A HOLISTIC APPROACH TO TECHNICAL ASSET MANAGEMENT

Improving and optimizing solar PV assets

A white paper by Envision Digital

Solar is set to become the main energy source in the coming decades. The immense scale of deployment calls for digitalization in every aspect of solar asset management. While several tools are available to address this, a truly holistic technical asset management (TAM) framework is required to maximize asset performance. What are the cutting-edge innovations? How can a digital platform synergize the use of available technologies? In this white paper, we will comprehensively explore the principles and best practices behind a good TAM solution.

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1. Introduction

Solar photovoltaics, or PV, has seen unprecedented growth in the past two decades –despite disruptions wrought by the COVID-19 pandemic. According to the International Energy Agency (IEA), solar PV is the lowest cost electricity generation technology in many places around the world. This has driven record increases in new PV generation capacity around the world. In 2020, the world added more than 130 GW_p of PV capacity – a 100 GW scale addition for the fourth year in a row. This brought the total global installed PV capacity to over 760 GW_p. If the current trend of PV capacity addition continues, PV generated electricity will grow by 15% annually and more than quadruple to reach 3,300 TWh by 2030.

Solar energy is poised to become a major energy source for the world to meet the carbon emission goals of the Paris Agreement. According to the Energy and Climate Intelligence Unit, more than 130 countries have made commitments to carbon neutrality, with most of them pledging to achieve it by around 2050. For example, China, as one of the largest emitters as well as a rapid growing economy, had announced the 30·60 goal, which pledges carbon neutrality by 2060. As a result, many countries have put forward ambitious plans for renewables to take over conventional fossil fuels as the main generation source.

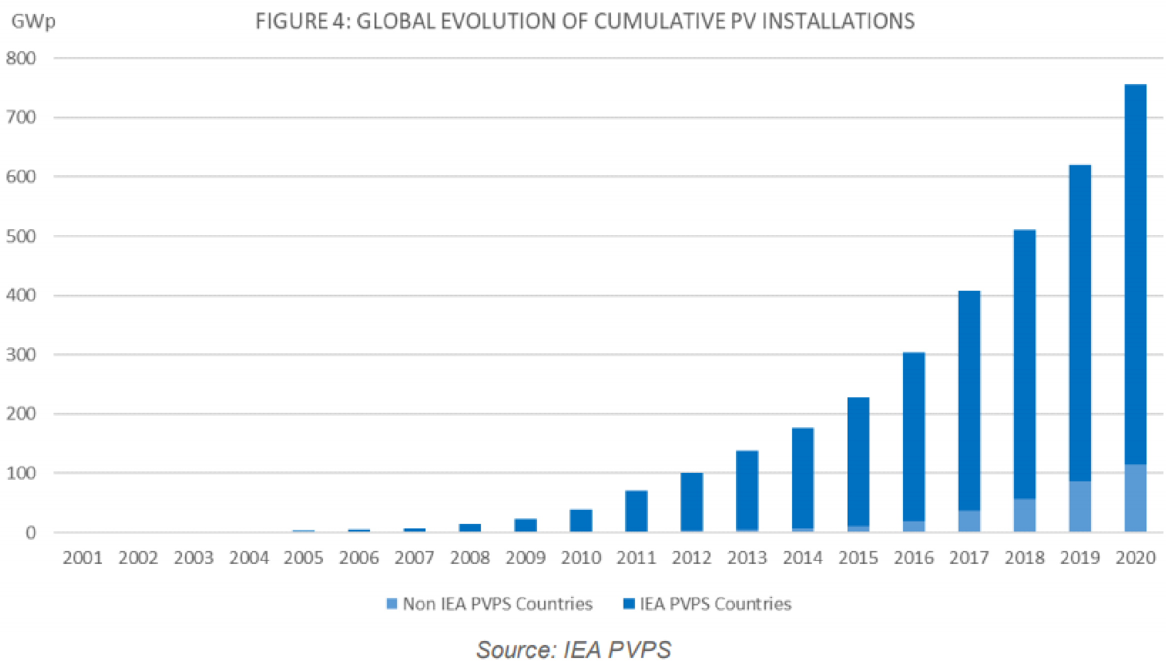


Figure 1: The total cumulative installed capacity at the end of 2020 globally (Source: IEA-PVPS T1-39:2021)

Arguably, one very attractive point of a PV power plant is its “simplicity”. Compared to conventional thermal power plants, which require sophisticated equipment, safety features, and extensive civil construction work, PV systems are considerably less complex. PV systems have few moving parts and do not require high maintenance. In theory, a well-designed PV system should run robustly with little outside intervention. However, this does not mean they do not require supervision and management. As the PV industry matures, experienced stakeholders have increasingly realized that asset management is crucial to ensure the long-term performance and the financial health of their PV investments. In fact, according to kWh Analytics, solar assets on average underperform their target production, highlighting the need to improve operational standards.

The impression that PV systems can be left unattended and still generate a handsome return as long as the sun continues to shine, is flawed.

Asset management is a broad concept that involves a wide variety of elements. When talking about managing a portfolio of PV assets, may include among others, the following items:

- Business administration, policy, and governance structure
- Process and organization designs
- Asset performance management and value optimization
- Legal compliance
- Financial management
- Project management, inventory, supply chain
- Risk management (operational, financial, and technical)
- Daily asset operation and maintenance
- Information and data management
- Communication with various stakeholders, coordination between business units, reporting
- Health, safety, and environment

Achieving excellence in asset management requires the deployment of resources, skills, and strategies. As more and more solar PV plants are built, each with its own characteristics, the challenge of managing the plants also increases. Asset owners and managers often find themselves confronted with a sizable and diverse portfolio in several aspects:

- Asset type – from large utility-scale farms facilities to commercial and industrial (C&I) systems, or even small residential systems
- Deployment scenario – from ground-mounted to floating solar
- Climate – from tropical areas to snowy regions
- Business model – from generation side with power purchase agreements (PPA) arrangement to virtual power plant (VPP) participants with various value streams

Managing a heterogeneous portfolio calls for the technical capability to handle different O&M regimes, types of problems, and even differing data quality or completeness. Moreover, the asset manager is expected to ensure that the owner's goals, which can be multi-dimensional, are met. The asset manager's task is therefore complicated, and success requires that a good framework and process be in place. Different players in the PV industry may have their own ways and strategies, but common best practices are starting to emerge.

While business processes are specific to organizations and the bigger environment that they are in, a large portion of the technical activities can be standardized and thus "externalized" by the asset managers.

Therefore, when it comes to technical asset management, dedicated tools such as specialized digital asset management platforms are naturally useful.

The transition to an asset-centric information management approach is picking up speed. Many large organizations such as TotalEnergies, ORIX, SPIC and Neoen are adopting sophisticated monitoring platforms. Such platforms aim to increase data transparency, simplify reporting and analysis, minimize asset downtime and production losses, adequately manage events, and conveniently administer maintenance work. These are early milestones in the journey towards digitalization. Moving forward, more value can be generated from mining the data using advanced analytics and applying advanced diagnostic techniques.

In this technical white paper, we will perform a deep dive into the subject of technical asset management to explore the best practices of harnessing the power of digitalization and advanced technologies.

1.1 Technical asset management just became more technical

Technical asset management, or TAM for short, is a loosely defined term that refers to the technical portion of asset management. This usually includes anything related to:

- The regular operation and maintenance of the PV fleet.
- The evaluation of asset performance level and health status.
- Optimization of asset performance to maximize value.
- Risk mitigation and safety.
- Reporting, extracting insights from the operation, and communicating efficiently.

Several key **stakeholders** are involved in TAM. They are the *investors/financiers*, *asset owners, asset managers*, and *operators* (i.e. operations and management (O&M) and field personnel). In the ideal world, stakeholders' interests should be aligned. Vertical integration or service contracts with properly structured incentives may facilitate the alignment. Asset managers and operators are then motivated to achieve excellence in asset management to maximize the values for asset owners. We can collectively refer to these parties as *asset stakeholders*. To perform TAM-related tasks, the asset stakeholders must be supported by specialized digital solutions and teams with relevant experience and expertise. Good **processes** need to be in place too. There should be standardized, streamlined workflows for daily routine situations and for responding to asset downtime, underperformance events, warranty claims, and for preventive or predictive maintenance.

Figure 2. Key elements involved in the technical management of solar assets, and the relationship among them.

Managing a solar plant involves taking care of the safety, reliability, and performance of all the components, from PV modules and inverters to AC side electrical equipment. The ability to monitor the condition of the electrical generator – the DC field up to the inverters- is key to understanding asset health status and performance level. This is one of the most important and complex pieces of TAM.

The DC field is the most dynamic part of the entire PV system. Unlike managing electrical equipment on the AC side, which is generally mature and standardized, the DC side poses the following challenges:

PV systems have diverse designs. They can come in different sizes, tilts and orientations, string configurations and topologies, PV module technologies, and inverter models. In many cases, a single plant may have more than one design. For instance, systems deployed on uneven terrains might have different tilts, orientations, and even string lengths. Mixing and matching components is not rare either. To complicate matters further, some systems are located in areas that are difficult to access.

PV systems comprise a large number of components. A 100MW_p plant can easily have more than 200,000 PV modules, 10,000 strings and 2,000 string inverters (or hundreds of combiner boxes). Granular data is required to understand system behavior and comes at the cost of increased data volume and the effort required to process the data.

PV modules operate under a wide range of environmental conditions that are constantly changing and fluctuating. Moreover, the conditions are often inhomogeneous across different parts of the array, especially sunlight illumination and module temperature.

The monitoring system may not be adequate to fully capture the reality on site. Data collection systems differ, resulting in a wide spectrum of data quality and completeness. For larger sites or complicated rooftops, more than one weather station may be needed. But even that may not be sufficient to represent what is going on in every corner of the plant.

Due to the large number of components and varying operating conditions, system behavior may be complex. The energy output comes from individual PV modules, which are connected in series as strings, then further combined in parallel to feed into a maximum power point tracker (MPPT) of an inverter, with a certain tracking strategy. Although at the first glance, the output may look like a simple linear addition, it is not, especially when shading, soiling, power limitation, or DC health problems are present. The actual inverter operating point results from a complex interplay and nonlinear superposition of the inputs through the various stages.

The quantification of incoming solar resource that falls onto the panel surface is one major source of error and uncertainty. The amount of incoming solar irradiation (plane-of-array insolation) is critical for evaluating system efficiency. However, this amount is highly variant across geographic regions. Even for the same location, different module surface orientations can have very different total insolation as well as temporal patterns. Currently, operators deploy pyranometers or reference cells to measure the input solar energy for each site.

