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Planning for the future in uncertain times

Analysis of utility scale wind and solar plant performance in South Africa relative to daily electricity demand

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Abstract

The performance of variable electricity generation sources such as solar PV and wind is an important consideration in their integration into a power system. The expected performance may affect a number of decisions related to network planning, tariff determinations, energy planning as well as future policy decisions. This study analyses the capacity factor performance of utility scale solar PV and wind on the South African power system. Measures of capacity factor relative to electricity demand are considered and performance is assessed during Eskom’s seasonal peak and off-peak demand periods.

1. Introduction

South Africa has seen a significant increase in renewable energy generation in recent years owing to the introduction of the Renewable Energy Independent Power Producer Programme (REIPPP) championed by the Department of Energy and the National Treasury of South Africa. By the end of 2016 a total of 1 473 MW of onshore wind and 1 250 MW of solar PV generation was operational and had fed 3 697 GWh and 2 508 GWh respectively into the grid during 2016 [1].

Wind and solar power technologies have been referred to as variable or non-dispatchable renewable energy sources because they are dependent on a varying primary energy source (wind and sunlight) [2]. Their variability has three inherent properties: variability over time, limited predictability and the fact that they are location bound [2]. As a result, their plant output or capacity factors vary on an hourly basis. Dispatchable generating technologies (such as coal, gas-combined-cycle, nuclear) are controlled by the system operator and can be turned on or off based on their economic attractiveness at a particular point in time to supply electricity as well as to supply ancillary network services such as frequency regulation and spinning reserve [3].

As more Renewable Energy Independent Power Producers (REIPP) feed power onto the South African electricity grid, further data becomes available to study the time of day at which these plants effectively contribute to the national power demand. This information is useful in assisting grid operators in predicting and balancing system supply as more REIPPs lock onto the grid and may contribute to decisions related to network planning, tariff determinations, future energy planning and carbon reduction objectives.

The objectives of this study are as follows:

- To report on the performance of solar PV and wind generation in South Africa since the REIPPP was initiated
- To define and quantify capacity factors during peak and off-peak demand times
- To assess aggregate solar PV and wind performance relative to South Africa's system demand

This study analyses the performance of solar PV and wind electricity generation in South Africa, specifically highlighting the contributions of solar PV and wind outputs during national peak and off-peak demand periods. The dataset used for this study consists of the aggregate hourly solar PV and wind generation and the corresponding total solar PV and wind capacity for the same hour. The dataset set is dated from 1 January 2014 – 31 August 2016 and includes hourly outputs for periods 0 through to 23 (i.e. 00:00 – 01:00 hourly through to 23:00 – 00:00). It should also be noted that within the data set, 3 high season periods are aggregated but only 2.5 low season periods since the dataset only runs through to 31 August 2016.

2. Capacity Factor

The U.S Energy Information Administration's defines capacity factor as '*the ratio of electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period*' [4]. The term can be used to convert installed or rated capacity into an aggregate annual output [5].

It is essentially the ratio of a fleet's actual generation to its maximum potential generation or nameplate capacity and can be used to define how intensely a generator is run [6]. Capacity factor is defined as follows [7]:

$$Capacity\ Factor = \frac{\sum_{x,m} Generation_{x,m}}{\sum_{x,m} Capacity_x * Available\ time_{x,m}} \quad (1)$$

Where $'x'$ represents generators of a specific technology and $'m'$ represents the period of time (month or year).

In many cases, a technology's capacity factor is used to determine a plant's annual expected generation hours. A plant's annual expected generation hours directly impacts its Levelised Cost of Electricity value (LCOE) [8]:

$$LCOE = \frac{FCR * Capital\ costs\ (\frac{R}{MW}) + Fixed\ O\&M(\frac{R}{MW.year})}{Annual\ expected\ generation\ hours} + Variable\ O\&M\ (\frac{R}{MWh}) + Fuel\ \left(\frac{R}{MWh}\right) \quad (2)$$

'FCR' refers to fixed charge rate and *'O&M'* refers to operating & maintenance costs. A plant's LCOE is inversely proportional to the plant's capacity factor (i.e. the higher the plant's capacity factor, the lower the LCOE value).

