Estimation of energy production decrease due to shading for the NamPower rooftop photovoltaic system

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Abstract. Photovoltaic (PV) energy has become one of the most important renewable energy technologies and the installation of PV systems on rooftops in industrial, commercial and residential sectors has become common. The operation of these systems is not without challenges one of them being the effect of shade on the performance of the system. Potential shading of arrays or parts thereof needs to be carefully considered when designing a system. In this study an operational 63.45 kW rooftop PV system, on the roof of the NamPower building in Windhoek, was investigated. The focus of this paper is the effect of the partial shading that some of the module strings of the system experience during part of the year due to surrounding buildings. We estimate the loss in energy production due to shading using simulation software and compare this to actual performance data. In the analysis of the effects of shading the current-voltage (I-V) curves for module strings that experience varying levels and configurations of shading are compared to unshaded strings. The results highlight the importance of considering the effects of shading on system performance and illustrate potential negative impact of unsuitable string configurations.

1. Introduction
Solar energy in general and photovoltaic (PV) energy in particular have become one of the most important renewable energy options, recording strong levels of growth in both small-scale and large-scale projects. The improved cost effectiveness of the solar sector and the ever-increasing cost of electricity provided by national grids drives an increase in rooftop and larger scale PV installations [1]. The urban environment, where PV systems are often installed on rooftops, presents serious challenges to these systems. Rooftop PV installations almost inevitably experience shading due to roof topography, adjacent buildings and poles, trees, overhanging cables, etc.

Shading has direct and indirect effects on the energy production. The direct effect is the drop in energy output due to decrease in the radiation incident on the modules. The indirect effect is the drop in energy output due to electrical mismatch arising from shading part of a module or string of modules.

These effects are best illustrated by considering the changes caused by shading in the I-V curve of a string. Most modules incorporate bypass diodes that prevent the formation of hot-spots when a cell becomes reverse biased. A diode protects a group of cells that will be referred to as a sub-module or cell-string. The bypass diode starts conducting whenever a cell in its sub-module is shaded. The bypass

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diode carries all the current generated by the unshaded parts of a module past the shaded part. Once a bypass diode turns on, the voltage of the module drops by an amount equal to the voltage of the sub-module protected by that diode. If a module has three bypass diodes and one of them starts conducting, then the voltage of the module drops by one-third (and, in addition, by the forward bias of the diode) [2]. This means that the sub-module whose bypass diode turns on is, effectively, removed from generation capacity and the output power of the module decreases by one-third. The number of sub-modules that are affected by shading can be read straight from the current-voltage (I-V) characteristic curve and the shift of the maximum-power-point (MPP) to lower voltage is easily discernable. It is well established that the decrease in energy output of PV cells, modules and systems due to partial shading is highly non-linear [3, 4], which means that the decrease in electrical performance is not proportional to the percentage of shaded area but is significantly higher.

Partial shading, unlike uniform shading, is particularly troublesome for PV plants. In uniform shading the whole module or string of modules experiences a uniform decrease in light intensity, which directly reduces the current but has little effect on the voltage, since the voltage only varies logarithmically with light intensity. In contrast, in the case of partial shading, part of a module/string of modules experiences shading while the rest is under full illumination. This results in switching on of bypass diodes so that the full current produced by the unshaded parts can be conducted but it causes significant reduction in the voltage. The decrease in the voltage is responsible for the non-linear decrease in power output of a module/string of modules under partial shading.

This study considers only the effects of shadings that arise with change in the sun's angle like shading due to nearby objects and inter-row shading (shading of the second row by the first and so on). The NamPower roof top grid-connected PV system experiences shading during part of the year yet no studies on the effects of partial shading on the output of this system have been conducted.

2. System Description

The PV system studied in this paper is installed on the rooftop of the national power utility of Namibia, NamPower in Windhoek (coordinates: 22.5^0 S, 17.1^0 E). Figure 1 shows a photo of the system taken from the North on 18 May 2015 at 15:29h local time. Initial shading due to an adjacent building is clearly visible. On 18 May the solar transit in Windhoek took place at 11:48h local time and the day was perfectly cloudless.