The measurements may not be perfect. Even for sites with a proper monitoring setup, measurement imperfections are common. Irradiance sensors may be misaligned or misoriented, giving a wrong estimate of the available solar resource. Sensor soiling, degradation, drift, and communication problems are ubiquitous. Also, healthy sensors too do not entirely reflect what the PV module sees, especially during cloud passage, low light, and large incidence angle situations, frequently giving systematic bias and even causing performance ratio (PR) values to go wild.

It is very tricky to compare or benchmark performance across assets. Other than the fact that solar resource measurement standards vary across sites, the different configuration and local conditions of solar plants mean that they have inherent differences in efficiency (normalized performance as measured by PR). While it is possible to calculate the designed difference, some of the assumptions that go into the calculation can be inaccurate and arbitrary (depending on who is performing the calculation). PR calculations may be affected by resource availability uncertainty, congenital design differences, and plant maintenance level, which are hard to tease apart. Thus, a simple comparison across assets may be unfair for evaluating asset management standards and estimating the amount of unrealized potential.

Traditional PV asset performance evaluation practices usually focus on high-level key performance indicators (KPI) such as energy yield, PR, and system availability. This approach is good for the first-order estimate. However, many problems may hide under the covers of uncertainty without being noticed for a long time until they grow out of control and strongly impact the KPIs (Figure 3). This is not the best way to assess asset performance. Sometimes, with a simple intervention, the system PR can improve by a few percentage points, but that requires understanding the problem and how to fix it. In fact, squeezing the last electron out of the system is technically much more difficult than ensuring a baseline. That has undoubtedly deterred the industry from pursuing the last mile of TAM excellence.

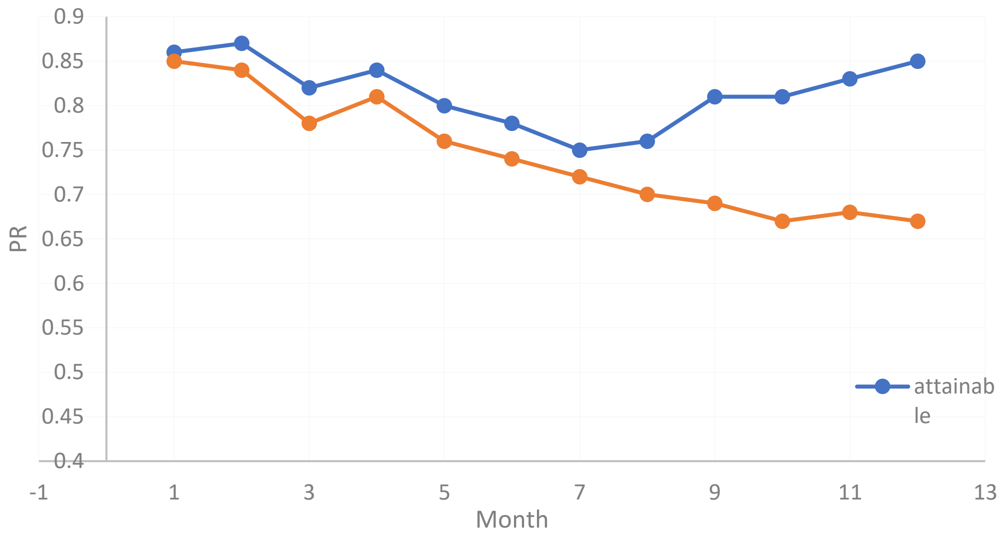


Figure 3. A case where an underperformance issue persisted for a prolonged period before it manifested noticeably in PR.

However, this is changing with the new tools and techniques available today. A shift to the new paradigm is happening. With the help of digitalization, solar assets can be monitored much better, producing granular data down to inverter and even string level. Advanced analytics, done in an automated way, helps to locate even the minor faults and underperformances, hence giving more transparency on asset conditions. Advanced diagnosis techniques are becoming more mature too. IV curve tracing and drone imaging had become proven concepts for a complete understanding of asset problems. These tools and techniques are enabling TAM to be done in a more sophisticated way.

For many reasons, it is not the most effective to develop everything in-house. Specialized vendors who can embody the best practices are important. However, the asset manager is still the one to orchestrate and pull things together. Therefore, TAM approaches should be properly considered and designed at the outset as a framework, which defines internal scopes as well as the involvement of external solution providers. In this way, long-term plant yield is maximized at a low operating expense (OPEX) when performance issues do occur, without the need for ad hoc solutions or retrofitting, which may be costly.

1.2 Digitalization and Automation

The essential element in the design of an efficient TAM framework is digitalization and automation. This is especially so for managing PV assets for reasons such as:

The scale problem:
Solar deployment is set to grow rapidly in the coming decades and many of the PV assets will be distributed in nature. The number of sites in asset owners' portfolios will be too large and too diverse to be handled manually. Furthermore, optimal management requires skilled personnel, such as experienced performance analytics engineers well versed in PV technology, but they are constantly in short supply. The conflict between scale and manpower resource (*scale-manpower conflict*) is only going to exacerbate.

The trend to be unmanned:
Solar plants, especially remote ones, are increasingly going to be unmanned in the future to save labor costs. Asset monitoring and decision-making will happen in a centralized place by a small core team of dedicated experts.

Complex operation:
The activities involved in operating and maintaining a large number of components within a solar fleet are complex. The supply chain, inventory, safety, scheduling, reporting, validation, compliance, device lifecycle, and many other aspects need to be managed regularly.

Smart grid and connected energy:
Solar plants in the future will need to be smart. This is integral for a power system based heavily on renewable energy sources. Hybrid PV plus wind or hydropower plants, storage coupled PV, virtual power plants, grid-friendly or grid supporting PV are becoming popular. Managing smart solar plants requires intelligent status sensing, control, market participation, and the ability to coordinate with other sources of energy, all of which need digitalization as the underlying infrastructure.

Hence, it is not only desirable but necessary for solar TAM to adopt digitalization and automation, without which none of the above requirements can be met at a reasonable cost. Digitalization and automation require the use of an Artificial Intelligence of Things (AIoT) framework, software tools and state-of-the-art techniques, and build them into the TAM framework from the very start.

1.3 Data-driven decision making and optimization

Data plays a central role in optimizing business processes and decision-making. A study conducted by the Massachusetts Institute of Technology (MIT) showed that companies using data-driven decision-making are 5% more productive and profitable than their competitors[1]. Similar findings on the boost on profitability were reported by McKinsey & Company[2]. This is very important for the solar industry too, where cost competitiveness is key to success. With digitalization, information becomes easily accessible on a centralized platform, which enables rich possibilities of data-driven approaches to

[1]Brynjolfsson, Erik and Hitt, Lorin M. and Kim, Heekyung Hellen, Strength in Numbers: How Does Data-Driven Decision-Making Affect Firm Performance? (April 22, 2011). Available at SSRN: https://ssrn.com/abstract=1819486 or http://dx.doi.org/10.2139/ssrn.1819486

[2]McKinsey & Company, Artificial intelligence: The next digital frontier? (June, 2017).

eventually increase efficiency and revenue. Concrete examples include knowing when best to clean the PV panels, rectifying downtime events on time, evaluating the effectiveness of O&M practices (e.g. snow removal technique, power plant control settings), using predictive maintenance to stock up spare parts and reduce downtime, providing supportive evidence for warranty claims, and many others.

The essence of the data-driven approach is efficiency and sophistication. It helps sniff out the last bit of suboptimal performance

Data-driven approach accurately evaluates the impact of an issue and the implications of an action, thereby reducing uncertainty and arbitrariness. Furthermore, by holistically combining multiple sources of data, more insights can be mined, and synergies achieved. In later sections, we will explore some advanced TAM concepts and practices that can optimize asset performance and the use of resources.

2. Toolkits for advanced TAM

2.1 Remote performance monitoring

In the paradigm shift to digitalization, the remote performance monitoring platform forms the backbone of future-ready TAM. Essentially, the automated Internet of Things (IoT) - style monitoring generates the following types of data:

- Real-time and historical time series data for the various measurement points from equipment and sensors.
- The time-series weather data associated with a site.
- Historical generation and various derived KPIs.
- Anomalies and alarms
- Events and work performed

These data types provide transparency into asset condition and operation, based on which efficient TAM workflow can be crafted. They also help to provide greater transparency and confidence for stakeholders. The importance of remote performance monitoring is already well recognized across the industry, as witnessed by the growing popularity of monitoring solutions. There are many software applications in this space, such as EnOS™ Monitoring (Figure 4). The core functionalities offered by various vendors mainly include asset portfolio overview, data management, visualization, alarms, and reporting. Currently, comprehensive monitoring solutions are more common for utility or larger C&I assets. For very small distributed systems, inverter manufacturers' own cloud platforms are good options to offer a basic set of monitoring functions.

Figure 4. EnOS™ Monitoring dashboard for Solar.

2.2 Advanced diagnostic techniques

Performance data analytics

For ordinary daily operations, the rudimentary use of monitoring data may suffice. However, when performance issues occur, the asset managers and operators often find themselves struggling to dig deeper into the data for the insights they need. Many asset managers and operators do not have a deep understanding of their assets' performance levels, and many problems exist unnoticed for a long time. Given the complexity of PV system behavior discussed earlier, it is sometimes difficult to judge whether the performance is suboptimal by simply looking at KPIs such as PR. Hence, if the KPI is within the bands expected from the project design calculation, which may be itself flawed, no further examination is made.

To truly optimize asset performance and avoid the underutilization of data, advanced performance analytics is needed. Performance data analytics makes heavy use of time-series performance data generated by remote monitoring. By using a combination of techniques such as modeling, calculation, inter-comparison, correlation, and advanced machine learning methods, analytics can detect performance anomalies, calculate production losses, and point out optimizable areas.

EnOS™ Advanced Analytics for Solar (EnOS Analytics for short) from Envision is an industry-leading performance analytics app, which is an exemplary illustration of the concept. First, EnOS Analytics does tight quality control of data, checking data quality and sensor health. With reliable input, it calculates more advanced or customized KPIs (such as weather corrected PR without counting curtailment periods). Furthermore, it performs more in-depth analysis such as inverter efficiency, DC health, degradation status, and downtime statistics. Most importantly, EnOS Analytics dissects the performance data and employs sophisticated machinery of interconnected algorithms to disentangle performance losses into over 15 major loss categories.

