PERFORMANCE ANALYSIS OF CSIR'S SOLAR PV PLANTS

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Abstract

The Council for Scientific and Industrial Research (CSIR) in Pretoria is rapidly reducing reliance on energy supply from Tshwane Municipality with the implementation of renewable energy projects as part of its drive to assess the potential of renewable energy in the South African energy industry. South Africa faces a two-fold energy challenge where it struggles to meet its electricity demand, while being one of the largest emitters of greenhouse gases in Africa. One of the CSIR's Energy Centre objectives is to provide some expert intervention in the South African energy sector, with focus placed on expanding the energy system in order to meet demand while becoming less carbon intensive. This paper analyses the performance of CSIR's first three photovoltaic projects. The paper focuses on energy yield, performance ratio and the levelised cost of energy (LCOE).

Keywords: Solar PV, Performance Ratio, LCOE, energy autonomous, energy yield.

1. Introduction

In recent years, energy production using solar PV has received a lot of attention due to its attractive levelised costs of energy and its contribution to the reduction of carbon emissions. The falling prices of power generated by solar PV has been driven by PV technology advances, mass manufacturing (economies of scale), and this was stimulated by substantial subsidies from first mover renewables regions such as the US, Europe, Japan etc. In the African continent, South Africa has been leading in the adoption of solar PV technology, with a significant rollout of PV plants through the Department of Energy's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). The department introduced a competitive bidding process, which has resulted in very attractive tariffs i.e. cheaper than traditional electricity supply sources such as coal. The latest round of the Department of Energy's programme resulted in tariffs as low as 0.62 R/kWh [1]. These prices, coupled with the abundance of sunshine, makes South Africa a perfect country for massive rollout for solar PV plants. The government has also embraced renewables as part of the solution for the country's energy challenges.

The CSIR has taken the lead in exploring this enormous potential to solve numerous electricity grid related challenges and provide economic value for the South African consumers. Electricity prices in South Africa have increased significantly over the past decade, as can be seen in Figure 1. The figure compares inflation with the annual standard tariff increases approved by the National Energy Regulator of South Africa (NERSA), as well as South Africa's national utility Eskom's actual average annual tariff increase, calculated as total annual electricity sales revenue divided by total annual GWh sales.

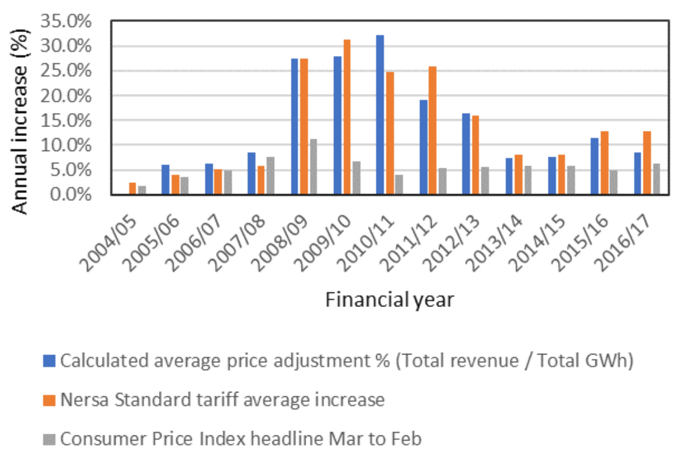

Figure 1: South African inflation vs Eskom tariff increases [2-4]

These significant price increases, combined with rolling load-shedding starting in 2008 and again for a period in 2015, resulted in an increased awareness and implementation of energy efficiency measures, and stimulated the growth of privately owned distributed generation (DG) systems. This energy transition also brings about a lot of uncertainties, such as its variability and distributed nature.