The system consists of 259 Solar World SW 245-poly modules and six SMA 12 000 Tripower inverters. The SW 245 modules consist of 60 cells connected in three sub-modules so that a bypass diode protects 20 cells. A sub-module is located along the length of the module.

Due to varying slope of the roof, 42 of the modules are installed at a tilt of 13° while the rest of the modules are installed at tilt of 7°. All modules are orientated at 5° W. The modules are distributed into seven strings of 22 modules and five strings of 21 modules. One string is connected to each inverter input.

The SMA Tripower inverters have two inputs, each with its own independent maximum-power-point-tracker (MPPT), with power split asymmetrically between the two (2/3 on Main and 1/3 on Secondary input). This allows strings of different lengths to be connected to the different inputs. The first 84 modules are installed at a module row pitch of 2.05 metres while the rest of the modules are installed at a pitch varying from 1.96 to 2.14 metres. All modules are arranged in portrait orientation. Inter-row shading occurs for a large part of the day during the winter months. The system experiences shading due to a nearby building and previously installed solar water heaters from March to September.

3. Modelling

The modelling of the system in this paper was done with PVsyst modelling software. PVsyst allows extensive input from the user on system orientation and configuration, de-rate factors and three-dimensional system modelling. The 3D-scene created in PVsyst allows for a detailed analysis of shading effects on a PV system at fifteen minute intervals on a string-by-string basis. Figure 2 shows a snapshot of the 3D-scene that was created to study the effects of partial shading on the NamPower system. The image corresponds to 18 May, 15:30h. In this installation the strings run along the rows of modules (PV sheds) from North to South with String 1 starting on the first northernmost row. Inter-row shading is indicated by the yellow colour on the PV sheds while the grey colour indicates shading by nearby objects.

Figure 1. Photo of the NamPower system taken on 18 May 2015 at 15:29h from the North direction.

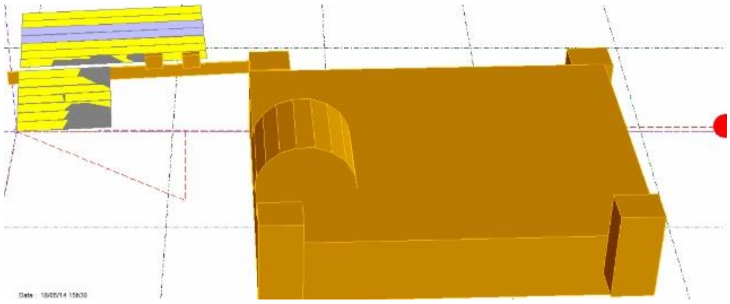

Figure 2. PVsyst 3D scene of shading on 18 May 15:30h as viewed from the North. The building in the foreground is casting shadow on the PV system in the background.

The electrical configuration was modelled according to the installation data. Two orientations (corresponding to the tilts 13^0 and 7^0) were selected and eight sub-arrays were defined. A sub-array connects to either the Main or to the Secondary inverter input. DC wiring loss was taken at 1% with respect to STC (standard-test-conditions) running conditions. The soiling de-rate factors were chosen to vary from 0% to 4% depending on the rainfall and the system owner's cleaning schedule. The light-induced-degradation (LID) factor was taken at default value and module efficiency loss was assumed to be -1.5% (indicating over-performance) as per module manufacturer data. The effect of wind was assumed to be the default value for semi-integrated modules with air-duct underneath and the unavailability was assumed to be one day per year [5].

4. Results

The effects of shading are analysed for a particular day – 18 May. For accurate modelling to take place, it is essential that an accurate 3D-scene is created. PVsyst uses the one-diode model to simulate the electrical behaviour of the modules. To assess the effects of partial shading, the electrical behaviour of each sub-module of each string connected to each MPP inverter input is computed.