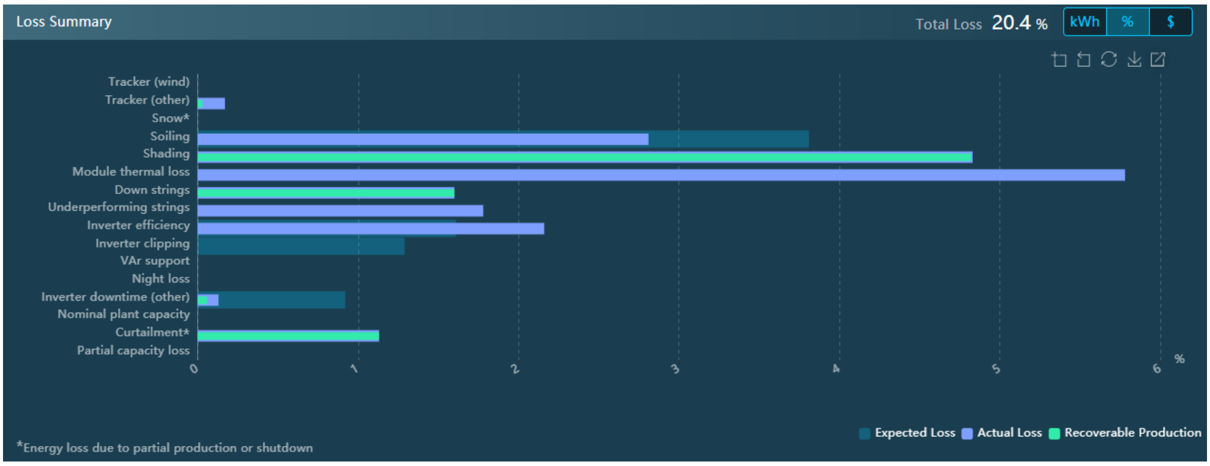


Figure 5. EnOS Analytics breaks down performance losses into refined categories according to root causes or mechanisms, in doing so helps provide an in-depth understanding of asset performance as well as actionable insights.

Accurate loss breakdown may not always be feasible, but a good estimate provides the first useful in-depth diagnosis into system performance issues, particularly the less visible ones. Loss breakdown helps to segregate expected/unavoidable losses (due to shading, snow, clipping, reactive power support, elevated temperature) from truly undesirable losses due to suboptimal O&M. Analysis on DC sides performance problems such as underperformance strings and soiling accumulation is very useful and offers concrete actionable items to recover production loss. EnOS Analytics also detects inverter issues such as low efficiency, late start and frequent restart, which are related to safety and predictive maintenance. On top of offering operational insights, some loss quantification such as thermal and clipping can also provide valuable feedback to system design, and in doing so closes the loop of project development.

Performance analytics is not only meant for optimized operation and production in a technical sense, but also fulfils the essential need of asset management as a business. For example, many big asset owners and energy producers that manage large portfolios use performance analytics to achieve goals like:

- Accountability: have total asset transparency by knowing where the production losses come from and compare against budgets (See Performance Waterfall function in Figure 6 for example). This is very important for reporting to stakeholders and assigning responsibilities.
- Benchmarking: meaningfully compare across assets, device types, geographic region, etc. This requires disentangling effects from weather, device performance, O&M service standards, etc.
- Vendor compliance: ability to validate service efficacy, convincing shortfall assignment to avoid ambiguity and prolonged argument. This significantly facilitates contract and warranty administration.
- Administrative efficiency: clear allocation of responsibilities, enable the use of effective incentive schemes to motivate all levels of personnel.
- Opportunity discovery: discover possibilities to improve asset management practices.
- Transaction support: facilitate due diligence by thoroughly assessing asset health condition to mitigate risks.
- Strategic planning: Empower management to answer big questions. E.g. what proportion of loss is due to a certain failure mode and what that means to future projects? Should a certain technology upgrade be pursued for existing assets?

Some advanced players have internal teams of performance analytics engineers to perform these tasks. However, manual analysis of PV system performance requires advanced domain knowledge and data skills, especially with challenges of data quality and design diversity. It is also time consuming. Given that skilled performance engineer is scarce and expensive, software solution is much needed to help keeping the analytics team size small. In addition, it is desirable to have a single system of record to ensure consistency across portfolio. Both scalability and consistency needs can only be satisfied via automation.

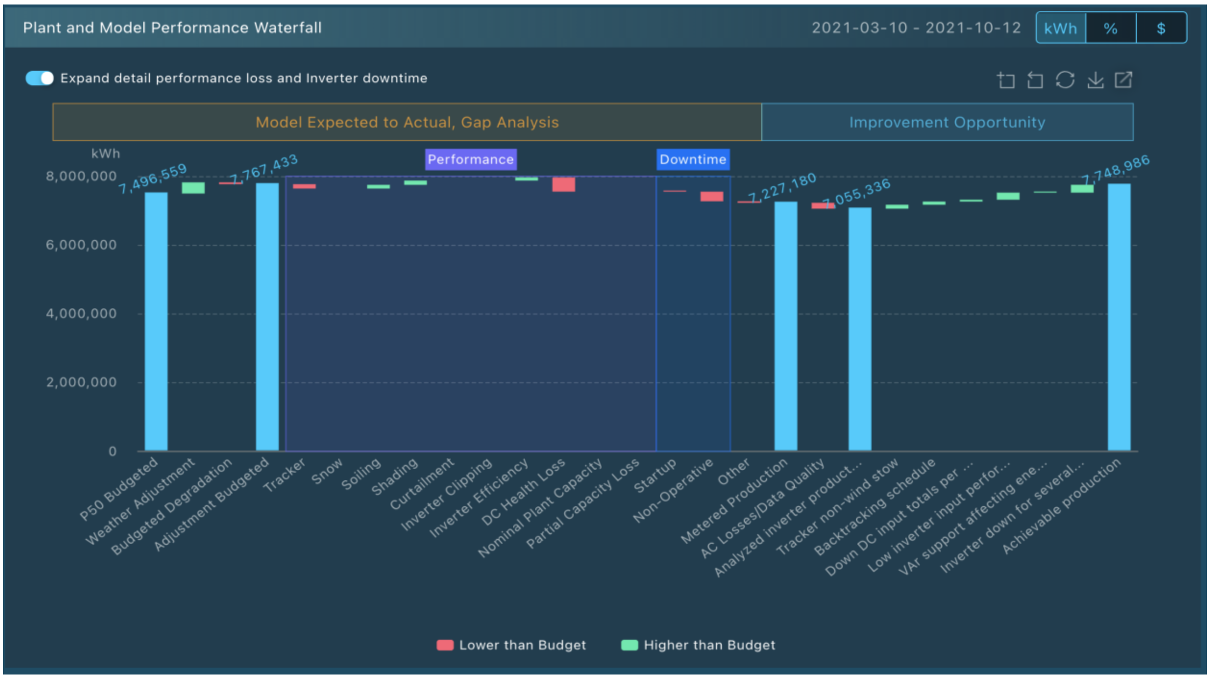


Figure 6. Waterfall breakdown of losses by EnOS Analytics to benchmark against budgeted production and facilitate financial performance tracking.

IV curve scanning

PV modules are made of an assembly of solar cells, which are essentially large-area diodes. When illuminated with light, solar cells can produce power by outputting a certain amount of current at an applied terminal voltage. The current values change with different terminal voltages and can be described by a diode equation. The collection of the possible current-voltage pairs is referred to as an IV curve. An IV curve varies with changes in sunlight (irradiance) and temperature.

IV curves can be obtained for solar cells, modules, and strings by biasing the relevant terminals at different voltages and recording the corresponding currents. This process is known as IV scanning or IV tracing. This is traditionally done by going to the PV field and performing the scan manually with handheld tools called IV tracers. In recent years, many string inverter manufacturers had integrated IV scanning function into their products. IV curves are generated for each maximum power point (MPP) tracking unit by remotely-triggered scanning. This has been a natural addition to the inverter electronics since inverters typically obtain MPPs by measuring currents at different voltage values. The ability of the string inverter to scan the entire voltage range of the strings from short circuit to open circuit allows the inverters to monitor the health of the strings, thus making them even smarter.

Measurements performed using dedicated IV tracers are generally more accurate that inverter-based measurements and provide the flexibility to zoom in to specific areas of a PV string, even down to a single module. However, this manual process is typically time consuming and requires personnel on the field. In contrast, inverter-based IV scanning is much faster and more convenient. Therefore, inverter-based solutions are attracting attention from asset stakeholders.

Why is IV curve scanning useful? This is because IV curves can faithfully reflect the health status, both internal and external, of the DC field of PV strings. A healthy string will show a smooth curve with a signature shape. The short circuit current (Isc) and open-circuit voltage (Voc) should be close to expected from theoretical values. Any impairment or problems in the DC field result in changes in the shape or values, such as the formation of steps, changes in the slopes, or reduction of Isc and Voc, as illustrated in Figure 7. The problems can be internal health issues of devices, caused by degradation, mismatch, cell cracks, or external issues of the operating environment, such as shading and soiling. These issues may or may not be visible in the basic performance monitoring. This is because when PV is in operation, the inverter will bias the voltage at the point that gives the maximum voltage and records only this voltage-current reading. Information about the complete IV response is lost. As a result, the phenomenon behind the scenes is obscured. Especially during the early stages of the problem, the symptoms may be well hidden, and production losses are not at all obvious as the MPP may not get affected as much as other regions in the curve. IV curve scanning, as an advanced diagnosis method, can add back the lost dimension of information, help sniff out health issues early and, in many cases, pinpoint root causes, a task which may sometimes be difficult to achieve by just analyzing performance data or doing a visual inspection.

