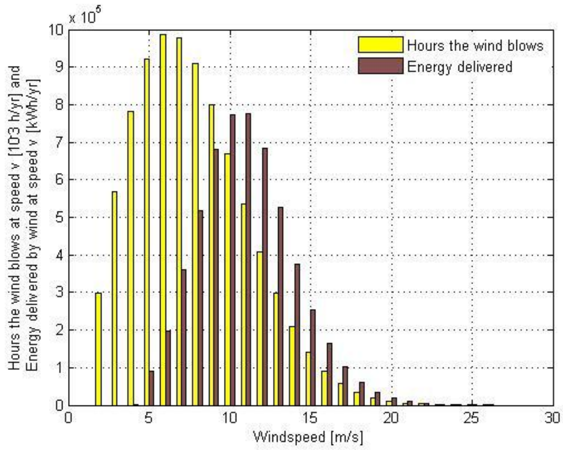


**Figure 9:** Hours per year and energy delivered per year at each wind speed for the Vestas V90-1.8 turbine at the WM12 site for 80 m hub height and average wind speed of 6.72 m/s

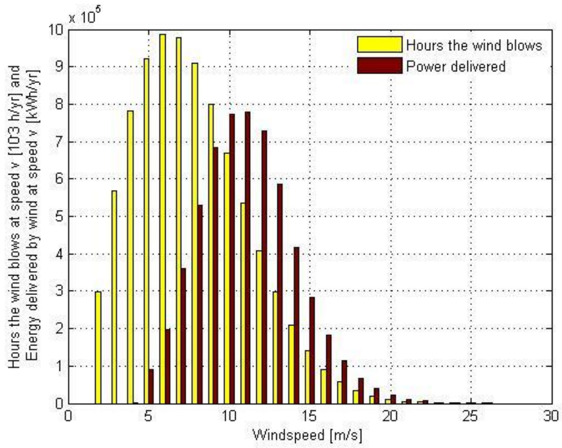


**Figure 10:** Hours per year and energy delivered per year at each wind speed for the Vestas V90-2.0 turbine at the WM12 site for 80 m hub height and average wind speed of 6.72 m/s

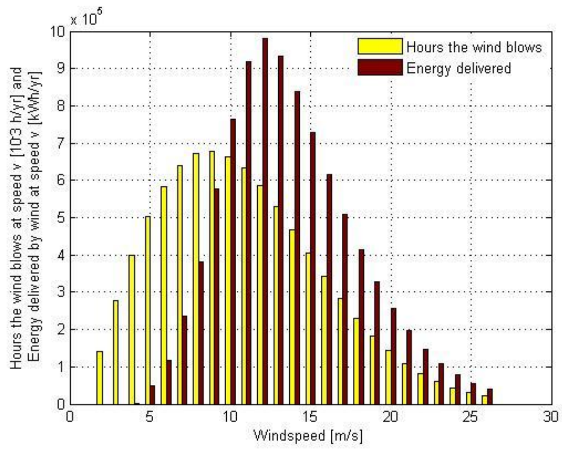


**Figure 11:** Hours per year and energy delivered per year at each wind speed for the Vestas V90-1.8 turbine and Rayleigh winds at the WM13 site for 80 m hub height and wind speed of 9.81 m/s

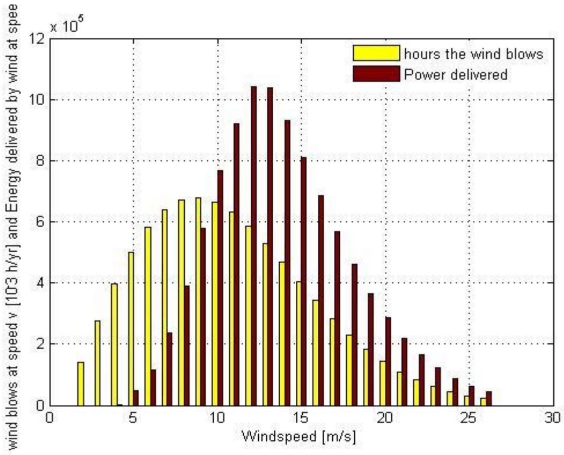


**Figure 12:** Hours per year and energy delivered per year at each wind speed for the Vestas V90-2.0 turbine and Rayleigh winds at the WM13 site for 80 m hub height and wind speed of 9.81 m/s

The same situation is represented in Figure 11 and Figure 12 for both turbines at the site WM13. It can be noticed that the turbines produce low energy at low wind speeds in spite of the large number of hours of wind blowing at these speeds. The performance of the Vestas V90-2.0 is higher than the performance of V90-1.8 at the site WM13. This is justified by the cubic relationship of the power and the windspeed. This means that the large turbines perform much better in higher windspeed sites than in the lower windspeed sites.

The turbines V90-1.8 and V90-2.0 at the site WM12 present low capacity factor of 0.357 and 0.335 with efficiencies of 0.28 and 0.29. This means that the turbines captured much of the wind energy at this site. This is supported by the efficient which is closed to 30% described as the overall wind turbine efficiency. Details of results from the analysis are given in Table 4.

**Table 4:** Summary of V90-1.8 and V90-2.0 wind turbine performances at WM12 and WM13 sites.

| Site | Turbine | Energy delivered [MWh/yr] | Efficiency [-] | Productivity [kWh] | Capacity Factor [-] |
|---|---|---|---|---|---|
| WM12 | V90-1.8 | 5.6427 | 0.28 | 886.97 | 0.357 |
| | V90-2.0 | 5.8571 | 0.29 | 920.67 | 0.335 |
| WM13 | V90-1.8 | 9.2799 | 0.15 | 1458.70 | 0.588 |
| | V90-2.0 | 9.9213 | 0.16 | 1559.50 | 0.566 |

## 6. CONCLUSION

From the analysis of the values obtained in Table 3 we conclude that the V90-1.8 perform much better in both sites than the V90-2.0 dispute the difference in rated power. Two sites of higher wind potential were assessed for wind turbines Vestas V90-1.8 and Vestas V90-2.0 wind turbines. Based on the characteristics supplied by the manufacturer for those wind turbines and the data collected at the sites, the energy delivered by the wind turbine were calculated using the Rayleigh statistics of wind speeds. Then, the turbine efficiencies, the productivity and the capacity factor are determined. We found that the V90-1.8 wind turbine and the V90-2.0 wind turbine are 0.28 and 0.29 for the annual energy delivered of 5.6427 MWh and 5.8571 MWh respectively for WM12 site. These efficiencies are closed to 0.30 described as the overall wind turbine efficiency in literatures. The efficiency at WM13 site is 0.15 and 0.16 for the V90-1.8 and the V90-2.0 wind turbines respectively. Those values are very low compared to the expected overall efficiency of 0.30. This shows how the turbines are more efficient at the WM12 site than WM13 site. Nerveless, the energy delivered, the productivity and the capacity factor of the two turbines at WM13 site are higher than those obtained at the WM12 site. This is due to the higher wind speed at the WM13 site. Comparing the results obtained for the two machines, it can be noticed that the V90-1.8 wind turbine performs much better than the V90-2.0 wind turbine dispute the rated power of 2000 kW of the V90-2.0 wind turbine for the same rotor diameter of 90 m.

From those results, it can be concluded that the WM12 site is potentially rich in wind energy that can be converted into electrical energy than the WM13 site, using the latest wind turbine technology for the wind turbines with low rated power. To decide for the wind turbines to be used for the generation of electricity at those sites, an economic analysis must be performed based on the determination of the optimum rated power and the swept area of the wind turbines to be used.

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