On the 18th May the system experiences inter-row shading up to 8:45h in the morning and then, again, from 14:15h in the afternoon. The dramatic effects of inter-row shading on the power output of a string can be demonstrated by the behaviour of a particular string. Figure 3 shows the I-V curve of String 1 that extends over two rows, with 12 modules in the first row that is free from inter-row shading and 9 modules in the second row. At 14:15h the cells at the bottom of the modules in the second row become shaded while the others are fully illuminated. With the modules in portrait orientation, this means that all sub-modules (except for one) of the nine modules in the second row are affected, their bypass diodes start conducting and the voltage of the string decreases by an amount equal to the total voltage of all 26 sub-modules. This causes significant reduction in the power output of the string, as can be seen in Figure 3. The dashed curve indicates the I-V curve of the string if it were unshaded. The solid green curve is the I-V curve with shading on the string. The vertical solid blue line indicates the minimum voltage input of the inverter (which is 150 V in our case).

The voltage of the string at the operating current is just below 400 V and the MPP of the string has shifted to lower voltage. The total effect of the inter-row shading on String 1 at 14:15h on 18 May is a reduction of the power output of the string by 46.0% (from 3.37 kW to 1.81 kW) even though only 4.3%

of the string area is shaded. While the power decreases by only 17.5% due to drop in irradiance, it experiences a decrease of 28.5% due to electrical mismatch caused by the shading (giving a total loss of 46.0%).

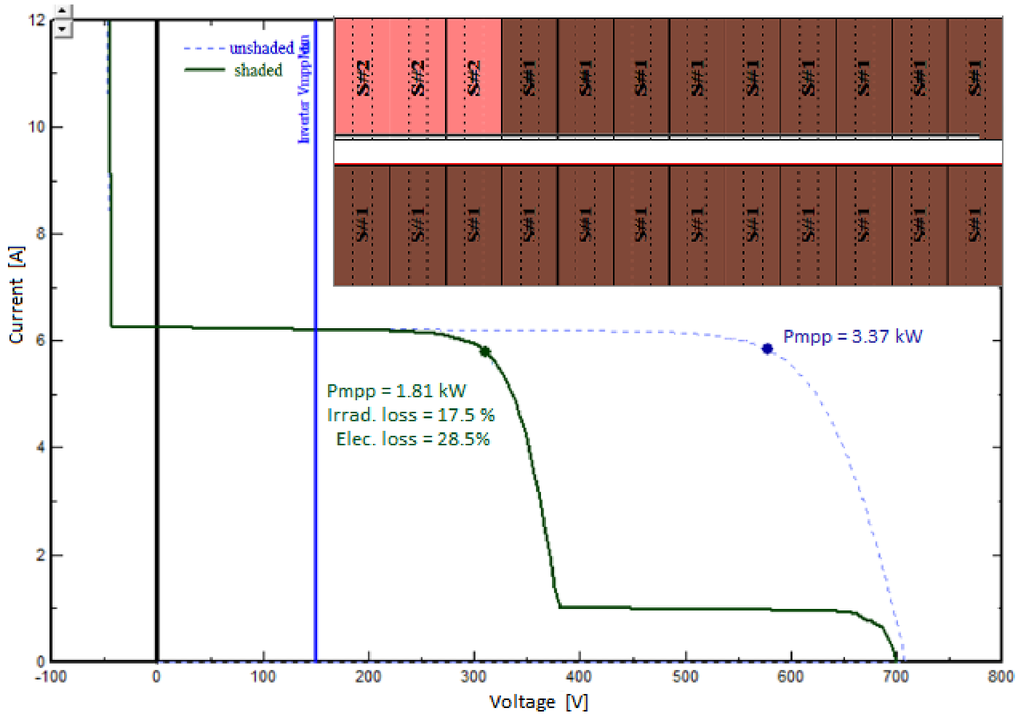

Figure 3. IV-curve of String 1 at 14:15h on 18 May. The inset shows initial inter-row shading on String 1 (S#1) and part of String 2 (S#2).