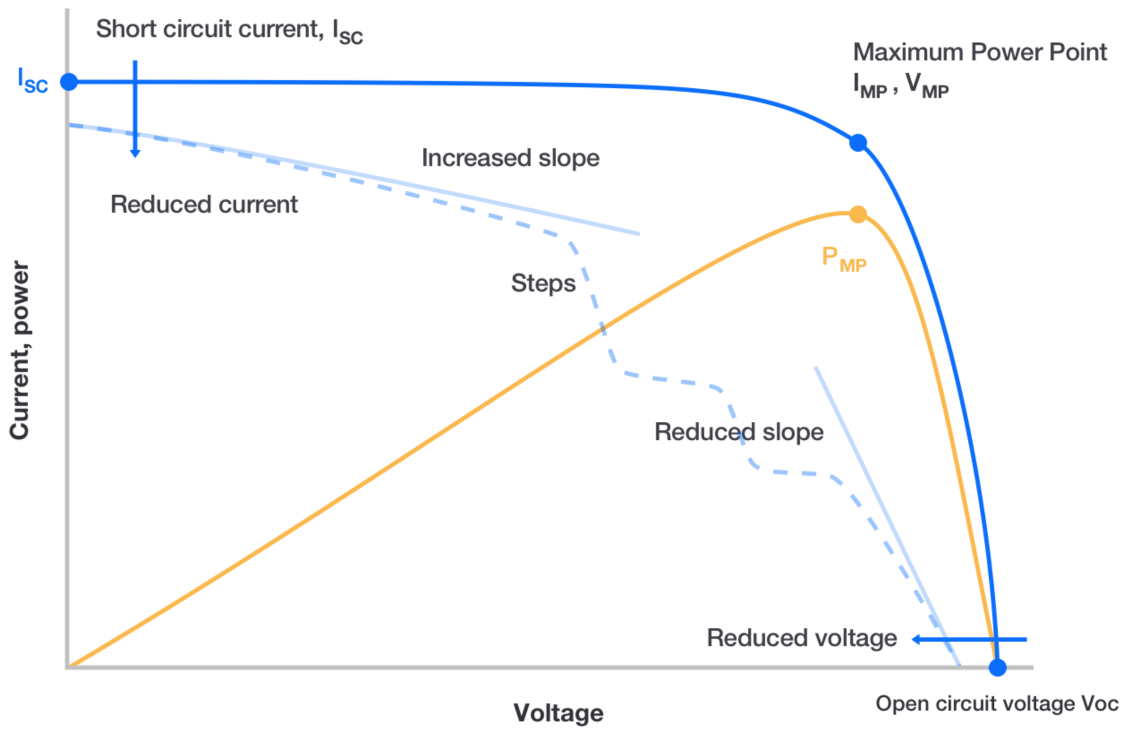


Figure 7. Illustration of the IV curve from a PV string. (Source: PVEducation, Wikipedia)

Therefore, IV curve scanning had been an important exercise for assessing plant condition and during the transaction of solar assets. During O&M, when performance issues are suspected, IV scanning is often used for troubleshooting underperformance. Sometimes, it is also an O&M obligation to perform periodic IV health checks to make sure things are on track (for example, annual health audit assessments).

However, the main drawback of the currently prevalent way of performing IV scanning is cost, due to manual labor and low throughput. This greatly hinders the large-scale adoption of IV scanning as a routine O&M activity. Moreover, in many cases, interpretation of the IV curve remains largely manual work that requires skills and significant domain knowledge. Moving forward, autonomous, intelligent, targeted, and reliable IV curve diagnosis is a must. In the latter chapter, we will see how Envision innovates and leads the way in this endeavor.

Imaging

Imaging can be useful to pinpoint exactly where potential problems may be in a large solar power plant. When accompanied by powerful spatial analytics, imaging adds a new dimension for analysis to help stakeholders better determine ground truth. It helps to answer the question "where?" more precisely compared to time-series analytics. Specifically, infrared (IR) imaging – also known as thermography, has seen widespread use to help maintenance crews pinpoint issues in the field.

Figure 8. Photo showing field personnel taking an IR image of a solar PV array

At the core of IR imaging, cameras with special sensors more sensitive to IR wavelengths are employed to produce images called thermograms, much like how a consumer digital camera produces RGB images of visible wavelength emissions. Because the intensity of IR emissions is directly related to the temperature of the target being measured, thermograms help a viewer quickly identify parts of an image that are at a higher relative temperature compared to others. In the context of solar PV power plants, the elevated temperatures hint at potential problems.

IR imaging itself is not new in the solar O&M toolkit. It is not uncommon for the maintenance crew to bring a handheld IR camera to the field to help identify faulty modules and overheating connectors. What has changed drastically in recent times are a combination of three key developments: (i) the breath-taking growth in the number and sizes of solar power plants being installed worldwide, (ii) the advent of unmanned aerial platforms capable of carrying sophisticated imaging systems, and (iii) advancements in computing power and algorithms able to quickly make sense of large numbers of images.

According to the International Renewable Energy Agency, installed solar PV capacity grew at a compound annual growth rate of 34% between the years 2010 and 2019. At the same time, individual project sizes are also increasing rapidly. Reports from Bloomberg NEF showed that developers set a record in 2019 by commissioning at least 35 projects of at least 200 MW worldwide, up about 17% from the year prior. Data from Wood Mackenzie Power and Renewables also indicate that the tally of projects larger than 120 MW going into service in the US will jump from 11 in 2019 to 32 in 2021. If these trends persist, it will become increasingly difficult for any sort of inspection, IR imaging included, to be conducted by a limited maintenance crew on foot (the scale problem).

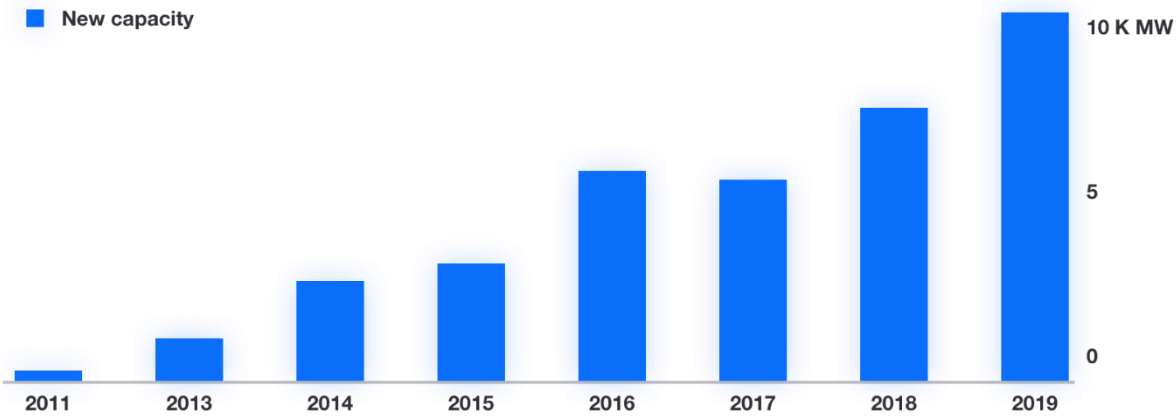


Figure 9. New PV capacity additions contributed by solar PV projects at least 200MW in size (Source: BloombergNEF, 2020)

Fortunately, there have also been significant advancements in unmanned aerial systems (colloquially known as drones) in recent years. Driven by technological innovation from companies like DJI, drones have found widespread commercial use in many sectors ranging from surveying to cinematography. Modern commercial drones are flying sensor platforms, capable of carrying a whole Swiss-army knife's worth of imaging equipment – IR and RGB cameras, laser rangefinders and even LiDAR sensors. In the hands of capable pilots, these drones allow large areas to be imaged within a short period of time, and so open a door for IR imaging to be conducted for solar PV farms at scale, and at a reasonable cost. Rugen Heidbuchel, a product manager at drone analytics company Sitemark, shared that "With improving sensors and image processing, coupled with more power-dense solar PV modules, we can inspect up to 120 MW_p of solar PV assets per day." In comparison, a thermographer would be lucky to image more than a couple of MW_p a day using a handheld IR camera.

Figure 10. A stylized image showing aerial IR imaging conducted by a consumer drone

The last factor that has changed IR imaging for the solar PV industry is the veritable revolution in machine learning algorithms in the past decade, which has enabled the vast quanta of images gathered from the field to be interpreted with little need for human supervision. The same algorithms that help us categorize pictures of cats on the internet and our online shopping can be modified to help automatically detect and classify the various types of defects that show up on an IR image. However, it should also be noted that there are gaps in IR imaging as not all types of solar PV defects readily show up. Defects such as cell cracks and corrosion may not manifest as hotspots and so will not be discernible through IR imaging.

One highly advanced technology that may be able to fill in the gaps in IR imaging is electroluminescence (EL) imaging. EL imaging works by passing an electrical current through a solar PV panel, turning it into a light-emitting diode. The intensity of light given off by different parts of an imaged panel is affected by defects that may be present, and so areas of a solar PV panel that is problematic tend to turn up darker on an EL image. Through this property, various types of defects can be detected. EL imaging is already used extensively in manufacturing plants, where newly minted solar PV panels are imaged to sieve out ones that do not pass quality assurance checks.

