COMPARING LONG-TERM ACTUAL VERSUS SIMULATED PV SYSTEM PERFORMANCE: A REVIEW AND CASE STUDY

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Abstract

With the decrease in photovoltaic (PV) installation cost, increasing electrical tariffs, increasing volatility of electricity availability in South Africa and a general increase in awareness of the environmental benefits of using renewable energy, the number of people installing PV on their rooftops is increasing. The owners of these systems often have unrealistic expectations of their system's performance, which are typically defined by themselves, manufacturers or installation companies. This study investigates how a rooftop PV system performs compared to the initial predictions made by the installers. This is done using a case study of a 22.5 kW$_p$ photovoltaic (PV) system installed on a rooftop at Stellenbosch University, which has been operating over the last 4 years. This study aims at investigating the relationship between predicted (by installers) and actual PV performance and also attempts to conduct a more accurate performance prediction of the system using an improved techno-economic model (using PVsyst).

The study found the error between the predicted performance and the actual output of the system to be 5.4% on average for the energy production and 6.8% for the yearly financial gain, over the 4 years. This was then decreased to 4% for the energy production and the yearly financial gain through a more detailed techno-economic model, using more accurate technical and financial inputs.

The study also found that the system is not being maintained and cleaned as it was intended to be, which may be a factor in the misalignment between the predicted and actual output of the system.

Keywords: *Photovoltaic; simulation; performance investigation; PV soiling; PV customers; SSEG; PVsyst.*

1. Introduction

Renewable energy is one of the active topics in the electricity industry with an aim to create a greener and more sustainable environment. Solar PV, particularly in the form of Small-Scale Embedded Generation (SSEG) is a renewable energy technology that helps reduce the carbon footprint of residential, commercial and industrial activities, while also providing a means of generating financial savings for the PV system owner. With PV cell efficiencies improving and PV module cost continuing to decrease, solar PV has become highly competitive with conventional energy sources.

Within this macro context, residential, commercial and industrial owners considering investment in PV SSEG systems typically approach solar PV installers with more specific questions, such as; "How much electrical energy (kWh) will I produce with this system during the day and year?"; "How well will it perform over time?"; "How much financial savings will the system provide?" [1]. The risk exists that the answers to these questions are overestimated and unrealistic. This is either done by unscrupulous installers to try and promote installations or by incorrect system feasibility studies that do not adequately consider the technical and financial parameters involved. The misalignment between performance expectation and reality can cause solar PV owners to communicate doubt publicly and privately about the technology, discouraging the uptake of future systems.

These misalignments are investigated in this study by using a 22.5 kW$_p$ rooftop PV system at Stellenbosch University, as a case study. While the results presented in this paper is location and context specific,) the value of the study lies in providing a generalised perspective on actual versus predicted long-term performance of a typical SSEG installation.

The study is divided into two sections. The first section discusses literature regarding the reason behind the misalignment between predicted and actual PV system performance as well as the possible PV losses that reduce the expected PV performance. The second section uses the 22.5kWp PV system that is owned by Stellenbosch University as a case study which aims at highlighting the differences between the predicted and actual performance of installed PV system over its four year operation.

2. Literature Review

2.1 PV performance misconceptions

A common issue related to the uptake of SSEG PV systems is the misalignment between the expected or predicted performance and the actual output of the system. There are various causes for this misalignment such as over-estimation by installers, incorrect modelling of the system, unpredictable resource and environmental effects and inadequate maintenance of the system.

Informal and non-reputable installers may overestimate the performance of a system to increase their competitiveness against larger, more reputable installers. Often this might also be coupled with the installation of low-quality modules and inverters to save costs that subsequently degrade at a much faster rate; and ineffective installations (such as installing modules that are shaded by trees most of the day). Such installations are more likely where the customer lacks PV-specific knowledge, and in countries where the PV industry is not yet adequately regulated.

Incorrect modelling of the installation in the design phase may lead to over- and under estimation of the system's performance. This may be due to installers not having access to effective modelling software or the skills to correctly model the system. There is an abundance of simplified prediction tools online that provide inaccurate outputs.

