The 'PV System Doctor' – smart diagnosis for photovoltaic systems

O&M | Every photon and electron lost in a PV system represents unrealised revenue. The Solar Energy Research Institute of Singapore has developed a holistic diagnosis package – the PV System Doctor – to identify and cure underperforming PV power plants in real time. The team behind the service explains how it helps maintain a healthy PV system and ensure expected returns – or even surpass them

Do you know how many photons are converted into electrons in your photovoltaic module? Do you know how many of those electrons get lost in the inter-connections and the inverter until they finally reach the revenue meter? Every photon that does not generate revenue reduces the 'health status' of your PV system.

Solar PV has seen an unprecedented growth over the past couple of years with the global installed capacity reaching nearly 290GW by end of 2016 [1]. However, like any other industrial technology, PV systems are also vulnerable to failures [2] due to anomalies in PV modules, other system components or inadequate system design leading to a performance reduction or even a complete breakdown. These negative consequences will lead to unachieved expected returns, which negatively affects investors' confidence to further finance the growth of the global solar deployment.

The need for cost competitiveness and rapid scaling of the industry has caused a number of installation companies to compromise on quality, thereby providing sub-standard products and designs for the installation of the systems. A small underperformance in PV systems, however, cascades to higher revenue losses when analysed over the operational system lifetime [3]. In addition, such sub-optimally performing assets also cause operation and maintenance (O&M) cost to go up, reducing the return on investments even more. Therefore, regular maintenance of PV systems is imperative to ensure optimum operational quality. However, in reality, O&M services are widely employed on an 'as-needed' basis where the owners only react when the systems are in distress. The installation companies usually provide standard O&M services after commissioning such as visual inspections, electrical checks, repair or replacement of damaged components, conditional monitoring of data and occasionally infrared imaging of modules.

It is essential for the industry though to adopt innovative methods to detect actual or nascent underperformance of PV systems for continued growth of the industry and to keep risk premiums for investors at affordable levels. To ensure optimum quality of PV assets and help system owners to maximise financial gains, the Solar Energy Research Institute of Singapore (SERIS) has launched a new industry service – the 'PV System Doctor'.

Motivation

It is often underestimated or not known how severely any deviation from the expected PV system performance affects the cash flow of the project.

Figure 1 shows the cash flow projections of a 1MWp commercial rooftop system in Singapore as an example. Since the city-state does not have monetary support schemes such as a feed-in tariff for renewable energies, the net present value (NPV) considers SERIS' most-likely future electricity price scenario [4]. Based on an initial performance ratio (PR) of 80%, the system would yield an NPV of ~US$500,000 over an assumed 20-year lifetime, with a project internal rate of return (PIRR) of ~12% and an equity internal rate of return (EIRR) of ~18%.

Figure 2 visualises the financial impact on the project cash flow for different degrees of underperformance. A small deviation of 5% in PR (75% instead of 80%) leads to cumulative NPV losses of nearly US$90,000 (i.e. -17% of its expected level), and a reduction of between one and two percentage points in the expected IRRs.

This underlines the need for advanced and innovative O&M services such as the PV System Doctor for early detection, and quick and cost-effective rectification of underperformance of PV assets.

The PV System Doctor

The PV System Doctor is an advanced and innovative O&M service that provides a comprehensive 'health check' for PV systems. The service aims to provide timely identification of underperformance in PV assets and to proactively evaluate solutions to mitigate risks and prevent revenue losses.

Target users are typically PV system owners and operators, investors and insur-

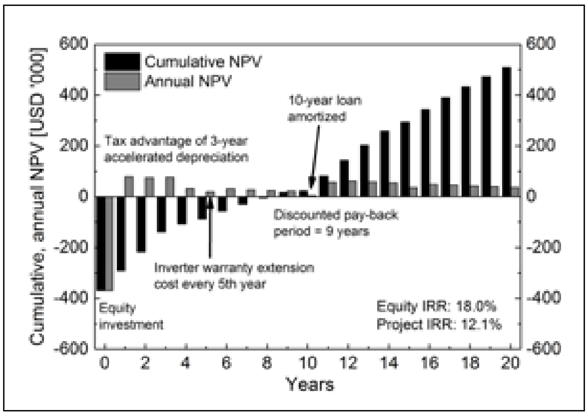

Figure 1: Annual and cumulative NPV, EIRR and PIRR of a 1MWp PV asset on a commercial rooftop in Singapore. NPV = net present value, EIRR = equity internal rate of return, PIRR = project internal rate of return