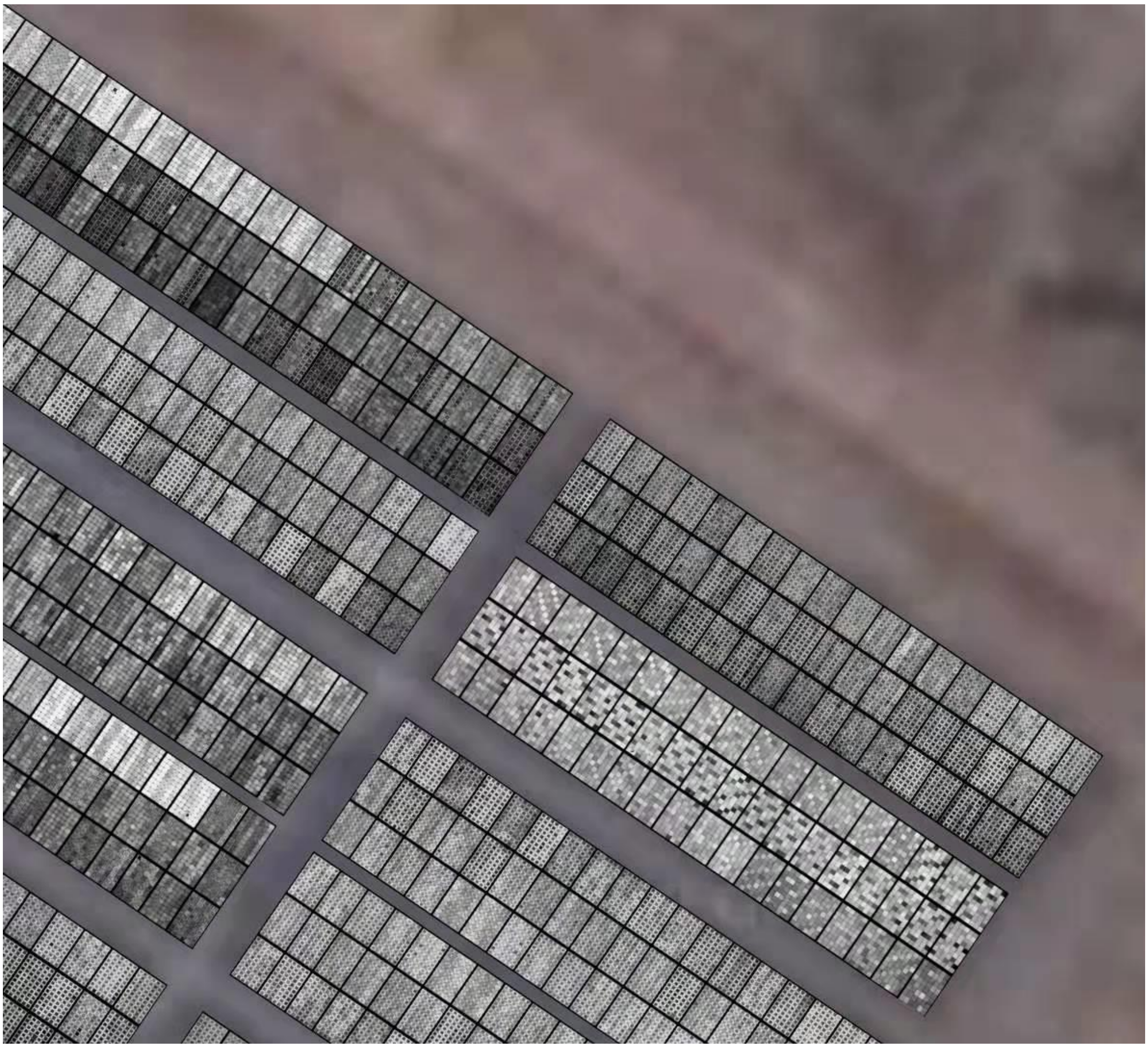


Figure 11. An outdoor drone EL map of a severely degraded 10MW utility-scale PV plant. EL imaging was conducted according to IEC TS 60904-13. The EL imaging served as strong supporting evidence for a warranty claim (Source: QE-Labs real-world EL inspection).

Presently, EL imaging is still not widely used in the field yet. One of the biggest technical hurdles to this is because a power supply needs to be provisioned to inject electrical current into the panels for imaging. If EL imaging is conducted during the day, this power supply can come from another PV string in the array. If the imaging is done at night, however, then another generator will need to be stationed on-site.

Today, there are a few technology start-ups that have begun to venture into conducting field EL imaging. Their success could very well revolutionize how solar PV inspections are done in the future. One such example is Quantified Energy Labs (or QE-Labs), a deep-tech spin-off from the National University of Singapore that offers a semi-autonomous drone-coupled EL inspection service. In an interview with CEO Dr. Wang Yan, he highlighted that “EL imaging rates of 10,000 panels per night can be achieved with a drone now. Aerial EL imaging and processing can be done according to relevant standards, with power loss due to various defects quantified.” As field EL imaging further matures and standards are further codified, we can expect this technology to gain wider adoption in the future and become an integral part of holistic technical asset management for solar PV systems.

2.3 When to use what: a technical deep dive

To better understand the differences and synergies among the different techniques, it is necessary to understand the solid technical details a bit better. It is not true that one technique is necessarily better or simply more advanced than the other. Which is a more suitable choice depends on the problem at hand, the goals that one wishes to achieve, how best one can extract insights from a given method, as well as the resources available.

IV curve scanning

Conventional time-series monitoring can reveal some types of DC health-related issues, as they manifest as distinctive patterns in the data across time. However, other issues are notably harder to resolve. For example, strings with minor current mismatches can be difficult to pick up without access to long-term time-series data. However, IV-curve analysis will be able to identify this problem more readily.

To further elaborate, Table 1 below lists issues that can be uncovered using IV scanning, based on claims from a leading inverter manufacturer (with some trivial items removed). The middle column describes if and how performance analytics based on time-series data can achieve the same task.

Table 1. Comparison between time-series monitoring and IV curve scanning capabilities using the list of IV-uncoverable issues from a leading inverter manufacturer.

SN	Failure types detectable by IV curve scanning	Time-series monitoring capability	Remarks
1	Open circuit of string	Yes.	Downtime or open circuit of a string is easy to detect as power is zero and voltage is at open-circuit voltage.
2	Current mismatch in string	Limited. Can detect low-performance string.	Mismatch within a string may lead to a string having low performance, which is then picked up by performance monitoring.
3	String with a minor current mismatch (Dust/slight shade/glass breakage)	No, except for dust accumulation.	A minor mismatch is hard to detect since performance losses are often drowned out by noise. However, consistent long-term trends such as dust accumulation can be quantified using statistical or machine learning methods.
4	Abnormal module current output (shadow, Glass breakage, hidden cracks)	Partially. Can detect shading or consistently low current.	Currents may be lower than expected due to a variety of reasons such as shading, soiling, mismatch, cracks, or simply inaccurate irradiance measurement.

5	Extremely low current output by module/cell (panel cover-up / cell damage)	Yes.	Extremely low current or power output is obvious from data.
6	Low string short circuit current (Note: for this IV scanning needs reliable irradiance measurement as input.)	No.	In a strict sense, time-series monitoring only captures MPP current, without exact knowledge about I_{sc}.
7	Diode fault (diode short circuit / Bracing breakage)	No.	Time-series monitoring cannot pick up quantum drops in V_{oc} resulting from diodes being shorted but will be able to notice low string voltage, see below.
8	Low string voltage	Yes.	Voltage health can be actively tracked to reveal a variety of problems if string level monitoring is available.
9	Panel with hidden cell cracks	No.	Major cracks can be picked up by IV scanning, but hidden cracks can hardly be detected either.
10	String with high series resistance / low parallel resistance	Limited. Can detect low-performance string.	Resistance issues will lower MPP current or voltage or both, dragging down string performance. This may be vaguely detectable by big data analytics on long-term patterns.
11	Abnormal curve near MPP in the PV string (Hotspot/hidden crack/glass breakage)	No.	Note: abnormal pattern near MPP may simply be due to mismatches
12	High decay speed of string	Yes.	Degradation trends are better revealed from time-series data via degradation analysis instead of IV scanning.
13	Risk of PID	Partially (via degradation analysis)	Note: IV scanning cannot confirm degradation is due to PID either due to lack of info from low irradiance.

Overall, IV scanning can diagnose DC related issues more definitively. However, there are some limitations to inverter IV scanning nowadays that makes it less versatile compared to time series monitoring and analytics:

- For fault type categorization that makes use of information of current levels, diagnosis cannot be accurate without appropriate and highly synchronized irradiance measurement. This can be hard to come by for larger farms which shares irradiance sensors.

- IV scanning usually needs a high irradiance level (typically above 600 W/m^2) under clear sky conditions. This misses a large portion of possible operating environment space that a PV system sees, and thus fails to capture device response under those conditions. This is undesirable for example in the case of PID, as its effect manifests more strongly under low irradiance than high irradiance. From time-series data, on the contrary, it may be possible to infer insights from the divergence of behavior under different conditions.

- IV scan needs to be triggered manually. This implies a manual decision process, which may not capture the best time and condition to do the scanning.

There is yet another factor that favors time-series analytics. Although one reading at a single timestamp is feeble at telling what exactly is going on, when readings across time are connected, they might reveal interesting stories. For example, PV system voltage is relatively smooth and consistent under normal conditions, only varying slowly with temperature. But when a PV system is afflicted with vegetation overgrowth issues, its voltage tends to be lower and jump around excessively, effectively depicting a wiggly IV curve.

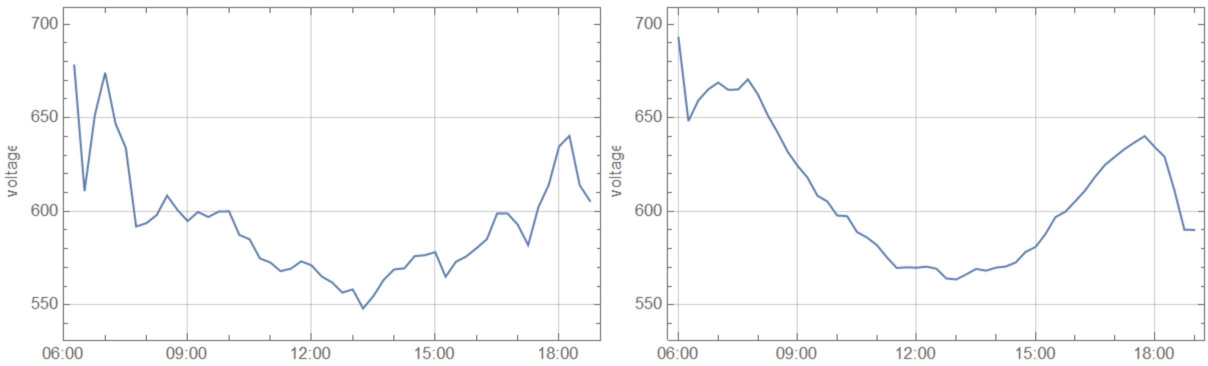


Figure 12. Reading of MPPT voltage in a particularly clear day for a PV system affected by vegetation shading (left), and that of the same system on another day after grass cutting (right). The level of fluctuation is a clear indication of changing shadows throughout the day.

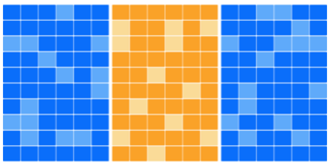
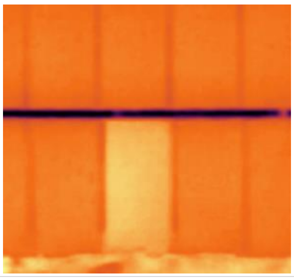
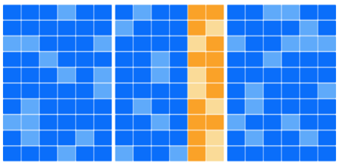
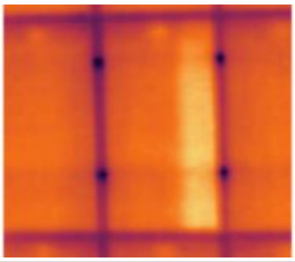
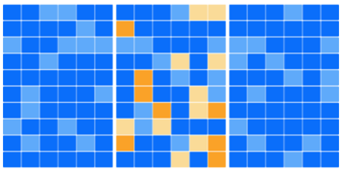
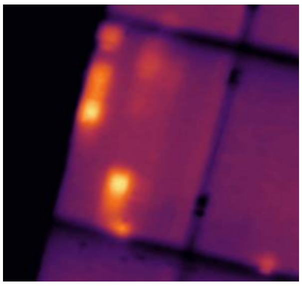
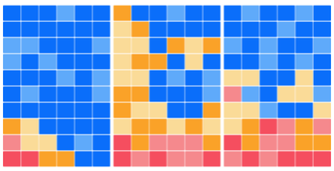
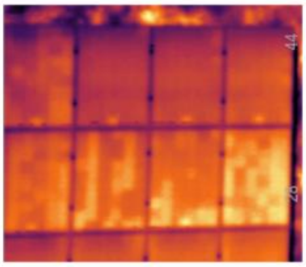
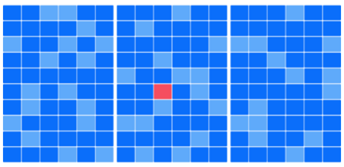
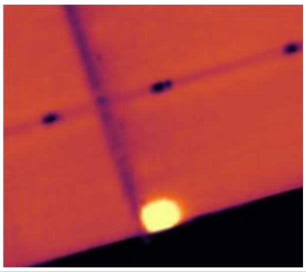
In a nutshell, time-series-based performance analytics can identify many types of issues encountered by solar PV power plants in the field, but IV curve scanning can help to narrow down possible root causes much better, especially electrical issues directly related to PV modules. For example, when time-series data shows that operating current is slightly low, it can still be hard to tell whether the root cause is due to consistent shading/mismatch, or due to dust / EVA browning. On the other hand, IV curve scanning would be able to make this distinction more easily since the latter will result in lower Isc but not steps in the curve. Furthermore, maximum benefit is reaped not via using any one method alone, but when they are used to reinforce one another (see section 3.2).

