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ENERGY YIELD MODELLING OF PV SYSTEMS OPERATING IN NAMIBIAN CONDITIONS

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ABSTRACT

The greatest part of Namibia (except the coastal region) receives a large amount of solar radiation throughout the year, yet very few photovoltaic (PV) systems have been installed. The installation of PV systems is associated with high initial capital cost and, typically, an investor would seek a maximum return on investment at minimum risk. To increase the confidence level in the performance of PV systems it becomes imperative that an accurate prediction of the energy yield of systems, operating in the specific Namibian conditions, be achieved. One of the most reliable criterion for the assessment of the performance of a PV system is its annual energy production. The accurate estimation of the energy yield requires the use of a PV simulation software. A number of modelling software packages are currently available that provide a greater or lesser success in accurately predicting the energy yield of PV systems. The success in modelling the yield accurately depends on the skills, knowledge and understanding of the modeller as well as on the uncertainties of the modelling technique. In this work, PVsyst 6 package has been used for modelling an already operational roof-top grid connected PV system. The uncertainties in the modelled and measured data have been assessed and comparison of modelled and measured energy yield has been performed.

INTRODUCTION

The installation of PV systems is on the increase worldwide and this trend is set to continue. Namibia would, certainly, follow a similar trend, even more so because the greater part of the country receives a large amount of solar radiation (in excess of 2300 kWh/m^2 per year on a horizontal plane).

The installation of a PV system is associated with large initial capital costs. Energy yield of a PV system is of direct importance to system owners, investors, financiers, even to utility planners, because it directly determines revenue or savings and to researchers because it determines the performance of the PV system [1]. The prediction of energy yield of a PV system varies from one modelling software to another, as well as, from one modeller to another [2], [3].

This paper presents initial results on a grid-connected rooftop PV system installed at the headquarters of the national power utility of Namibia, Nampower. It compares the modelled and actual energy yield over a year of operation of the system. The uncertainties in the modelled results are assessed since they can strongly affect investment decisions and they play important role in long-term forecasts [4].

FACTORS AFFECTING THE ENERGY YIELD OF A PV SYSTEM

One of the most important factor affecting the energy yield of a PV system is the solar radiation available at the site. The amount of solar radiation is determined by the geographical location and by the local climate. Long-term weather data for a site, which allows estimation of the variability of the climate and the amount of solar radiation, is necessary for an energy yield forecast. Such forecasts are, typically, accomplished with the deployment of PV simulation packages that rely on the long-term climate data and system performance parameters to estimate the energy output. In addition to the solar radiation, a number of other factors, known as system de-rate factors, affect the performance and energy output of the system. Examples of such de-rate factors are: conversion efficiencies of modules and inverters, mismatch of modules, deviation of the power output of a module from the rated, thermal losses, resistive losses in DC and AC wiring, shading, soiling of the modules, degradation of the modules with age, unavailability of the plant. These de-rate factors are accounted for in the simulation software but require input from the user. Uncertainties in the solar radiation and de-rate factors lead to uncertainty in the forecasted energy production and affect the reliability of the forecast.

SYSTEM DESCRIPTION

The system, studied in this paper, was installed in late 2012. The system is grid-connected and consists of 259 poly-crystalline silicon modules, connected to 6 SMA Tripower 12000 TL inverters. The inverters are mounted in a shed to protect them from the elements and reduce dust exposure. The system consists of two sections mounted on separate roofs – the sub-system on the North roof (as in Table 1) consists of 84 modules, 42 of which are mounted at tilt of 13 degrees and 42 at tilt of 7 degrees; the subsystem on the South roof consists of 175 modules, all of which are mounted at 7 degrees tilt. All modules are orientated at 5 degrees West of North. No connector boxes have been used and the strings are connected directly to the inverters, two strings per inverter.

Due to surrounding buildings, part of the system on the North roof is subject to shading in the later afternoon from March through to September. Figure 1 shows a photo of the system taken from the North in the afternoon of 27 July.

Figure 1: Photo of the Nampower system taken from the North direction

Initial shading of the sub-system on the North roof is clearly visible on the photo. There is a ridge, separating the two roofs, but care has been taken during installation that the ridge doesn't shade the system on the South roof. The system is located in the central business district of Windhoek, which has a semi-desert climate and low pollution levels. The system owner has adopted a washing and maintenance schedule, recurring every four months. The system operation is monitored with a sensor box, connected to Sunny Portal [5]. It is acknowledged that the accuracy of inverter-integrated measurements is not very high [6]. The system has been operating reliably since commissioning, no component failure has been experienced (from personal communication [7]).