Capacity factors vary significantly by plant type, fuel availability and due to economic reasons. The term *capacity factor* should not be confused with *availability factor*. A power plant's availability factor is the ratio of the amount of time that a plant is available to produce electricity divided by the amount of time in the period. Plants that operate less frequently (i.e. with a low capacity factor) tend to have higher availability factors because they require less maintenance [9]. A plant can be out of service due to maintenance whether planned or unplanned and this contributes to its capacity factor because it affects its actual energy generation. A plant may not have fuel available to operate, this may be due to fuel shortages or limited availability of sunshine and wind (in the case of renewable sources) – this too would reduce a plant's actual generation output impacting its capacity factor. In some cases, capacity factors are purposefully kept low in peaking generators due to the high variable costs associated with the peaking technologies or where the price of electricity is too low to make production from a certain source feasible. Generators can also have a lower capacity factor due to a decreased demand for electricity.

Traditionally, base load generators such as nuclear units have high capacity factors, while peaking generators have low capacity factors [6]. Relative to nuclear and coal technologies, renewable generating technologies such as wind and solar PV have lower capacity factors but these capacity factor values can vary depending on geographical locations. Table 1 illustrates the annual capacity factor data from selected generating technologies according to the U.S. Energy Information Administration (2017). The data is based on annual data from over 4 100 plants across the United States of America [10]. The generator data is grouped according to its primary fuel type [11].

Table 1: Average capacity factors for utility scale generators calculated for 2014-2016 (Adapted from U.S. Energy Information Administration, 2017 [12])

Nuclear	**Coal**	**Wind**	**Solar PV**	**Conventional Hydropower**	**Natural Gas Fired Combined Cycle**	**Natural Gas Fired Combustion Turbine**
92.2%	56.1%	33.6%	26.3%	37.0%	53.4%	6.8%

The average capacity factors for South Africa's solar PV and wind plants are presented in Table 2 alongside the values used in the 2016 draft Integrated Resource Plan (IRP).

Table 2: Comparison of average capacity factors for wind and solar PV

	Production Data (01/01/2014 – 31/08/2016)		***Draft IRP Update Base Case 2016***	
	Wind	Solar PV	Wind	Solar PV
Average Annual Capacity Factor (%)	31.8	24.9	34	26

While capacity factor provides information on the average performance of a technology, it does not provide any information on when the electricity is actually produced. However, hourly production data can be analysed to calculate plant capacity factors within certain periods. Paul, L. Joskow [3] demonstrates that by considering the production profiles of each source of energy, one can use this information to determine the market value of the electricity at the time at which the technology supplies it. This is achieved by considering a plant's capacity factors within certain periods of the day. These periods are pre-defined by the wholesale price of electricity and consumer demand (i.e. peak and off-peak). This information is essential to economic discussions and comparisons between various generating technologies [3]. In some cases, the capacity factor during peak load hours of peak load months is used to define a generator's capacity credit. Capacity credit is a number specific to a generator representing the fraction of its installed capacity by which conventional generation capacity can be reduced without affecting the system reliability [13].

For this study a detailed analysis of the capacity factors during peak and off-peak periods is conducted to provide information on how much generation value a renewable technology contributes during these periods. Based on Equation 1, peak and off-peak capacity factor equations are defined as:

$$Capacity\ Factor_{Peak} = \frac{\sum_{x,peak\ periods} Generation_{x,peak\ periods}}{\sum_{x\ ,peak\ periods} Capacity_x * Available\ time_{x,peak\ periods}} \tag{3}$$

$$Capacity\ Factor_{Off-Peak} = \frac{\sum_{x,off-peak\ periods} Generation_{x,off-peak\ periods}}{\sum_{x\ ,off-peak\ periods} Capacity_x * Available\ time_{x,off-\ peak\ periods}} \tag{4}$$

The benefit of defining capacity factor specifically for peak and off-peak periods is that it provides production data in relation to the time of day in which it occurs. With an expected increase in renewable generation going forward, it is important to determine the time of day at which renewables contribute to electricity generation.