Imaging

While examining time-series data can reveal a treasure trove of information about a PV system, sometimes it is simply more effective to make a direct observation through imaging. For example, short-circuits, soldering issues and activated bypass diodes all exhibit clear patterns in an IR image. However, these defects can be rather difficult to spot just by looking at time-series or even IV data. Additional factors such as heavy soiling, washing and cloudy days do get mixed in with the signal, and these can be complicated to tease apart.

Different PV defects exhibit distinct patterns on an IR image. It is these distinctive patterns that defects exhibit which allow pattern recognition algorithms to identify and classify them automatically. Table 2 below shows a few examples of common defects that can be seen. Compared to other techniques, IR imaging is relatively powerful in its capability to detect localized defects, which is extremely useful should the exact location of a defect be needed. This capability is useful to minimize the truck-roll costs accrued by service personnel in the field.

Table 2. Common patterns that appear in IR images, a description of the pattern and the likely associated type of fault. (Source: Adapted from IEA-PVPS T13-01 2014 and Sitemark)

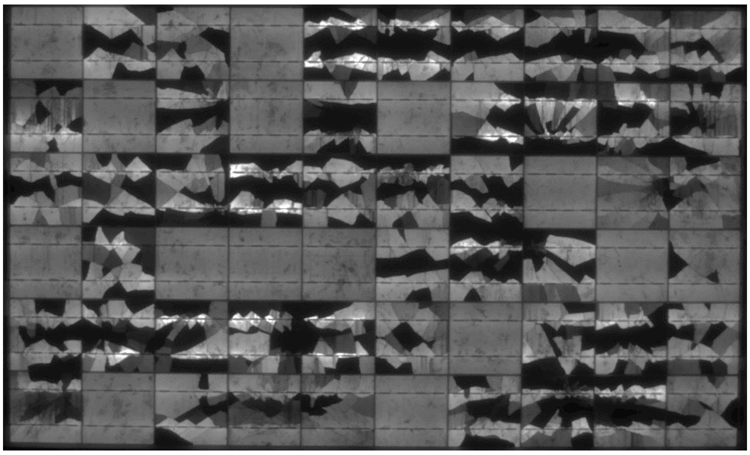
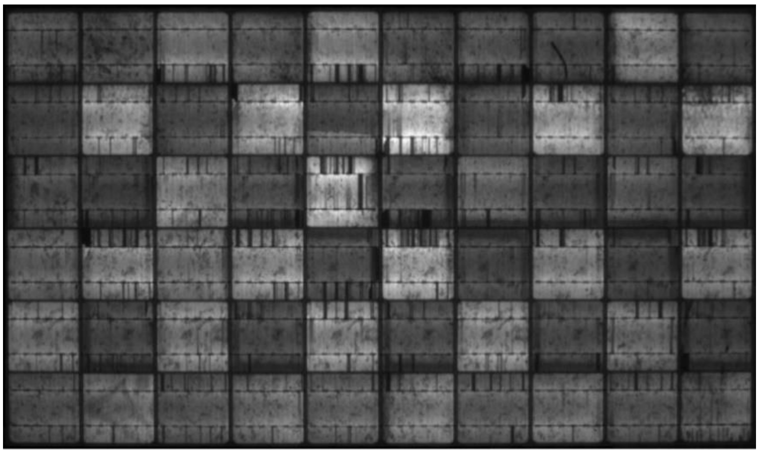
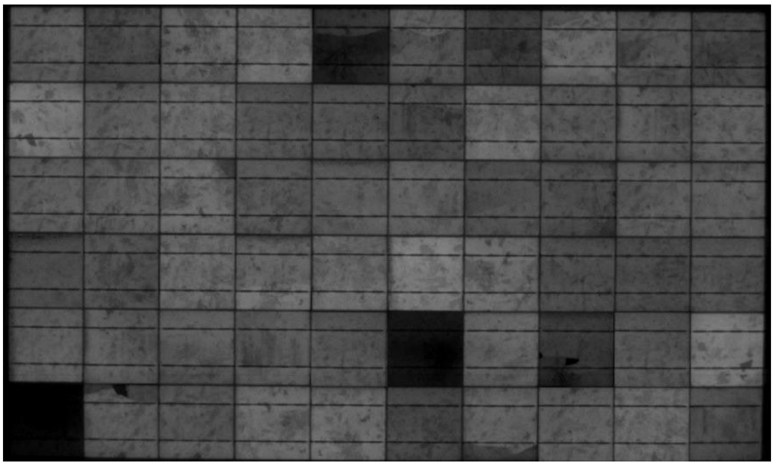
Pattern	Real example	Possible reason(s)
		A disconnected cable, damaged or burnt welding point
		Damaged bypass diode or physically disconnected sub-string
		Damaged sub-string bypass diode
		Massive shunts caused by potential induced degradation (PID)
		Spot soiling (e.g. bird droppings), shadowing (e.g. from vegetation, electrical poles) or physical defects (e.g. delamination)

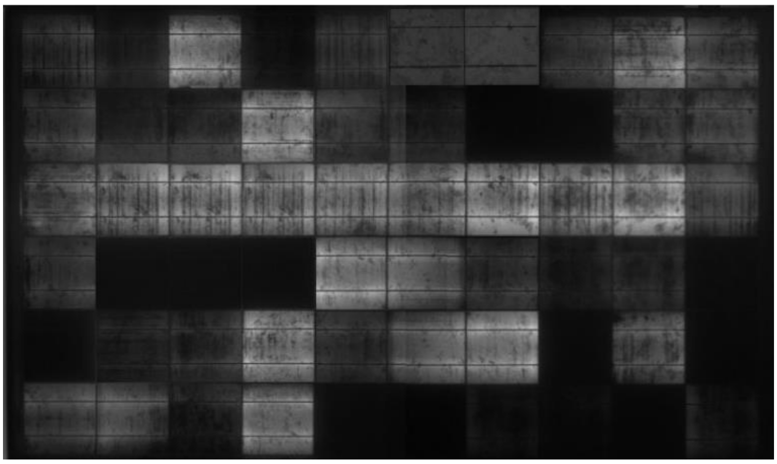
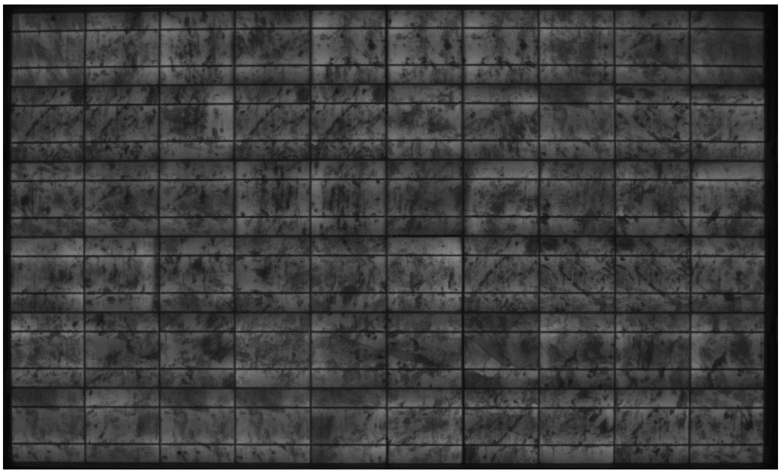
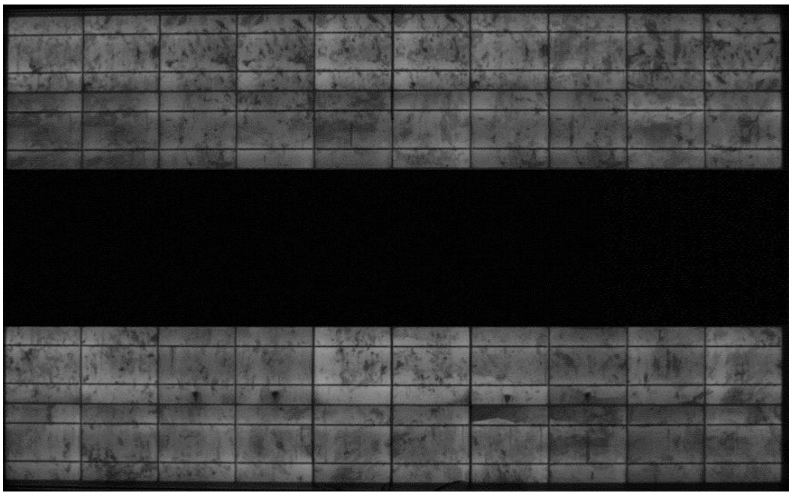
However, just like other forms of analytics, spatial analysis of IR images has its limitations. IR thermography works because defects in a PV array often lead to localized temperature differences (e.g. hotpots), which can be picked up. However, not every type of problem results in noticeable temperature changes, and so not every defect can be detected. For example, mild soiling that blankets an entire site can be difficult to pick up, even though time-series analysis should be able to identify a trend over a long enough period. There is also a trade-off between the imaging throughput and the granularity of defects that can be picked up. Imaging close-ups can resolve smaller defects, but this slows down the rate at which inspections can be carried out.

In addition to technical limitations, certain environmental conditions must be met in the field for IR images to be properly captured. For one, the IEC TS 62446-3:2017 standard recommends that irradiance conditions must be stable and high enough, ideally greater than 600 W/m^2, with less than 2 oktas of cloud coverage and less than 10% change in environmental conditions throughout the imaging exercise. If a drone is used, wind speeds should be lower than 28 km/h so that the drone can be stable in the air. Lastly, of course, IR imaging cannot be carried out at night without providing a power source for the PV strings. These conditions are not specific to IR imaging itself but should nonetheless be noted.