Resource and environmental factors may play the biggest role in the misalignment between prediction and reality. In a study by [2] on the gap between the predicted and measured output of PV systems, it was found that the most influential effects include the use of weather data, future climate change, adverse weather conditions and various other environmental factors. Accurate weather data, such as that from a ground station, are not easily available. PV installations have a long lifecycle (20 – 25 year) and thus it is impossible to accurately predict the performance during this lifecycle given constantly changing climate. Many other environmental effects can also play a role such as a nearby construction of a building resulting in increased soiling losses on the panels, hail storms, heat damage, etc. [3]

The operation and maintenance of installed systems also plays an important role in maintaining the performance of the modules. Regular cleaning and the monitoring of output parameters are important for maintaining optimal performance and fault finding. As seen in the case study in this paper, this maintenance is often not carried out as intended.

2.2 Photovoltaic system losses

A photovoltaic installation is not a lossless system; just like any other electrical system losses from internal and external factors are prevalent. The external factors can include shading. Internal factors are sometimes non-avoidable and these losses can be due to environmental and installation factors. The efficiency of the system can be reduced by the following factors: reflection losses, unabsorbed or excessive radiation, shading effects and losses due to series and parallel resistance [4].

2.2.1. Shading losses

Near shading refers to objects in close proximity with the modules that block light coming from the sun (cast shadows). This is often due to other buildings, trees, air-conditioning units, etc. Shading can have a drastic effect on the output of a PV string as typically cells connected in series will all perform according to that of the worst performing cell (acting as a blocking diode). This is mitigated by avoiding shading between specific times of the day and through the use of bypass diodes by manufacturers [5]. Best practise dictates that the system should be designed to receive no shading between 10 am and 3 pm on winter solstice (21 June for the southern hemisphere) [5]. Soiling is also categorised as near shading as dirt build-up on the panels interferes with light falling on the cells. Regular cleaning through a maintenance plan as well as angling the panels at least 15°, so rainwater may clean the panels, helps to mitigate this type of loss.

Far shading consists of the shape of the horizon. If the system is in a very mountainous area, the sun will not pass over the horizon until later in the day and will set much earlier in the evenings. This loss is usually very small unless the system is constructed very close to a hill or mountain.

2.2.2. PV degradation

PV module degradation can be defined as the decline of output power over time. Degradation is influenced by a number of factors, mainly UV exposure and weather cycles [6]. To acknowledge the fact that PV modules degrade with time, PV module manufactures provide a power warranty of 25 years and a product warranty for the 1st 10 years in use for performance failure or drastic power reduction.

3. Case Study: Stellenbosch PV system

Stellenbosch University installed a PV system with a nominal power of 22.5 kW_p, on the rooftop of the Centre for Renewable and Sustainable Energy Studies (CRSES) in 2015. This system is connected to the Stellenbosch municipal network. The data of energy production from this system is kept and monitored for financial billing purposes.

3.1. Description of the PV system

The system (Figure 1) consists of a single inverter rated at 20 kW (Socomec SUNSY B20) with two maximum power point tracker

(MPPT) inputs and polycrystalline solar modules that are rated at 250 W_p each under Standard Testing Conditions (STC). The system consists of 15 modules connected in series and includes 6 strings, thus having a total of 90 PV modules on the roof area, occupying 147m^2. The roof has an azimuth angle of 24° north-east (NE) and a tilt angle of 15°.

The system has not been under a regular cleaning schedule. The University's Facilities Management confirmed that the system was cleaned at some point during the first year or two, but the exact date and record of this cleaning event could not be located. It is presumed that the system has not been cleaned since.

Figure 1: 22.5 kWp PV system at Stellenbosch University

3.2. Methodology

This study aims to simulate the performance of the system over its operational lifetime using locally measured irradiation data, and to then compare these predicted results to the actual measured data recorded as well as to the predicted data provided by the installation company at the beginning of the project. The differences (or lack thereof) will be used to establish whether the system is performing as expected. If the system is underperforming, then the possible reasons will be investigated. In addition to this the financial performance of the installation will be predicted and compared to the financial feasibility study provided by the installers, and to the actual system savings to date.