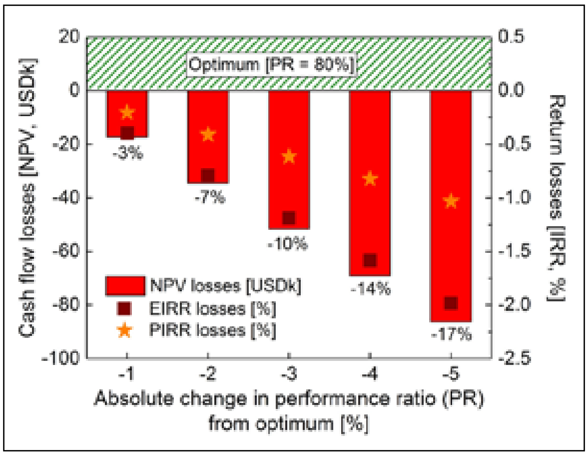

Figure 2. Cumulative NPV losses, EIRR and PIRR reduction due to absolute changes in PR compared to the originally expected value of 80%

ance companies. The three main reasons for calling the 'PV System Doctor' are:

Regular health checks, i.e. periodic independent assessment of PV system performance and benchmarking against expected yield;
Preventive maintenance, i.e. in-depth analysis of PV system performance, including on-site assessments of critical system components;
Detection of actual system faults or suspected underperformance, i.e. independent evaluation of system faults and root-cause analysis of suspected underperformance of PV assets.

The PV System Doctor is comprised of the following professional services that can be employed as an individual service or as a package by interested clients:

- Real-time monitoring of individual strings or system.
- Advanced on-site diagnostics using innovative imaging techniques and IEC-compliant PV system checks.
- Independent financial assessment.

SERIS provides a comprehensive diagnostic report for all these services that includes the recommended rectification works and their cost-benefit analysis.

PV System Doctor services

Real time monitoring of PV strings or systems

For this purpose, SERIS has developed and now is able to offer state-of-the-art performance monitoring solutions for PV installations, from small rooftop systems to ground-based utility-scale installations. The monitoring solutions from SERIS are customisable as per clients' requirements and can provide comprehensive data ranging from meteorological parameters (irradiance, module temperature, wind speed and direction, rain gauge, spectrum etc.) to DC and AC performance of individual strings or systems as a whole. The real-time monitoring of systems and meteorological parameters has been offered by SERIS since 2011 using robust data acquisition hardware with a data transmission and stability of 99.9%. The data is available to the customer through an intuitive graphic user interface (GUI) coupled with big data analytics, on SERIS' secured customer portal.

SERIS' monitoring solution integrates the meteorological data such as irradiance and module temperatures, and DC and AC data from PV strings or system for continual assessment of performance ratio. The monitoring hardware also has the capability to interact with the installed inverters for verification and/or control. This enables early fault detection by continuous benchmarking of:

- String performance against each other;
- System performance against simulated behaviour under optimal conditions;
- Plant performance against peer installations.

Only with such comprehensive analytics is it possible to detect any underperformance and develop rectification strategies in a timely manner.

It is noted here that the early-fault detection can also be carried out by using data from any type of existing PV monitoring system that is already in place, meaning additional investments in hardware may not be required.

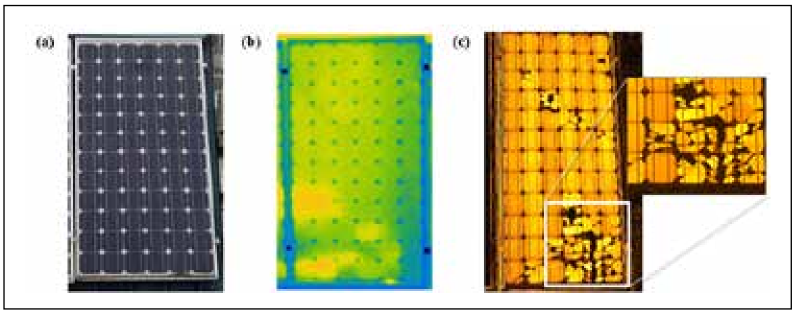

Figure 3. Representative comparison between (a) visual image (b) infrared (IR) image and (c) daylight electroluminescence (DEL) image of a PV module with severe micro-cracks

Advanced on-site diagnostics of PV systems

Remote monitoring solutions can provide an insight into the quantitative aspect of the PV modules or systems as a whole. However, the root cause of losses in a system often remains a question unanswered without an on-site inspection. Therefore, it is essential for the system doctors to carry out certain on-site diagnosis to find the reasons for the underperformance and develop solutions to improve the health status of the PV systems.