3. Peak Demand in South Africa

The peak and off-peak periods in South Africa are taken as defined by the national utility, Eskom [14]. Eskom divides the year into two defined demand periods, i.e. a high demand season which coincides with the cold winter months and a low demand season, comprising the rest of the year. These seasons are highlighted in Table 3.

Table 3: Eskom Seasons [14]

Season:	***Month:***
High Demand Season	June, July, August
Low Demand Season	January, February, March, April, May, September, October, November, December

Within each season, depending on the day of the week, the tariff system is divided into peak, standard, and off-peak time periods as shown in Figure 1 [14]. For this study, standard and off-peak periods will be merged and considered as one period, the 'off-peak' period. The Eskom grid is constrained specifically during peak periods and the study focuses on isolating this period from the other periods for the analysis. Since the other periods do not occur during constrained periods, they are grouped together.

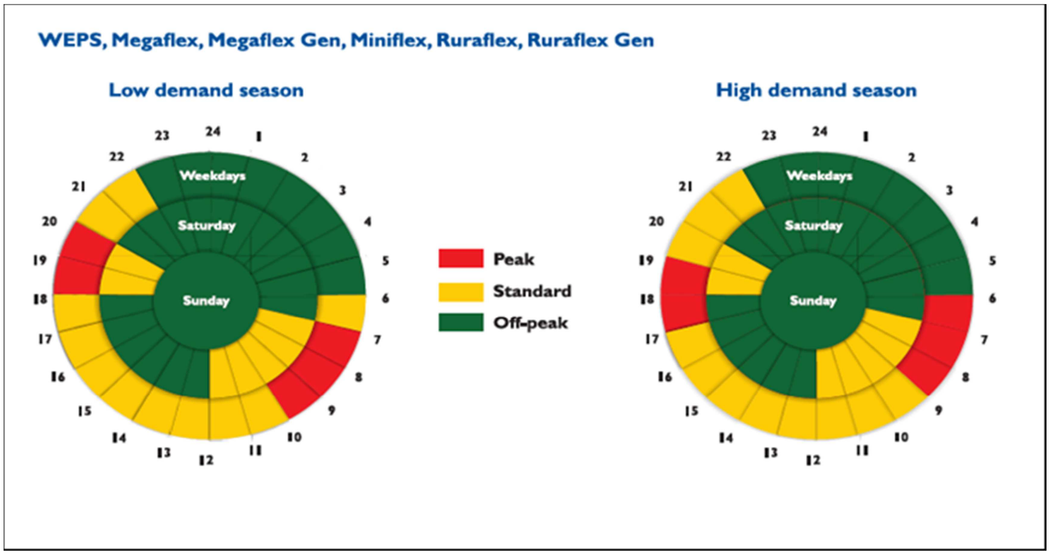

Figure 1: Low and High Season Tariff Structures [14]

Peak periods are summarised in Table 4 and off-peak periods are considered as any time of day falling outside of the peak periods.

Table 4: Peak Periods

Day of the Week:	***Low Season:***	***High Season:***
Weekday	07:00 – 10:00, 18:00 – 20:00	06:00 – 09:00; 17:00 – 19:00
Saturday	-	-
Sunday	-	-

The Eskom high and low season system output curve is depicted in Figure 2 as green and blue lines respectively. The curves represent the applicable average hourly system output for the dataset starting from 1 January 2014 – 31 August 2016. Within the figure, the peak periods are highlighted using the broken red line. During the low season, the average morning system output peaks at 29 117 MWh at 10:00 and 29 833 MWh at 19:00 in the evening. During the high season, the average system output peaks at 30 299 MWh at 09:00 in the morning and at 32 110 MWh at 18:00 in the evening.