The CSIR seeks to clarify these uncertainties through a real life demonstration platform that will be a first port of call for all stakeholders in the region. The initial step in the energy transformation journey is to make the CSIR Campus energy autonomous within an 8-year period. The Campus will achieve this with energy from three primary energy sources: solar, wind and biogas from biogenic waste. The power generators will be combined with electricity and heat storage, integration of electric and hydrogen driven vehicles, power-to-liquid and power-to-gas processes, demand side management and energy efficiency measures. This programme will stand as a real-world research platform for designing and operating a primarily renewables based energy system at the lowest possible cost. [5]

This paper reviews the technical performance and cost analysis for the first three solar PV plants implemented in the CSIR's energy autonomous programme. It focuses on the determination of the performance ratio (PR), the levelised cost of energy (LCOE) and general issues around operations and maintenance.

2. The CSIR Solar PV Plants Description

2.1. General specifications

The total installed solar PV capacity at the CSIR is 1011 kW i.e. a 558 kW single axis ground mounted tracking solar PV power plant, a 203 kW ground mounted dual axis tracking solar PV power plant, and 250 kW east –west facing rooftop solar PV plant. This provides around 8 % of the total CSIR campus energy needs. The ultimate goal is to install a total of 8 MW solar PV plants that will provide approximately 55% of the electricity demand.

The single axis tracking plant is controlled by a device that allows the modules to tilt and follow the movement of the sun from east to west at module angles from +55º to -55º. The tracking system allows the plant to have a higher energy yield compared to a fixed tilt plant. The dual axis plant tracks the movement of the sun in all directions. It is approximately 20% more efficient than the single axis tracking plant. The rooftop mounted PV plant was specifically installed with east facing and west facing modules to minimize the maximum demand of the campus. The CSIR maximum demand occurs between 12:30 pm and 14:30 pm. A bulk of the remaining rooftop PV modules will be north facing, thus maximising on the energy yield. Figures 2 and 3 shows the three operation solar PV power plants installed at the Pretoria campus of the CSIR.

Figure 2: The 558 kWp single axis tracking solar PV plant

Figure 3: The rooftop and dual axis tracking PV plants at the CSIR in Pretoria

3. Methodology

3.1. Performance Ratio

The performance ratio (PR), is one of the most important variables for evaluating the efficiency of a PV plant. It is stated as a percent and describes the relationship between the actual and theoretical energy outputs of the of the PV plant. It indicates the overall effect of losses on the arrays rated output due to array temperature, incomplete utilization of the irradiation, and system component inefficiencies or failures. The equations below are utilized to calculate PR. [6] [5]

$$PR = Y_f / Y_r \qquad [6]$$

Where,

Y_f is final yield
Y_r is reference yield

The final PV system yield Y_f is the net energy output E divided by the nameplate dc power P_0 of the installed PV array. It represents the number of hours that the PV array would need to operate at its rated power to provide the same energy. The units are hours or kWh/kW. The Y_f normalizes the energy produced with respect to the system size. Consequently, it is a convenient way to compare energy produced by PV systems of differing size.

$$Y_f = E\ (kWh) / P_0\ (kW) \qquad [6]$$

The reference yield Y_r is the total in-plane irradiance (H) divided by the PV's reference irradiance (G). It represents an equivalent number of hours at the reference irradiance. If G equals 1 kW/m^2, then Y_r is the number of peak sunny hours or the solar radiation in units of kWh/m^2. Y_r is the function of the location, orientation of the array, and month to month and year to year weather variability.

$$Y_r = H\ (kWh/m^2) / G\ (kWh/m^2) \qquad [6]$$

At the CSIR, the reference yield is calculated using the global Horizontal Index (GHI) instead of the total in-plane irradiance. This is illustrated in the figure below:

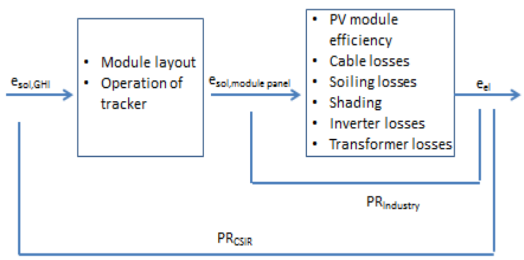

Figure 4. CSIR Justification behind using GHI for PR calculations [7]

$PR_{industry}$ takes the solar radiation in-plane as a reference. Other design related losses such as improper module layout, tracker operational issues are excluded.