While thermography can locate cell-level defects in a solar PV module based on localized temperature differences, EL techniques are capable of resolving and directly imaging these defects. For example, cell cracks appear as dark lines on an EL-imaged solar cell, and non-generating sections of a solar cell appear completely dark. Table 3 below provides a non-exhaustive list of PV failure modes that EL imaging can help identify. In addition, EL imaging can also quantify power loss arising from these defects, which potentially makes it a powerful specialist tool to have in the TAM toolbox.

Table 3. Common patterns that appear in EL images and a corresponding description of the likely fault. (Source: Adapted with modifications from Forschungszentrum Jülich's EL Dataset of PV modules v1.4 and other public sources)

Pattern	Description
	Cell cracks
	Disconnected fingers on individual cells
	Disconnected and poorly connected cells

	Severe Potential Induced Degradation
	Cracked cells with repeating patterns possibly caused by manufacturing faults
	Shorted bypass diode

While EL imaging is powerful, it is still relatively more expensive to deploy than IR imaging for routine full-site inspection. Hence, it is instead better mobilized to inspect targeted areas where defective areas are suspected to exist. Nonetheless, complete EL inspection can still be useful at certain milestones across a solar PV plant's 25-year lifetime to discover problems that may affect the optimal operation of the plant. These milestones include:

1. Initial site acceptance test (SAT) after the completion of system construction
2. Final acceptance test just before the expiration of the defect liability period (DLP)
3. Preventive maintenance at the 5th year
4. Preventive maintenance before the end of product warranty provided by the module manufacturer

Moreover, great strides are being made in the fields of both IR and EL imaging today. Compared to just half a decade ago, imaging can now be carried out much more efficiently through employing better sensors and algorithms. For one, Sitemark is launching EL imaging services and also expects greater adoption in the industry. It's product manager Rugen Heidbuchel comments that "EL will play a major role in the future of asset management and O&M of the PV industry. Module owners will get similar results through their own means, on-site, which before was only acquired by sending the panel to a laboratory."

Optimize the use of resources

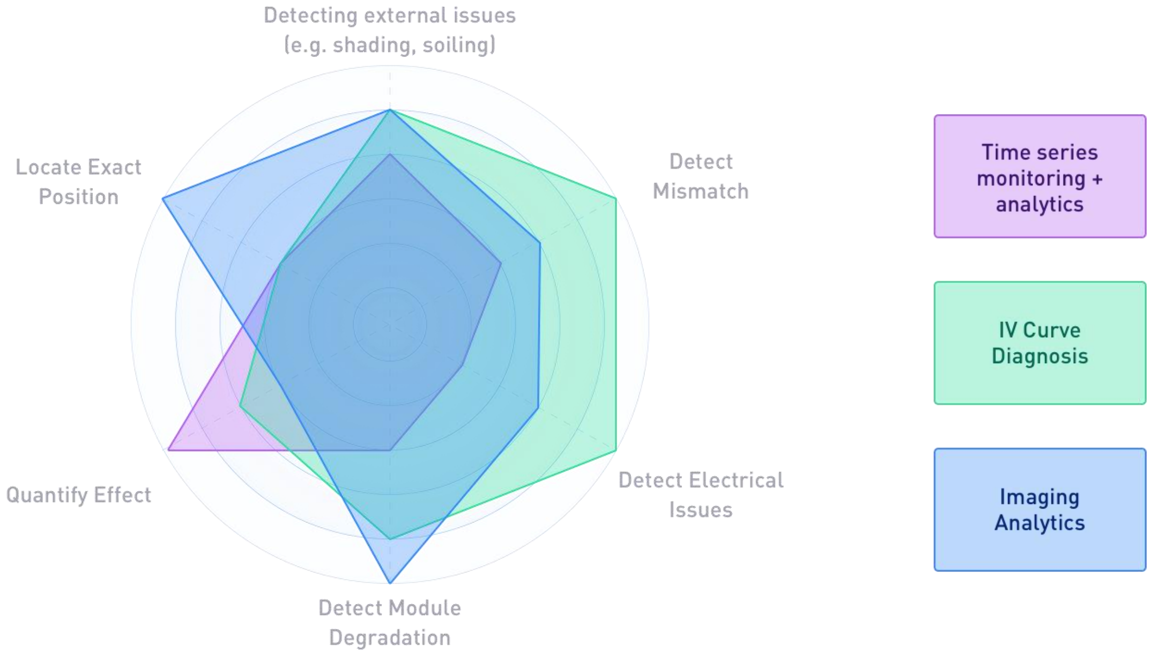


Figure 13. Comparing strengths of different techniques.

In summary, after examining the most important technologies in performing TAM, we can depict their relative strengths in Figure 13. IV curves and images offer more visibility into DC health in a direct manner. Together with performance data, they complement each other to form a complete coverage of DC health monitoring. However, asset managers and operators are often concerned about whether it is worthwhile to do it. Traditionally, despite the importance of O&M, it is usually the piece that is allocated very little budget for. Unless there is always an O&M team stationed at the site, who are adequately trained to perform these tasks, engaging external services or dispatching field personnel may incur significant expenses, which may be hard to justify in some cases. Of course, things also depend on the availability of solutions, e.g., how easy it is to claim a warranty for low-performing modules after they are identified.

Why dig into the root causes in such detail? Does it change the course of action? How much yield increase can be expected as a result? It is not always easy to answer these questions without an adequate understanding of the current system performance level and the costs associated with each possible action.

Hence**, it is always good to start with performance data analytics**. Since monitoring has become a standard solution for most solar assets with decent size, analytics is naturally the next step. With simple analytics, one can already identify where low-performance strings are. With more advanced analytics, it will even be able to suggest what potential issues are, their impact on the revenue, the corresponding corrective actions. Diagnosis does not stop here. If remote IV scanning or field personnel is available for a quick IR gun scan, the information gathered would tremendously help decision making and the arrangement of a more targeted field inspection or intervention. Sometimes, depending on the confidence level required, more inspections such as larger-scale IR/EL imaging, or even lab testing of selected modules may be needed, for instance, to form compelling evidence for warranty claims.

The ideal diagnosis path is illustrated in Figure 14. For all cases, analytics plays an important role in advising the next step, including whether it is better to go with IV scanning or imaging.

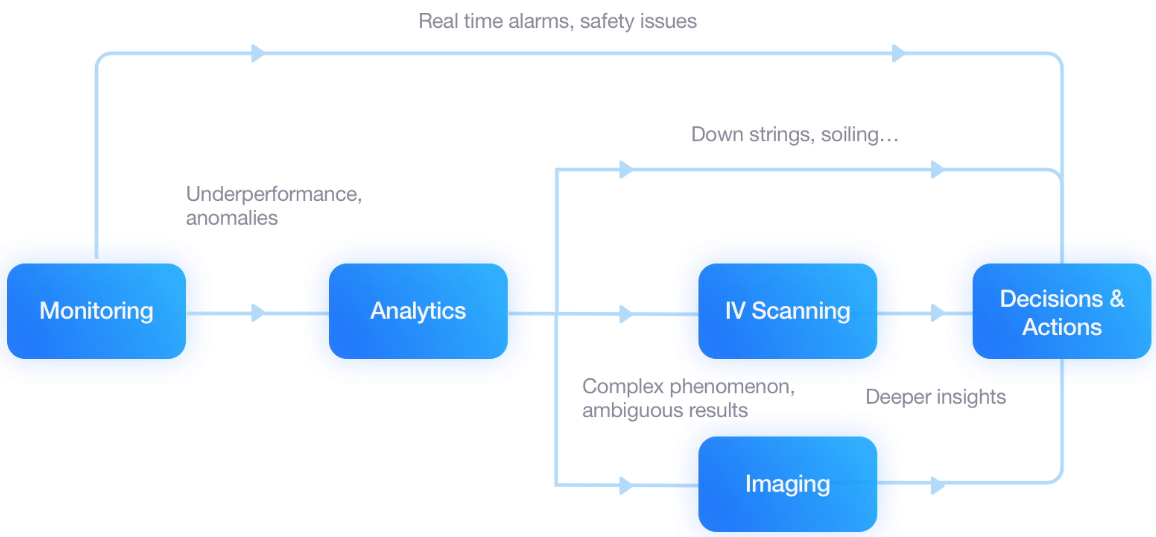


Figure 14. A typical path for discovering and diagnosing issues.

When a performance issue is suspected, asset managers and operators need to weigh potential gains against the cost associated with intervention activities to optimize resource use**.** Remote IV scanning comes with inverters, but inverter manufacturers may charge a license fee to activate this feature. Onsite IV scanning involves manual labor and has low throughput. Imaging costs vary. IR imaging using plane flyover or drones has higher throughput and thus lower unit cost, while EL imaging is more troublesome. The economics also depends on the availability of drone operators and vendor coverage. There is no fixed best solution.

This complexity highlights the necessity to have a well-designed TAM framework and streamlined workflow with good tools capable of quantification. It is usually more cost-effective than engaging ad hoc services when performance issues arise. This is not about invoking advanced techniques each time, but about having these options available, and a good process for judging what is needed and when it is needed.

Value of sophistication

Often, it may be tempting to resort to having only monitoring and jump straight to action when a low performance is observed. The assumption is that knowing better does not change the outcome, which is either fieldwork of cleaning or replacement of underperforming components. However, this will not be adequate anymore in the future due to the following reasons:

> **First, this process is susceptible to poor human judgment.** Often, field inspection turns out to be time-consuming and yet inconclusive, like a military operation without proper reconnaissance. This is because doing troubleshooting and judgment-making concurrently on-site is inefficient. Testing individual strings/equipment takes time, so is inverter log download and fault code inspection.

Furthermore, most field inspections are only done visually, and observations are difficult to relate quantitatively to performance data. Advanced analytics, on the other hand, helps to formulate strategies and plans beforehand for a more targeted and efficient operation. Applications like EnOS Analytics can also estimate potential gains from corrective actions to facilitate cost-benefit analysis to decide whether field action is worthwhile.

1. Manually keep track of daily site KPIs to identify drops in production.
2. Combs through inverter production data to identify underperforming inverter(s)
3. Travel down to site to inspect and test strings individually to find problematic string or fault locations
4. Investigations may sometimes yield ambiguous results, and no concrete actionable items. In some cases, not all underperformance issues are discovered, so rectification becomes a long drawn process.