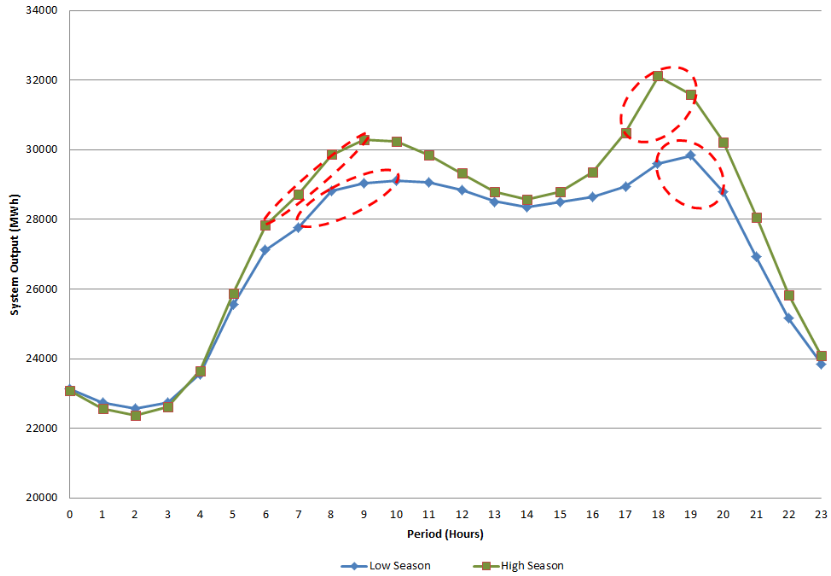

Figure 2: High and low season system average hourly output with Eskom peak periods highlighted

4. Results & Discussion

4.1 Solar PV

Analysing the production statistics relative to the system demand provides an opportunity to assess production patterns and variability relative to South Africa's system demand.

Figure 3 illustrates the high season hourly capacity factor for solar PV plotted against the high season national system average hourly demand. The average hourly capacity factor is plotted in addition to the best and worst day's performance within the high seasons.

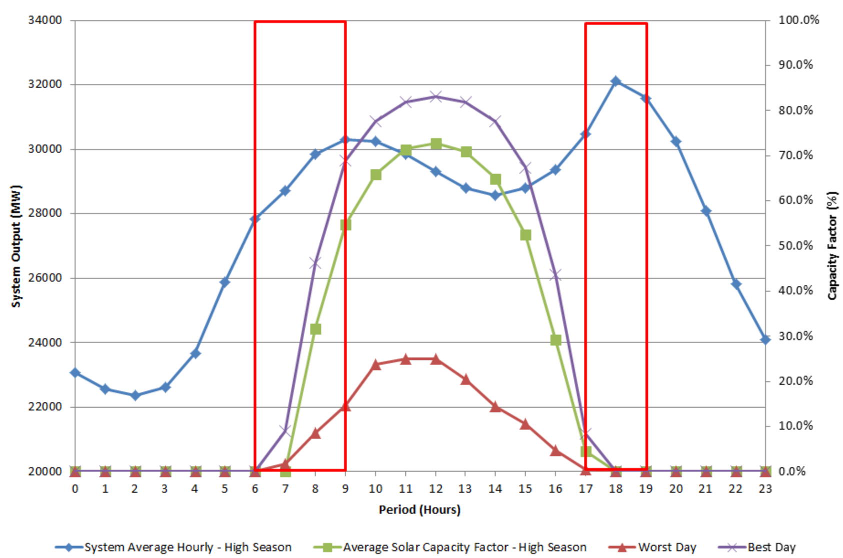

Figure 3: High season solar PV hourly average capacity factors and the high season national demand curve including best and worst days

From Figure 3 it can be seen that:

- Solar PV production occurs primarily during the middle of the day as demand is reducing
- There is a significant amount of variation between the best and worst days performance. The average capacity factor on the best and worst day is 26.9% and 6.23% respectively.
- Average solar PV capacity factor during the morning peak period in the high season is 12%. Average hourly capacity factors during this period are below 10% for 66% of the time.
- Solar PV production is virtually non-existent during the evening peak of the winter months when electricity demand is at its highest – average capacity factor during this period is 2%. A detailed analysis indicates that during the high season evening peak periods, solar PV average hourly capacity factors are below 10% for 94% of the time.