The PR_{CSIR} takes all losses into consideration. EPC contractors are forced to take responsibility for all design issues and optimize for better performance.

3.2 Levelised Cost of Energy (LCOE)

The cost of supplying power to the CSIR using the solar PV plants is determined using the levelised cost of electricity approach. The levelised cost of electricity is given by:

$$LCOE = (\text{lifetime costs/energy produced over lifetime}) \qquad [8]$$

A CSIR-developed Excel based mathematical model is utilized to calculate the LCOE. The model translates input parameters (see table1 below), installed capacity, EPC price, O&M service contract price and guaranteed performance ratios.

Inputs to be provided by bidder

Design system installed DC capacity		kWp
Tendered price for EPC part		R
Tendered price for O&M in year 1		R/yr
Guaranteed Performance Ratio (PR) during O&M period		

Inputs to be provided by procurer

Lifetime	25	yrs
Duration of O&M contract	3	yrs
Penalty factor for PR underperformance	1,5	
Efficiency loss after O&M period	0,4%	/ yr
OPEX after end of tendered O&M contract	150	R / kWp / yr
Replacements in year 11 as percentage of initial CAPEX	5%	
Inflation	6%	
WACC = discount rate (nominal)	10,0%	
Average GHI at site (historically)	2 050	kWh / m2 / yr
Specific energy yield during O&M period	1 538	kWh / kWp / yr

Figure 5. LCOE calculation input parameters used by the CSIR [7]

Once the LCOE has been determined, it is compared to other LCOE's from other sources, in particular the current source of electricity supply for the CSIR. The campus is supplied by a local municipality and a time of use tariff structure is utilized. The tariff also incorporates a maximum demand charge. The average tariff from the municipality in 2016 was calculated to be R1.02/kWh. Table 1 below shows the municipality tariff structure. The maximum demand charge was R1.04/kVA.

City of Tshwane's Energy Charge in R/kWh

Tariff week in high-demand season (July & August 2015, June 2016)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1 Sunday	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
2 Monday	0.58	0.58	0.58	0.58	0.58	0.58	3.11	3.11	3.11	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	3.11	3.11	1.07	1.07	1.07	0.58	0.58
3 Tuesday	0.58	0.58	0.58	0.58	0.58	0.58	3.11	3.11	3.11	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	3.11	3.11	1.07	1.07	1.07	0.58	0.58
4 Wednesday	0.58	0.58	0.58	0.58	0.58	0.58	3.11	3.11	3.11	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	3.11	3.11	1.07	1.07	1.07	0.58	0.58
5 Thursday	0.58	0.58	0.58	0.58	0.58	0.58	3.11	3.11	3.11	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	3.11	3.11	1.07	1.07	1.07	0.58	0.58
6 Friday	0.58	0.58	0.58	0.58	0.58	0.58	3.11	3.11	3.11	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	3.11	3.11	1.07	1.07	1.07	0.58	0.58
7 Saturday	0.58	0.58	0.58	0.58	0.58	0.58	0.58	1.07	1.07	1.07	1.07	1.07	0.58	0.58	0.58	0.58	0.58	0.58	1.07	1.07	0.58	0.58	0.58	0.58

City of Tshwane's Energy Charge in R/kWh

Tariff week in low-demand season (September 2015 --> May 2016)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
12 Sunday	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
13 Monday	0.50	0.50	0.50	0.50	0.50	0.50	0.70	1.15	1.15	1.15	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	1.15	1.15	0.70	0.70	0.50	0.50
14 Tuesday	0.50	0.50	0.50	0.50	0.50	0.50	0.70	1.15	1.15	1.15	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	1.15	1.15	0.70	0.70	0.50	0.50
15 Wednesday	0.50	0.50	0.50	0.50	0.50	0.50	0.70	1.15	1.15	1.15	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	1.15	1.15	0.70	0.70	0.50	0.50
16 Thursday	0.50	0.50	0.50	0.50	0.50	0.50	0.70	1.15	1.15	1.15	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	1.15	1.15	0.70	0.70	0.50	0.50
17 Friday	0.50	0.50	0.50	0.50	0.50	0.50	0.70	1.15	1.15	1.15	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	1.15	1.15	0.70	0.70	0.50	0.50
18 Saturday	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.70	0.70	0.70	0.70	0.70	0.50	0.50	0.50	0.50	0.50	0.50	0.70	0.70	0.50	0.50	0.50	0.50