Table 1: System parameters

System location	Windhoek, Namibia Coordinates:22.5^{0}S, 17.1^0 E	Altitude: 1720 m
Total size and type	63.455 kWp	Roof-mounted grid-connected
PV generator	259 × SW 245 poly-Si, Module efficiency =14.62%	Area = 434 m^2
Sub-system, North roof	42 modules of tilt=13°, Azimuth=5° West of North; 42 modules of tilt=7°, Azimuth=5° West of North	2 strings × 21 modules 2 strings × 21 modules
Sub-system, South roof	175 modules of Tilt=7°, Azimuth=5° West of North	7 strings × 22 modules, 1 string × 21 modules
Inverters	6 x SMA Tripower 12000 TL Inverter power = 12 kWac	Main input = 8 kWac Secondary input = 4 kWac

DESCRIPTION OF MODELLING SOFTWARE

The primary modelling in this study is done with PVsyst. Another PV simulation tool (PV*SOL Expert 6 [8]) was used as a cross-check for total energy yield and shading losses.

PVsyst is a modelling software developed by a group at the University of Geneva [9]. It uses irradiance and climate data from the Meteonorm database. It calculates irradiance on a tilted plane and determines average ambient temperature. PVsyst uses the one-diode-model with current-voltage (I-V) parameters adjusted according to manufacturer and measured data to simulate the electrical behaviour of the modules. The user provides inputs on geographical location of the system, tilt and orientation of the system, system components, electrical configuration of the system and de-rate factors. PVsyst has a 3D-scene capabilities, allowing the user to build an accurate 3D model of the PV system and its surroundings, which is then used for detailed calculation of the shade-induced losses.

MODELLING ASSUMPTIONS FOR THE NAMPOWER SYSTEM

The PV modules and balance-of-system (BOS) components are as listed above. In the PVsyst model two orientations were introduced and 8 sub-arrays were defined. The Tripower inverters have two unbalanced inputs with independent MPP trackers and their power is asymmetrically split between the two inputs. The electrical part of the system has been modelled according to the actual string configuration as outlined in the system description. A sub-array is connected either to the main inverter input or to the secondary inverter input. The DC cables are of cross section 4 mm^2 and the total length of the cables is approx. 300 m. Any possible convective cooling effects by wind were disregarded as these would be orders of magnitude smaller than the heating of the modules, resulting from large amount of incident radiation and poor possibilities for heat transfer to the warm surroundings.

Studies [10], [11] suggest soiling losses of 0.2% per day in dry climates. It would, however, appear that the soiling occurring at the Nampower system is lower than that. Soiling losses, varying from 0% to 4% per month, were assumed, taking into account the amount of rainfall and the washing schedule followed by the system owner. The losses due to shading are determined through the use of a 3D shading scene constructed in the modelling software.

RESULTS AND ANALYSIS

The solar resource data, used in the modelling, is derived from the Meteonorm climate database, which provides long-term monthly averages of global horizontal insolation from satellite resources and ground based stations. Based on that, the modelling software calculates monthly average plane-of-array (POA) insolation. Monthly ambient temperature averages are also obtained from the Meteonorm database.

The shading of the system by a nearby building (as seen in Figure 1) during part of the year is responsible for a drop in the energy production. The drop in annual irradiance in the plane of array due to shading is estimated at 1.3%. The relatively low drop in irradiance due to shading can be attributed to the fact that the shading takes place well after the daily irradiance peak as well as the fact that only a fraction of the array is subject to shading; also, the irradiance drop refers to the direct beam but not to the global radiation incident on the array.

The corresponding drop in energy output for the whole system due to shading is estimated at 3.0 %. The higher drop in energy output compared to that in irradiance clearly demonstrates that energy yield loss due to shading cannot be satisfactorily determined unless detailed analysis of the electrical behaviour of the system under shading is performed. Analysis of electrical losses due to shading was carried out on a string-by-string basis by PVsyst once an accurate shading pattern was created in a 3D scene.