Standard O&M contracts include IEC-compliant services for visual and electrical checks. In addition, qualitative measurements of the PV modules are occasionally carried out using infrared (IR) imaging. The IR images capture unusually high temperatures in operating PV modules ("hot spots"), providing hints about defects in modules. However, it is very difficult to detect macro- or micro-cracks in the modules, which gradually will lead to power losses. Therefore, in addition to providing these IEC-compliant services, SERIS'

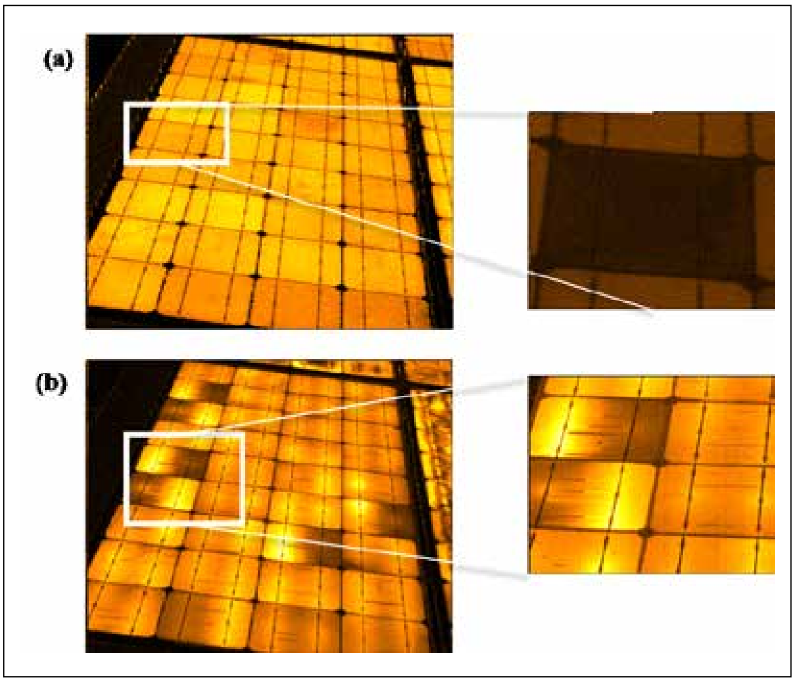

Figure 4. Comparison between (a) DPL image (contrast adjusted) and (b) DEL image captured for a PV module on-site in a 10-year old PV system in Singapore

PV System Doctor also employs highly specialised mobile daytime luminescence imaging technique to inspect the quality of PV modules either individually or as a complete string without removing them from the frames or from the site. The daytime luminescence system is an in-situ, non-destructive technique that provides information on material or electrical defects in PV modules or strings. The technique is capable of performing both daytime **electro**luminescence (DEL) and daytime **photo**luminescence (DPL) imaging.

Figure 3 shows a representative comparison between optical, IR and daytime electroluminescence (DEL) imaging of a module with cracked cells. These images have been captured on-site at the same time under identical irradiance conditions for comparative analysis. It can be clearly observed that the DEL image provides a much greater wealth of information compared to the IR image, which does not show any abnormally high temperatures of the affected areas.

The DEL technique employs electrical excitation of PV modules or strings, thus causing radiative recombination of injected carriers as photons emit from the surface of the PV cells. The intensity of the emitted luminescence is dependent on the electrical and resistive properties of the cell, thus areas of high series resistance result in low luminescent areas. This helps in mapping out bright and dark areas, thus identifying various defects in the PV modules. The DEL technique allows the detection of a multitude of defects such as micro-cracks, electrical shunts, broken contacts and interconnects, and many more.

On the other hand, the DPL technique employs sunlight as an excitation source to generate carriers. The material impurities or anomalous material compositions cause a loss of carriers in the flawed regions, thus affecting the emitted photoluminescence signal. DPL allows identification of material quality of the cells of the module, intrinsically or mechanically induced shunts and potential induced degradation (PID) defects.

Figure 4 shows a representative comparison between DPL and DEL images captured on-site during daytime for a PV module installed in a 10-year old PV system in Singapore. The DPL image shows darkened cells, which indicate the degrading material quality of the cells whereas the concentrated dark areas near the busbars and fingers of the cell in the DEL image show the electrical interconnection faults in the cells of the PV modules. Such defects lead to underperformance of the affected PV modules and eventually cause yield losses in the PV system.