Table 1. High and Low Season City of Tshwane tariffs [9]

3.3. Operations and Maintenance

The EPC contractor performs operations and maintenance of the plant for the first three years through a signed contract. This is handed over to the plant asset owner when the contract expires. This allows the asset owner to monitor the guaranteed performance ratio and an opportunity for O&M skills transfer.

4. Performance analysis

4.1. Performance Ratio

The calculation of the plant's performance ratio is done using the methods described in section 3. The figures below shows the performance results of the three PV power plants since commissioning. In 2016, the single axis tracking power plant achieved an average PR of 94.3%, with the dual axis tracking plant having a PR of 123% and building 17 has an average PR of 74%.

The average industry performance ratio for the year 2016 for a typical plant similar to the single axis tracker plant was calculated to be 80.5%, significantly lower than the stringent CSIR performance ratio. A comparison of the other two plants, yielded similar results.

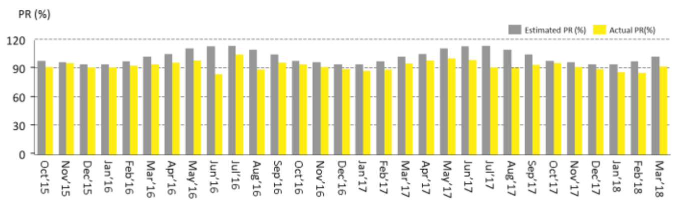

Figure 6: PR for the single axis tracking PV plant

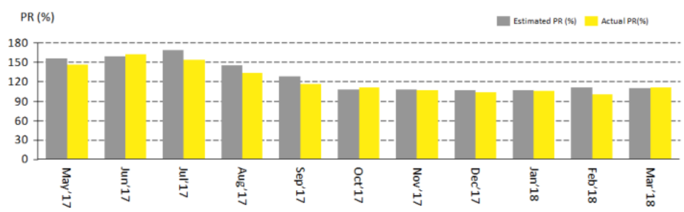

Figure 7: PR for the dual axis tracking PV plant

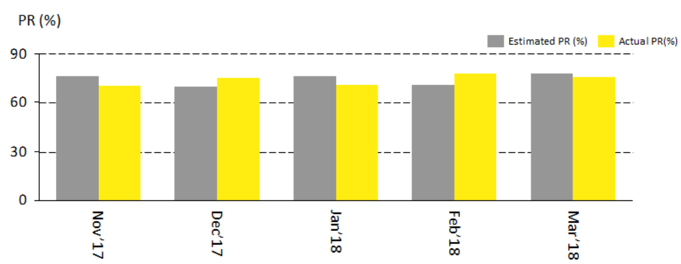

Figure 8: PR for the rooftop PV plant

4.2. Achieved levelised cost of energy

The achieved LCOE for the three operational plants is shown in table 2 below.

Plant	LCOE (R/kWh)
Single Axis Tracker	0.83
Dual Axis Tracker	1.00
Rooftop	0.87

Table 2. Achieved LCOE

The achieved LCOE is lower than the municipality average tariff e.g the single axis tracker has an LCOE that is 19% lower than that of the municipality. This has resulted in massive savings in electricity costs for the CSIR (see table 3 below). The total savings from commissioning to the end of March 2018 was approximately R4m. The average payback period for the three plants was calculated to be 12 years, with a 25 year plant lifecycle.

Period	Month	Savings (ZAR)
1	October 15- March 16	578 343
2	April 16- March 17	1 295 844
3	April 17- March 18	2 079 632

Table 3. CSIR savings from the three PV plants

The LCOE is also comparable to the current solar PV plant prices experienced by the South African market. This project demonstrates that solar PV prices are significantly going down. This is an important finding for the South African energy sector, especially for those stakeholders that still have doubts about the decreasing costs of solar PV.