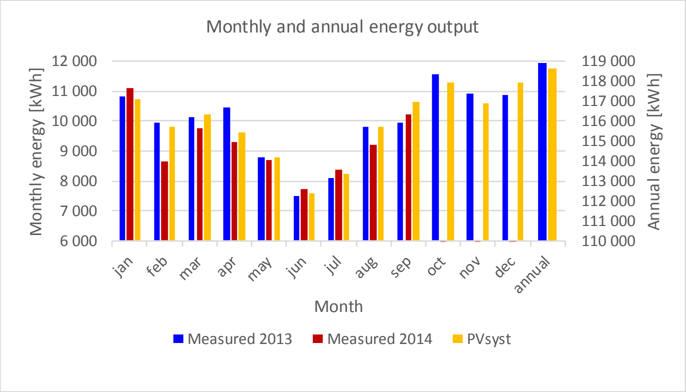

Figure 2: Comparison of measured (2013 and 2014) and modelled monthly and annual energy yield

Figure 2 shows a comparison between average monthly energy yield measured during 2013 and part of 2014 and the modelled results. The energy yield of the system demonstrates seasonal and annual variations, as can be expected. The month-by-month comparison of the measured and modelled yield highlights the fact that significant deviation of the weather from the long-term averages results in larger discrepancies between measured and estimated values. A point of attention is the discrepancy of approx. 10% between measured in April 2013 yield and the modelled value. This could be attributed to higher incident solar radiation in April 2013 compared to the one estimated by the model. The rainfall figures for April 2013 indicate fifteen times lower than the long-term average rainfall for April, which implies lower than expected cloud cover, higher insolation (direct beam insolation) and larger energy output. Likewise, the case for February 2014, when significantly higher than the long-term average rainfall has been received, shows notable decrease in energy yield. This underlines the notion that short-term yield predictions (shorter than a year) are unreliable.

Comparison between the modelled and measured 2013 data was carried out with the Normalised Mean-Bias-Error (NMBE) and the Normalised Root-Mean-Square-Error (NRMSE); the NRMSE is also referred to as Coefficient of Variation (CV) of the RMSE. The comparison of modelled and measured in 2013 energy output gives NMBE of 0.21%, which indicates slight underestimation by the model. The NRMSE is 3.7%. The smaller the CV, the closer the predicted value to the actual value.

The uncertainties considered in order to determine the uncertainty in the modelled energy value are summarised in Table 2. The uncertainties represent the standard deviations in the values and all uncertainties have been given as percentages.

Table 2: Uncertainties in the model

Uncertainty type	Uncertainty Value	Distribution
Solar radiation	5.0 %	Normal
Solar radiation on tilted plane	3.0%	Normal
Variability of solar radiation	2.5 %	Normal
Power rating of module	3.0 %	Normal
Conversion at module level	1.5 %	Normal
Simulation model PV module	2.0 %	Normal
Soiling	4.0 %	rectangular
Shading	3.0 %	rectangular
Others (inverter efficiency, module mismatch, wiring, unavailability)	5.0%	Normal
Degradation	0.35% per year	rectangular

The uncertainty in the solar radiation data obtained from the Meteonorm database is stated by Meteonorm to be 3.5%. In the authors’ opinion and experience, however, this uncertainty is no less than 5.0% and this value was used in the estimate of the model uncertainty. The amount of solar radiation incident on the tilted plane is calculated from the radiation incident on a horizontal plane via a transposition model. Taking into account that there is a correlation between the tilted plane radiation and the solar radiation data (i.e. the uncertainties in these two quantities are not independent of each other; correlation coefficient=1), inevitably results in significant increase in the uncertainty in the model. The variability of solar radiation at the system location was assumed to be 2.5% as per [12]. The uncertainties were combined according to the rule of propagation of uncertainties ($\sigma = \sqrt{\sum_{i=1}^{n} \sigma_i^{\,2}}$). The combined uncertainty of the model was determined to be 11.4% for 2013.

The degradation of the polycrystalline silicon modules is assumed to be 0.70% per year (as per manufacturer datasheet) with uncertainty of 0.35% per year with a rectangular distribution, as reviewed in [4]. The cumulative distribution function and exceedance probabilities for 2013 were then obtained. The result is presented in Figure 3.

For the Nampower system, exceedance probability P50 indicates that there is a fifty percent chance for the system’s annual energy output to exceed 118 665 kWh. Exceedance probability P90 means that there is ninety percent chance that the output of the system will exceed the value 101 312 kWh.