This study simulates the system using PVsyst (version 6.8.2) software, specifically designed to predict the technical performance of PV systems. The predicted production and actual performance energy data were then plotted on the same graph to compare the energy curves, with differences and similarities discussed. This study is classified as a long-term system analysis as the study investigates the performance of the PV installation from August 2015 to July 2019. The comparison of the PV system was analysed based on three variables, namely:

- PVsyst expected energy - defined as the electrical energy estimated by simulation software;
- Installer expected energy - defined as the electrical energy that was estimated in the initial feasibility study by the PV system installer;
- Measured (actual) energy - defined as the electrical energy that is actually measured from the PV system.

3.3 Meteorological (weather) data

A SAURAN weather station located at Stellenbosch University was used to collect weather data [7]. The ground station is located on top of a nearby building approximately 145m away from the PV installation. The measured parameters used from the station include global horizontal irradiance (W/m^2), diffuse horizontal irradiance (W/m^2) and air temperature (°C).

3.3.1 Accuracy of the meteorological data

The SAURAN station is a ground station, meaning it measures the actual irradiance and temperatures at a specific point, compared to satellite derived data, which averages data over large areas through satellite imagery. The accuracy of the meteorological data used has a major influence on the final results of the simulation, therefore it is important that the data is quality checked. Data quality from the measurement station depends on the instrument model used, calibration records and cleaning records. In this study the SAURAN weather data was used as the primary data source and satellite data (SoDa, HelioClim-3) was used as a secondary source. Quality checking was performed on the primary data and any missing or incorrect data was replaced with the secondary data.

3.3.2 Data quality checking findings

The following findings were observed while doing data quality checking and data inspections: the global horizontal irradiance (GHI) from the primary source was slightly higher compared to the secondary source, however on analysing and comparing the two sets of data through visual inspection of the graphs the sources of data followed a similar trend and no significant difference was noted between the two data sources. A significant difference between the two on a specific data point highlights a possible error. Missing timestamps of temperature and irradiance between the ground station and the satellite derived data found were replaced with satellite data.

3.4 Simulation losses and considerations

3.4.1 Unavailability losses

The number of days which the Stellenbosch grid (LV network) was found to be unavailable were 10, 36, 33 and 0 days in 2015, 2016, 2017 and 2018 respectively. These number of days were considered when simulating the PV system.

3.4.2 Soiling losses

The accumulation of dirt and bird droppings causes soiling losses in the PV system. PVsyst allows the user to define the soiling factor, however, due to the lack of a known cleaning event, a soiling loss could not be quantified for use in the simulation. The loss was therefore defined as the default soiling factor (3%). Currently (2019) there is building construction in very close proximity to the PV system roof; this may be affecting the PV production as there is a large amount of dust created by the construction.

3.4.3 Shading losses

Figure 2 shows a model of the PV system and the near building that causes a near shading loss of 0.8% during the day. The far shading of the surrounding mountains contributes a further 0.8% to the shading losses.

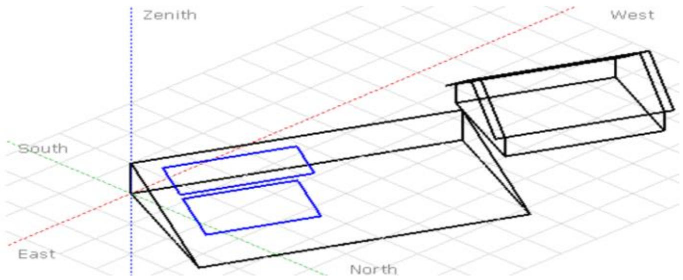

Figure 2: 3D rooftop construction for near shading modelling in PVsyst

3.5 Simulation results and discussion

3.5.1 Energy performance

Table 1 compares the predictions given by the installer at the beginning of the project, the energy predicted by PVsyst model and the measured data from the 22.5 kW_p system, starting from August 2015 to July 2019. From the simulation results the annual energy error between the expected and measured energy was calculated by the following equation:

$$\Delta\, Energy \;=\; \frac{E_{expected} - E_{measured}}{E_{expected}} * 100\%$$