Plotting the same data for the low demand season presents a slightly different picture, as shown in Figure 4.

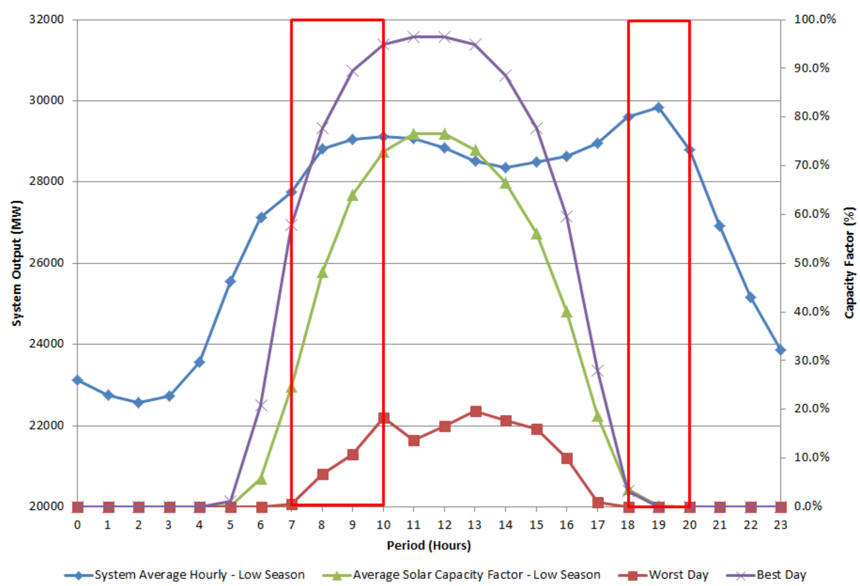

Figure 4 Low season solar PV hourly average capacity factors and the national demand curve including best and worst days

For the low season it can be observed that the increasing capacity factors during the morning hours, coincides better with the morning peak. Average solar PV capacity factors during the morning peak period of the low season are higher than in the high season at 46% indicating that solar PV contributes significantly more to the load during the low season morning peak periods. However, this is not the case for solar PV production during the low season evening peak which is 1.85%, almost identical to that found during the high season. The average capacity factor on the best and worst day is 37% and 5.5% respectively.

4.2 Wind

Similarly for wind, Figure 5 plots hourly capacity factor against the national system demand.

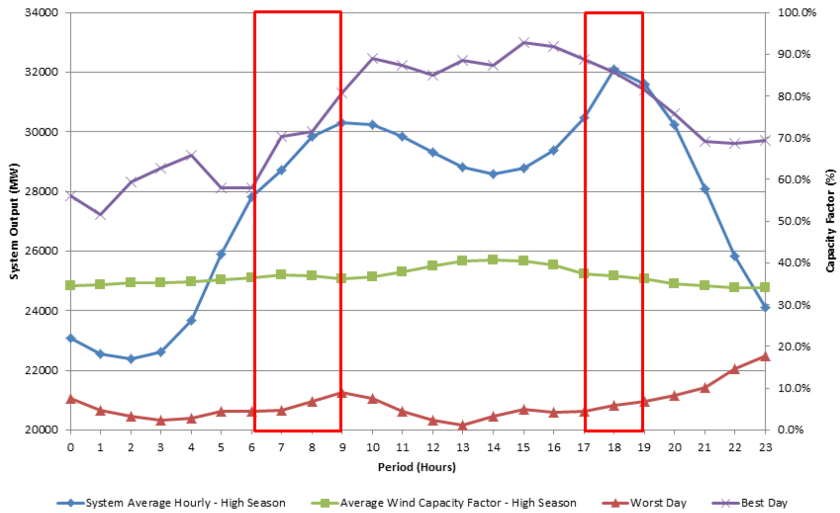

Figure 5: High season wind hourly average capacity factors and the national demand curve including best and worst days

Figure 5 shows that during the high demand season, average wind production is relatively constant throughout the day. Average morning peak period capacity factor is 37.2% and this is similar to the average evening peak period of 37.6%. On the worst day, wind output average capacity factor is 6.1% (with the lowest hourly capacity factor of 1.1%). On the best day, the highest daily average capacity factor is 74.8% (with the highest hourly capacity factor of 93%).