Any further shading of the modules in the second row will affect the output of the string only through the loss of the contribution of the single unshaded sub-module. Partial shading of modules in the first row will, however, further reduce the output of the string. The inset in Figure 4 shows String 1 at 15:30h when the adjacent building casts shadow onto it. Nineteen sub-modules in the front row experience shading due to the nearby building. The decrease in the light intensity causes a drop in current but the partial shading reduces the voltage of the string further by the voltage of those nineteen sub-modules. The IV-curve of String 1 at 15:30h is shown on Figure 4. The global maximum MPP of the string has shifted to a voltage below the inverter input threshold voltage of 150 V. The inverter then seeks the secondary maximum, which is 0.52 kW at slightly over 600 V, and which falls on the part of the I-V curve that is due to diffuse radiation only, resulting in loss of output of the fully illuminated part.

These examples and literature [6, 7] clearly illustrate the substantial loss in PV power caused by even a small amount of shading. The configuration of the shadow is significant only in the context of the number of sub-modules that it covers and the degree to which it shades them. It appears that the portrait orientation of the modules in the Nampower system is advantageous in the case of the shadow cast by the nearby building which strikes the modules along their length, affecting one sub-module after another with time and not all three at once.

The system was also modelled with the modules positioned in landscape orientation so that the inter-row shading would affect only a single sub-module at a time and not all three at once. The system would have produced 2.3% more energy on 18 May with modules in landscape orientation. The available roof area, however, doesn't permit the same capacity to be installed with modules in landscape orientation.

A comparison of the measured (on 18 May 2015) and modelled for that day energy output is shown in Figure 5.

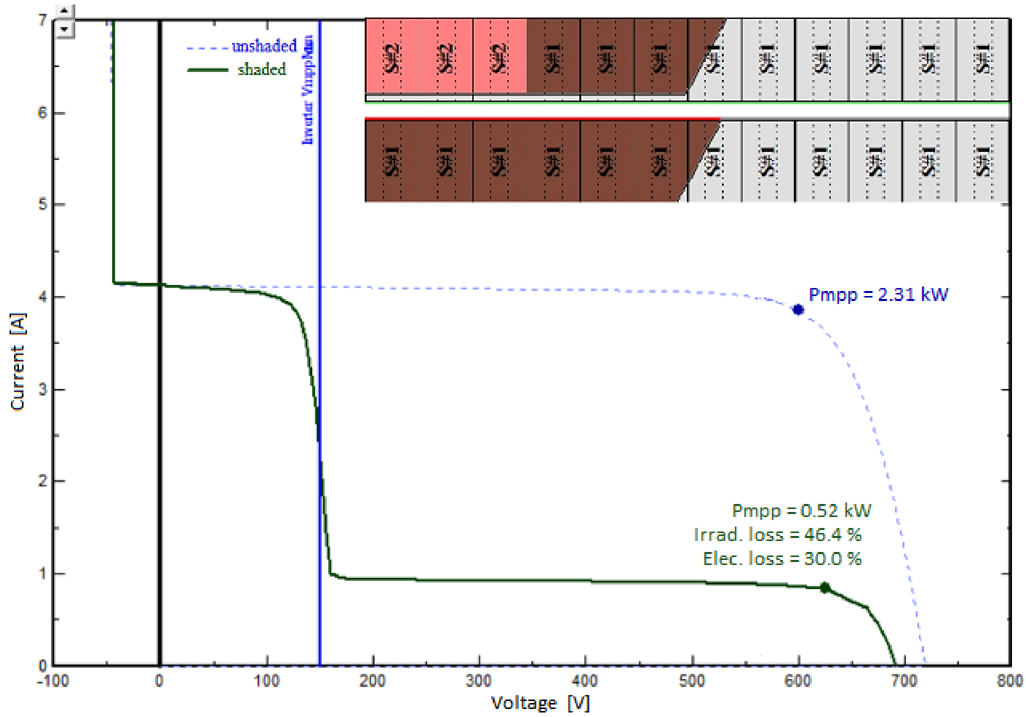

Figure 4. IV curve of String 1 at 15:30h on 18 May. The grey colour indicates shading