Table 1: System energy output comparison of the 22.5 kW_p PV system (2015 – 2019)

Year	Installer energy prediction (MWh)	PVsyst expected energy (MWh)	PV system measured energy (MWh)	Installer predict-ion error (%)	PVsyst predict-ion error (%)
2015 (Aug –Dec)	13.9	15.547	14.621	5.19	5.96
2016	33.054	33.003	32.371	2.07	1.92
2017	32.724	35.52	34.865	6.54	1.84
2018	32.397	37.029	35.862	10.70	3.15
2019 (Jan – July)	18.709	19.760	18.269	2.35	7.55

PVsyst indicates that the uncertainty of predicted annual energy is 1 – 2%, however, accurate evaluations depend on the input weather data and model accuracy [8]. The PVsyst error decreases initially and falls between the acceptable uncertainty for 2016 and 2017. However, it seems to diverge in 2018 and 2019. This could be due to the decrease in cleaning and maintenance or increase degradation of the panels. The energy predicted by the installer ranges from 2 – 10 % with no particular pattern. The meteorological (weather) data that was used by the installer was from NASA's Atmospheric Science Data Center (ASDC). This is satellite derived data and therefore less accurate than the ground data used by PVsyst.

Figure 3 shows the energy performance comparison between the PVsyst prediction and the measured output of the system for 2018. The installer did not provide monthly energy output predictions over a typical year, only providing the estimate yearly energy production.

Figure 4 and Figure 5 show the hourly system energy production for a week during the winter and summer solstices. These figures compare the PVsyst prediction to the measured output of the system.

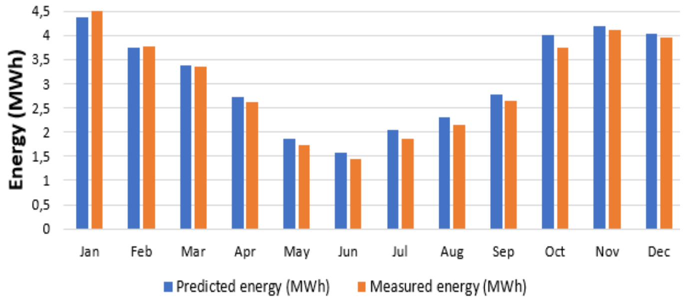

Figure 3: Monthly energy production comparison between the PVsyst prediction and the measured output of the system in 2018

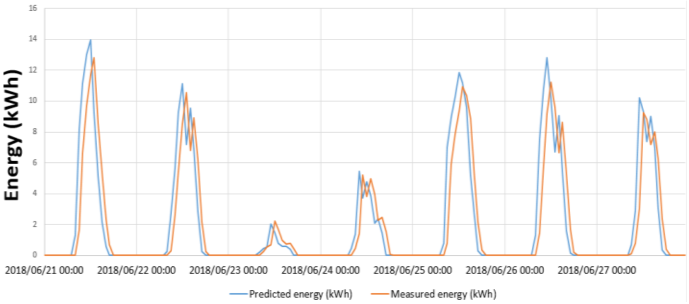

Figure 4: 2018 winter solstice week: 21 Jun to 27 Jun 2018

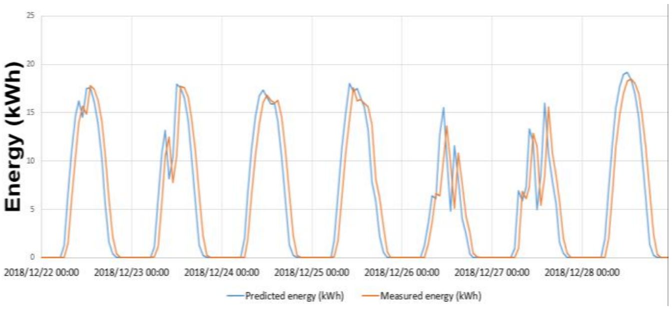

Figure 5: 2018 summer solstice week: 22 Dec to 28 Dec 2018

The data trends towards the predicted data being slightly higher than the actual performance. This is most likely due to the model not simulating all the loss factors that are experienced in reality such as cable losses and various others. Considering this, the predicted data follows the same trend as the measured data, with the error between the two being minimal. For January and December 2016 the energy production was lower compared to other years. This was due to unavailability of the PV system during those months.