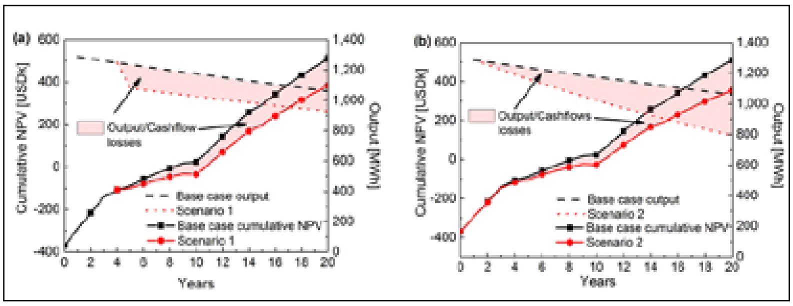

Figure 5. a) Cumulative NPV profile impact from a 50% underperformance of 25% of the modules, b) Cumulative NPV profile impact in case of accelerated degradation (2.5% p.a. as opposed to 1% assumed in the yield assessment), e.g. due to soiling and/or poor maintenance

Independent financial assessment

The possible root causes of sub-optimal performance of PV systems greatly varying from component defects to design-related issues or poor installation. A report on the long-term performance of PV systems [5] by the International Energy Agency (IEA) discussed real-world systems where performance ratios were significantly below optimum. While a nine-year old system in Germany, for example, had a PR as low as 50%, severely suffering from degradation of the PV cells, another 13-year old system in Italy experienced several unplanned outages, causing the annual PR to fluctuate significantly from 25% on the low side to 70% on the high side. Such underperformance in PV systems, if not detected and rectified within an appropriate time frame, can lead to significant revenue losses over the operational life of the system.

Using the 1MWp rooftop example as discussed before, two different scenarios of system underperformance are illustrated in Figure 5 to visualise their negative financial implications, in case no rectification work was implemented:

a. Scenario 1: A collective underperformance of 25% of the installed PV modules (only reaching 50% of the rated power anymore);
b. Scenario 2: Degradation of the PV system by 2.5% (rather than the 1% as assumed in the original yield assessment), e.g. due to excessive soiling and/or poor maintenance.

While the first scenario results in a sudden drop in output in year five, the second scenario shows how a small deviation in degradation might appear small in the beginning but, if left unchanged for the whole lifetime, can cause similar substantial losses in cash flows as in scenario 1. Thus, the scenarios highlight the requirement of a preventive approach to O&M using real-time monitoring systems that can alarm the project owners to request for a timely health check of their PV systems. In addition, for existing underperforming systems, a detailed cost-benefit analysis will be performed to decide whether potential rectifying measures are worth to invest in.

While real-time monitoring and early detection of underperformance can help to reduce unplanned outages, a probability-based technical risk impact assessment (Figure 6) can also be conducted to mitigate

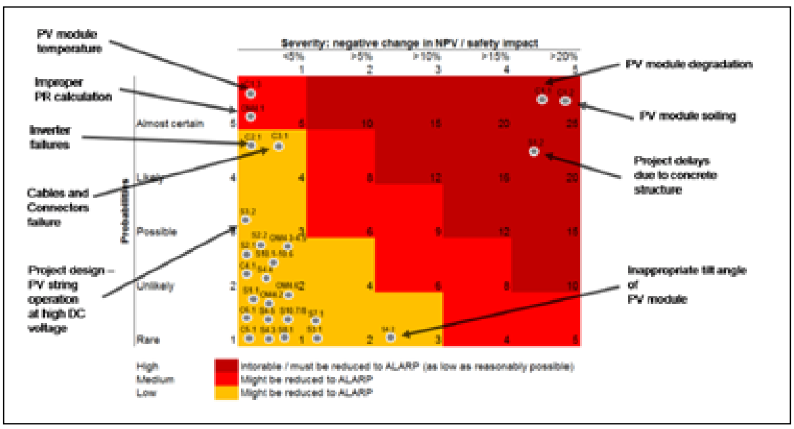

Figure 6. Example of a SERIS probability-based impact assessment of various technical risks illustrated in a mapping matrix. Method adapted from [6]

potential system underperformance in the future. All possible technical risks need to be identified, categorised and mapped based on their probability of occurrence and severity. The latter should not only be in quantifiable units (for example change in NPV or change in EIRR) but also in non-quantifiable units, such as safety impacts etc.

Conclusion

To allow a steady growth of sustainable investments in the PV systems industry, it is critical to maximise production with as little downtime and degradation as possible, over the entire operating life of PV assets. The complete financial value chain from upstream to downstream PV industry relies on the performance of these PV systems. In response to these needs, SERIS has developed a unique capability – the "PV System Doctor", a preventive and innovative O&M service that can contribute to realise and even surpass these goals. ■

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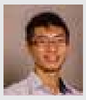

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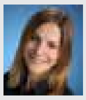

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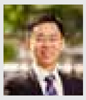

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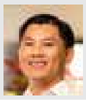

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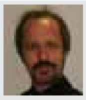

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