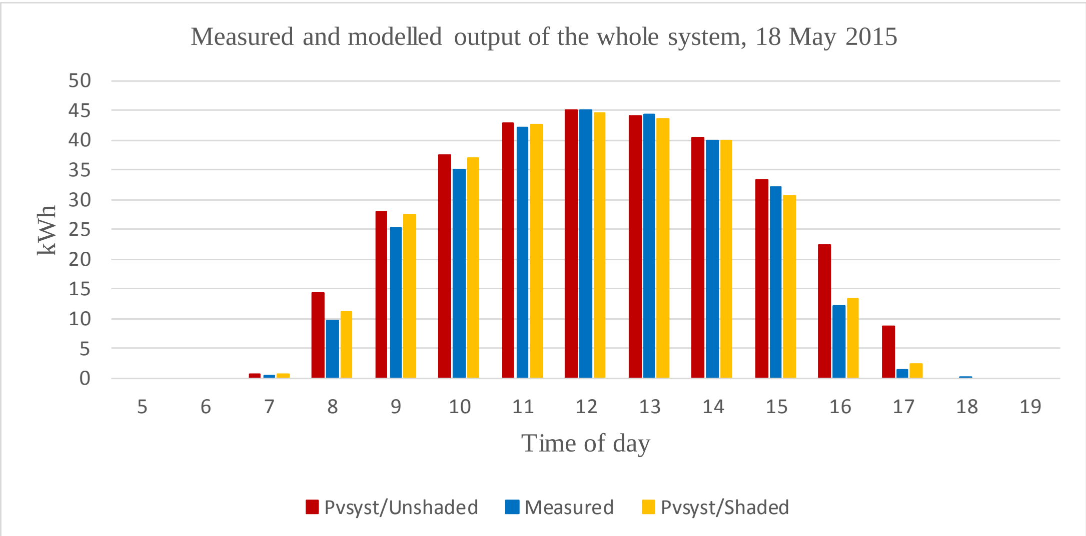

Figure 5. Measured and modelled hourly energy output for 18 May 2015.

The modelled energy output, with shading taken into account on 18 May, is 1.9% higher than the measured. Although the actual values are small in comparison with the overall uncertainty, estimated previously [8], there is a clear trend of good alignment between measured and predicted effects which become more pronounced with long term weather patterns and fluctuations. If the system were not experiencing partial shading, it would output 10% more energy on that day.

The interconnection of modules into strings also plays a role in the performance of a system under partial shading [9]. Further modelling was done by connecting together modules that experience similar

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shading conditions. This requires numerous inter-row connections, thus increasing cable length and resistive losses.

5. Discussion and conclusion

Our model accurately predicts the behaviour of the NamPower PV system under partial shading and allows the energy losses due to shading to be estimated. In Figure 5 the model suggests that the system is completely shaded after 17:00h and has negligible output while the measured output at that time is not zero. Since sunset in Windhoek takes place at 17:17h on 18 May, it is possible that some light reflected from the surroundings is incident on the system before sunset, thus contributing to higher production at that time of the day; such effect, however, has not been considered in the model.

The effects of inter-row shading can be reduced if the modules are installed in a landscape orientation, if the roof area permits.

Modules should be connected horizontally along a row even if they are subject to dissimilar shading conditions in order to keep wiring length and resistive losses to a minimum.

Another factor that affects the performance of a PV system under partial shading is the number of strings connecting to an MPPT input of an inverter. If two or more strings that experience different levels of shading connect to the same MPPT input of an inverter, then the voltage mismatch arising between them as a result of the shading causes further losses. The NamPower system design has a single string per inverter input which reduces the negative effects of partial shading on energy output.

For the NamPower system the expected (modelled) electrical loss due to shading stands at 1.3% per annum with ohmic wiring loss of 0.3%. The loss due to shading is low since shading takes place in winter months and only outside hours of high insolation. The effects of unavoidable partial shadings can be mitigated at the design stage by avoiding, as far as possible, multi-string connection to same inverter MPPT input, using suitable module orientation and string configuration.

Acknowledgements

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