3.6. Financial Analysis

Table 2 below shows the difference in avoided electricity cost between what was originally estimated by the installers, the simulation done in PVsyst and the actual results for the first four years of the system.

Table 2: Financial comparison of the 22.5 kW$_p$ PV system (2015 – 2019)

Year	Predicted total avoided electricity cost by installer	Predicted total avoided electricity cost after PVsyst simulation	Actual total avoided electricity cost	Installer predict-ion error (%)	PVsyst predict-ion error (%)
2015 (Aug – Dec)	R18 642	R21 223	R19 958	7.06	5.96
2016	R48 102	R45 052	R44 186	8.14	1.92
2017	R50 863	R48 488	R47 590	6.43	1.85
2018	R54 698	R50 993	R49 386	9.71	3.15
2019 (Jan – July)	R34 313	R36 013	R33 350	2.81	7.39

Overall the error in avoided electricity cost predictions by the installers was significantly higher than that of PVsyst, except for the incomplete year of 2019. However, bigger differences are seen in other financial parameters, such as Levelized Cost Of Energy (LCOE), which was indicated by the installer as R0.633/kWh but is determined as approximately R2.4/kWh by the financial analysis done using the PVsyst simulation, which is closer to what is seen in literature [9]. The installer also calculated a payback period of 7.95 years, whereas the payback period is more likely to be approximately 13 years. This difference is most likely due to inaccurate financial modelling by the installer with respect to the loan required and the interest due. Stellenbosch University's Facilities Management funds the installation of solar PV systems through a loan application to the university's Finances Department. The repayment of this loan is achieved through the PV system's measured electricity generation (AC side) multiplied by the Stellenbosch University blended electricity tariff. The SU blended electricity tariff is calculated as the total cost of all SU electricity bills, divided by the total electricity (kWh) consumption of all SU departments and buildings. This knowledge would have been available to the installer at the time of their analysis. Another error by the installers is not including the replacement of the inverter after 10 years, which is prudent in a 20-year financial analysis of a PV system.

4. Conclusion

This paper investigated the predicted versus actual performance of SSEG rooftop PV installations, using as case study a 22.5 kW_p PV system operating at Stellenbosch University over four years. The average difference in energy output between that predicted by the installer and the actual output of the system was found to be 5.4% over the four-year period. This prediction was improved by simulating the system using much more accurate local ground station weather data. The improved simulation saw an average error of 4% over the four years, with larger errors in the later years. This energy error may be due to the system not having been cleaned in the way it was intended to be during the planning phase, together with a nearby construction site creating dust (soiling on the panels) in the last year of analysis. This difference could also be from an increased degradation of the panels. Overall it is seen that the hourly predicted output of the system follows the trend of the measured output, with the prediction being slightly higher, most likely due to inaccurate loss assumptions related to insufficient panel cleaning.

With respect to the financial analysis, predictions tended to overestimate the actual financial value of the system. The error in yearly financial gains by the installer was 6.8% on average, while the error by the simulation in PVsyst was 4% on average. The installer calculated a much lower LCOE for the system and a payback that was almost half of what the system will actually experience.

Predicting the performance of a PV system over its 20-year life cycle is difficult. Many assumptions have to be made regarding weather, unavailability, increasing energy tariffs, the behaviour of the grid the system is connected to and various other factors. However, as shown in this study, using more accurate input data in the modelling of both the technical and financial performance of the system increases the accuracy of the predictions. More accurate predictions help installers to manage customer expectations and it promotes trust in the technology. Uncertainty will always be a big factor in PV installations but minimising this through correct modelling practises will promote the future uptake of the technology.

A more detailed study is advised on quantifying the exact soiling loss on the PV system due to the nearby construction site. This could be done by cleaning the system and noting the difference in performance.

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