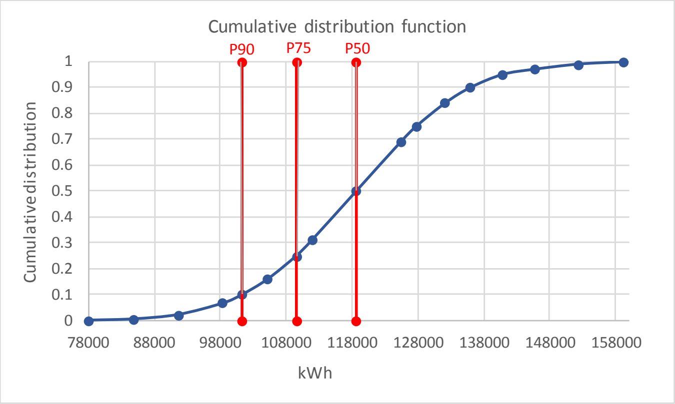

Figure 3: Cumulative distribution function for the energy output of the Nampower system in 2013

The energy yield exceedance values are subject to time variation. One of the important causes for that variation is the degradation of the modules with time. The long-term variation in exceedance values P50 and P90 due to degradation was determined using the degradation level for a particular year and the updated uncertainties for that year. The effects of module degradation on exceedance values P50 and P90 for the first ten years are presented in Figure 4.

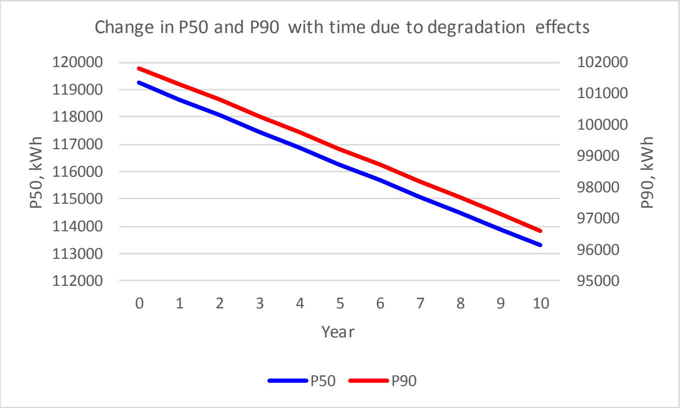

Figure 4: Long-term variation of exceedance values P50 and P90 due to degradation of the modules

The figure clearly illustrates that due to degradation alone, the P90 exceedance value will decrease from just below 102 000 kWh at installation to just below 97 000 kWh in the tenth year of operation.

The measured data was obtained from the inverters. The tolerance level of the inverter measurements given by the manufacturer is 4% for the DC measurements and 3% for the AC measurements. Taking into account that these two uncertainties are correlated and assuming normal distribution, gives an uncertainty of 4.0% for the measured energy output. Table 3 shows the total annual measured and modelled energy yield as well as the respective specific yield. The specific annual energy yield indicates the number of hours per year that the PV system must operate at nominal power to generate the amount of energy it actually produces. Clearly, the larger the specific yield, the greater the amount of energy output of the system (per given time interval). The specific yield is a quantity that allows comparison of performance between PV systems of different sizes since it is, in fact, the energy output normalised with respect to the size of the PV system (i.e. with respect to the installed peak power).

Table 3: Measured and modelled values for total and specific energy yield

Energy yield	Measured 2013	Modelled
Total annual yield [kWh]	118 917±4.0%	118 664±11.4%
Specific Yield [kWh/kWp per year]	1874±4.0%	1870±11.4%

DISCUSSION AND CONCLUSIONS

Relatively good agreement between modelled and measured energy values has been achieved with coefficient of variability (CV) of 3.7%.

This paper shows how the uncertainty in the forecasted annual energy production of the Nampower system can be determined. The total uncertainty of 11.4% means that the Nampower system has a 68% chance of generating between 105 161 kWh and 132 169 kWh of energy in 2013. The total uncertainty can be used for long-term forecast of expected production levels. For example, it is projected that there would be 68% chance for the Nampower system to produce between 100 269 kWh and 126 327 kWh of energy in the tenth year of operation. Long term predictions for performance of the system depend significantly on uncertainties in the solar radiation and de-rate factors. Decreasing these uncertainties increases the accuracy of the predictions. A reduction in modelling uncertainty can be achieved through accurate long-term measurement and assessment of the de-rate factors for a given location and type of PV technology.

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