4.3. Operations and maintenance

Maintenance of the three PV plants is done by the EPC contractor during the first three years of operation. Typical maintenance involves regular plant inspection, grass cutting, electrical tests, infrared scans etc.

A few incidents have been experienced, and these have provided valuable learning experience. These are:

- Communication system failure for the dual axis tracker
- Malfunction of the single axis tracking mechanism resulting in a few module damages
- Inverter failure on the rooftop PV system

These incidents were rectified timeously and minimum down time experienced.

4.4. Further analysis

The achieved performance ratio is also significantly higher than that of the industry. This is also a demonstration that the plant's technical performance is of acceptable standard. The project is a first step towards making the CSIR campus energy autonomous and lays a perfect foundation for a real world research platform for designing and operating a primarily renewables based energy system at the lowest possible cost. This is demonstrated by the high performance ratio and the low LCOE achieved. The PR achieved by the CSIR might be lower that the contracted PR per plant, but if the comparison is made against that of industry, the CSIR plants' performance is a lot better. Table 3 shows the LCOE's for the three plants and they all have values below the 2016 average tariff (R1.02/kWh) from the municipality supply. These results indicate that businesses similar to the CSIR (in terms of energy demand) could explore this energy supply approach and make huge savings while reducing carbon emissions.

This platform can be used to demonstrate in a real world setting, how a future energy system that is based on fluctuating and dispatchable renewables can be designed and operated in the most cost efficient manner.

5. Conclusion

The CSIR has successfully implemented the first phase of its energy autonomous campus using solar PV power plants. The company's goal of achieving energy savings by reducing the company energy bill has been achieved. The LCOE of R0.83/kWh, R0.87/kWh and R1/kWh for the single axis tracking plant, rooftop plant and the dual axis tracking plant respectively demonstrates that these prices are aligned with the declining global prices. The CSIR programme also demonstrates that the PRs are in line with those expected for solar PV plants. This finding is important for organisations similar to the CSIR as they can replicate this project to provide their electricity needs at least cost while positively contributing to carbon emissions by using renewable power plants (solar PV in this case.)

This finding also demonstrates that solar PV plants can compete with alternative new-built plants options or future scenarios for the energy structure in South Africa and the region. Solar PV plants change the entire paradigm shift on which energy systems were traditionally planned, designed, built and operated. Solar PV can be at the core of the energy system expansion, especially in the African continent.

References

[1] Department of Energy's publications on results of first four bid windows, http://www.energy.gov.za/IPP/List-ofIPP-Preferred-Bidders- Window-three-04Nov2013.pdf

[2] Eskom. 2017. Integrated Annual Report, 2017. [Online], Available: http://www.eskom.co.za/IR2017/Documents/Eskom_integrated_report_2017.pdf.

[3] Eskom. 2007. Annual Report 2007. [Online], Available: http://financialresults.co.za/2007/eskomar2007_fin/downloads/eskom_ar2007.pdf.

[4] Statistics South Africa. 2018. Consumer Price Index History. [Online], Available: www.statssa.gov.za.

[5] SN Simelane, M Basappa Ayanna, CSIR's Single Axis Tracking Solar PV Plant Performance Analysis, IEEE PES – IAS Power Africa Conference Proceedings, Accra, Ghana, 27-30 June 2017.

[6] IEC Guide for Photovoltaics System Performance Monitoring – Guidelines for measurement, data exchange and analysis, IEC Std. 61724-04, 1998.

[7] T Bischof-Niemz, KT Roro, A Guideline for Public Entities on Cost-Efficient Procurement of PV Assets, 2015, [online], Available: www.csir.co.za

[8]https://en.wikipedia.org/wiki/Cost_of_electricity_by_source J. Jones. (1991, May 10). Networks. (2nd ed.) [Online]. Available: http://www.atm.com

[9]http://www.tshwane.gov.za/sites/Departments/Electricity/Pages/Electri city.aspx