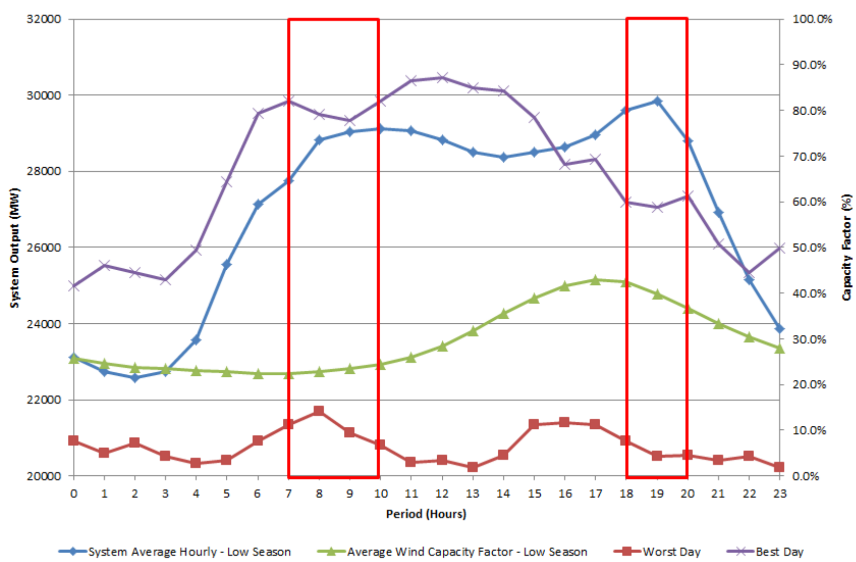

Figure 6: Low season wind hourly average capacity factors and the national demand curve including best and worst days

During the low season, wind output has an average morning peak capacity factor of 23.3% and an average evening peak capacity factor of 40.8%. On the worst day, the average capacity factor was 6.35% (with the lowest hourly capacity factor of 1.9%). On the best day, the highest daily average capacity factor was 65.6% (with the highest hourly capacity factor of 87%).

Putting some numbers on the peak and off-peak performance of wind and solar indicates both the difference in contributions during the high and low seasons as well as the difference in production between solar and wind. Table 5 indicates the seasonal capacity factors for solar PV and wind generation.

Table 5: Summary of High and Low Season Peak and Off-Peak Average Capacity Factors for Wind and Solar PV

	Wind		***Solar PV***	
	Peak	Off-Peak	Peak	Off-Peak
Low Season	30.3%	29.7%	28.3%	25.8%
High Season	37.4%	36.6%	8.2%	24.2%
All Year	32.3%	31.7%	22.6%	25.4%

5. Conclusions

South African solar PV and wind plant production data was analysed for the period 1 January 2014 to 31 August 2016. Peak and off-peak capacity factor was defined to provide production performance data that is related to system demand. Capacity factors were calculated for the high and low demand seasons as defined by Eskom. The average capacity factors calculated for wind and solar PV in South Africa to date is 31.8% and 24.9% respectively. These results are slightly lower than the input data used in the 2016 draft IRP, however the data set used is over a short period and a longer timeline of input data may be required to make any definitive conclusions about the relative performance of wind and solar PV in South Africa.

Relative to system demand, wind has significantly better performance during peak periods in comparison to solar PV. Solar PV contributes negligible amounts to the South African grid during the evening peak with average capacity factor during the evening peak being 1.94%.

The highest combined capacity factor for wind and solar PV from the dataset was 89.3% and occurred during the 11th hour of January 2015. The lowest combined capacity factor for wind and solar PV was 0% during the 20th hour of 6 June 2014 and during the 5th hour of 8 April 2014. The performance of wind and solar under worst case conditions indicates that there is significant variation in generation output and that any power system planning that includes increased amounts of solar PV and wind needs to account for high levels of variability as well as adequate backup for near-zero production from both solar PV and wind.

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