Traditional methods...

With advanced Digital Solutions...

Advanced analytics enables more efficient operations

John is an O&M team lead who oversees the operation of a large portfolio in the region. Many of his sites are remote and unmanned, so historically large amount of time is required to attend to individual sites, notably from transportation and troubleshooting.

One day, John finds a plant with lower production than expected...

1. Receives automated alerts on both faults and underperformance
2. Easily identifies underperforming string from digital analytics, with the software automatically ruling out data quality issues, seasonal shading, clipping/curtailment, and other non-actionable issues.
3. With advanced analytics and access to rich historical data, John is able to rule out inverter efficiency, capacity issues, and module degradation, instead focusing his attention on soiling, vegetation shading or acute DC health issues. Further AI driven analysis suggests vegetation growth as the most likely cause, based on voltage anomaly patterns.
4. For greater confidence, John triggers a remote IV scan. Finally, he looks at the economic evaluation and confirms the rectifiable loss amount justifies a site visit.
5. With a deep understanding of the issues at hand, John is able to plan his site visit with a high degree of preparedness. Equipped with the right tools and information, his team completes the inspection and correction work quickly, saving time for attending to other sites.

Second, this does not solve the *scale-manpower conflict*. Taking the best actions involves skilled judgment and decision-making. For this to be consistently reliable, the day-to-day operator must be somehow aided with the best information and recommendation. In addition, more intermediate steps must be "externalized": delegating specific judgment to a specialized external agent who has condensed rich experiences related to that specific task. AI diagnosis of IV curve and expert report on thermal images are good examples.

Third, sub-optimal actions systematically incur a higher cost, which is highly undesirable for large asset owners. To guarantee TAM service level, asset owners not only need to spend effort building a competent team but also diligently track its performance, which itself requires technical competency. Even so, quality control is hard since things may not be standardized.

A simple analogy is healthcare. A highly skilled guru may be counted on to prescribe correct medication based on very simple observations on patients' symptoms, but this is not practical for a large-scale healthcare system. Instead, the modern public health system relies on highly industrialized processes. Health screening or self-monitoring forms the basis. If something seems wrong, the potential patient goes to a generalist doctor, who may then direct the patient to do more specialized tests like X-ray, computed tomography (CT), or electro-cardiography (ECG). The patient comes back with various reports. With better information, the doctor arrives at a judgment relatively quickly, without pondering or following up on the case for too long. The beauty of it is that no doctor involved along the steps needs to be a grandmaster of everything for the system to run robustly. Many specialists handle only specific areas of the body and the interface among them is so standardized that they can work together almost instantly without much hiccup. Nowadays, doctors are starting to use artificial intelligence (AI) too, which is even more specialized in specific tasks.

In the case of solar, remote monitoring forms the basis just like health screening. The asset manager/operator is the doctor, who looks at data (symptoms), loss breakdown (X-ray), IV diagnosis (ECG), and IR/EL images (CT scan), to arrive at a decision (prescription). Without the streamlined process and the various steps "externalized" from the doctor, he/she would not be so efficient in treating many patients. The quality control of the doctor cohort would not be as reliable either. Similarly, asset owners would not need to worry about changing teams (whether in-house or outsourced) giving drastically different TAM service levels when a good system is in place.

Therefore, the most cost-effective path for large asset owners is not to simply lower costs by not investing in advanced techniques, but rather to set up a good system that embraces those solutions in an optimum way. When done right, sophistication will lead to value maximization with little additional input.

3. A new-era holistic solution for TAM

In previously chapters, we explored some relevant technologies and practices for performing TAM. It is then important to find out how to bring them together. As TAM and O&M constantly evolve to meet the demand of rapidly growing solar deployment, the solar team in Envision is always working hard to design and shape our solutions to best capture clients' needs ahead of time.

In our view, new-era TAM should meet the following criteria:

Asset-centric
As markets and regulations mature, the business side of things will be tidied up. More effort will be placed on optimizing the performance of assets, which is the most valuable part.

Advanced
There will be increased use of advanced technologies and algorithms in cost-effective ways.

Automated
Achieve maximum degree of automation including automated administrative processes and adoption of AI to perform technical jobs.

Adaptable
Comfortably deal with diverse types of solar assets while still optimized for large portfolio management. Easily adaptable to different administrative practices.

Streamlined
There should be a minimal manual effort to keep patching processes together, by having the maximum number of steps standardized and delegated to automation.

Versatile
TAM framework is easy to expand in response to the future development of VPP, smart grid, and hybrid power plants. Assets must still be operated in the optimal way to maximize performance and at the same time capture additional value streams.

To empower asset managers and operators to achieve excellence in TAM mentioned above, it is necessary to have a good platform to digitalize the various workflows, be it monitoring, IV scanning, or drone inspections. The digital solution needs to be **holistic**, which means the following:

- Complete knowledge about electrical generation units with a 360-degree view
- Unification of info sources in a centralized manner
- Close looped lifecycle management
- Best use of advanced technologies
- Hardware and technology agnostic
- Adaptable to different practices
- Covers performance, safety, and economic aspects
- Seamless integration with business processes

3.1 Multi-source data for asset health record

One key element to enable complete understanding and lifecycle management of assets is the ability to centrally curate and make use of asset-related data from heterogeneous sources. We can think of it as the health record for the asset. Just like the medical field, where health records can include many types of data from bio information to diagnosis reports and medication history, the concept of the asset health record is general. For a complete health profiling, the asset health record can include all the relevant information pertaining to the PV unit (Figure 15).

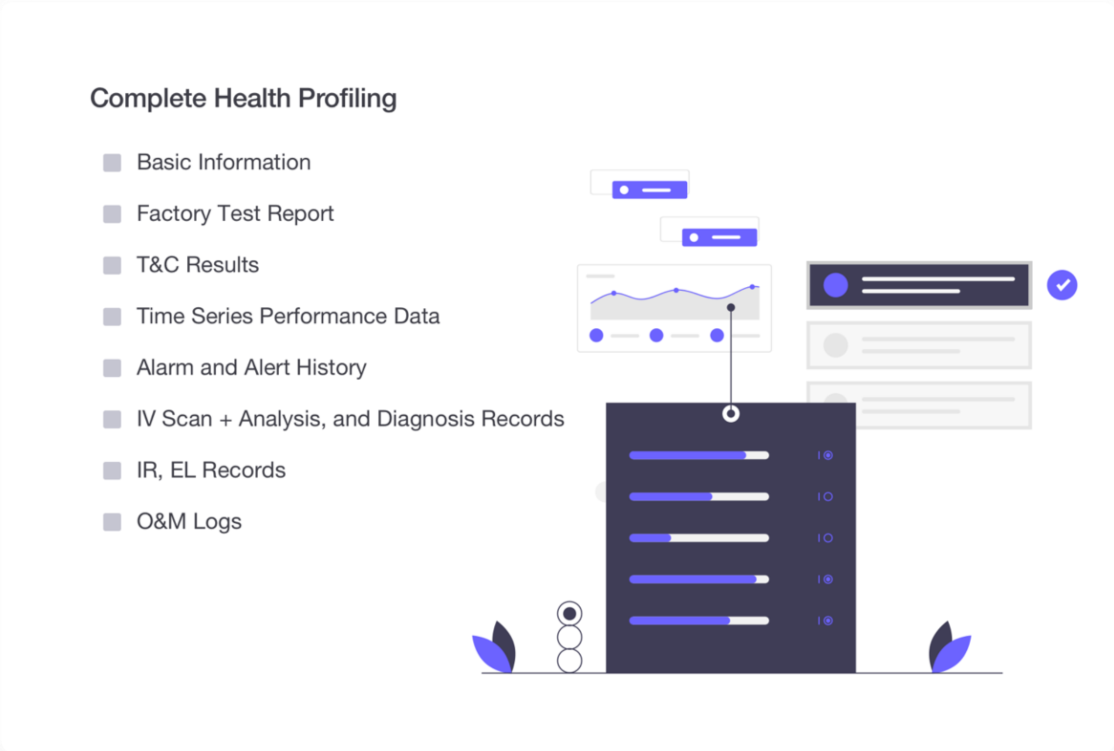


Figure 15. The concept of asset health records for complete health profiling.

Mere collection of this information and have them conveniently ready when needed is just the first step. It is desirable to actively correlate data points and extract insights, preferably in an automated way. Below are just a few examples:

- Factory tests and Testing and Commissioning (T&C) reports are useful in establishing asset baseline at its pristine condition and can be used to benchmark against when analyzing performance level.
- Alarm history and O&M records, coupled with performance data, may be useful for evaluating maintenance techniques and device characteristics, forming the basis of predictive maintenance, which helps to ensure safe operation.
- Time-series performance data, IV curves, and IR/EL images can be used to corroborate each other and refine diagnostic accuracy.

In the next section, we illustrate with a concrete example how the last point can be achieved automatically with Envision's IV curve diagnostic solution.

3.2 Advanced IV curve diagnostic

One good example to illustrate the holistic approach is the advanced IV curve solution recently being developed by Envision.

IV curve data can be obtained mainly in three ways: manual scan using IV tracer, remote scan using inverters equipped with IV scanning function, or (much less commonly) by approximately tracing out operation points by ramping down power using automatic generation control (AGC). Currently, IV curve scanning data is not actively managed by monitoring platforms. It is usually consumed on the spot as a form of evidence by O&M personnel to facilitate troubleshooting and then discarded or shelved. For asset managers, this approach has a few obvious drawbacks:

- The information is fragmented. IV curve and historical production data are not curated coherently.
- As a result, the technical evaluation step is a largely manual effort. Users need to manage and piece together patches of information to understand what they are seeing.
- The existing auto diagnosis provided by inverters is quite rudimentary. The results often lack precision and adequate actionable insights.
- The entire process is hardly automated and streamlined in a digitalized manner. There are gaps between IV data acquisition, data management, analysis, decision making, and follow-up actions.

To address these shortcomings, the various stages should be better connected, giving an end-to-end IV solution. This is what Envision's digital platform aims to do.

Different modes of data acquisition are supported to suit different practices. Manually collected IV data can be labelled and uploaded using an upload tool. The record is then attached to the corresponding digital twin, which is implemented as a device instance on the AIoT operating system (EnOS^{TM}). In this way, the records are properly curated together with the device's other information and historical data. Alternatively, the user can use the inverter's platform to trigger a scan, and EnOS then uses a cloud-to-cloud data ingestion service to take in the IV data. The best way, which is fully automated, is to use an EnOS connected edge device to control inverters and read off the scanned data. The scan can be triggered from EnOS without switching to another platform.

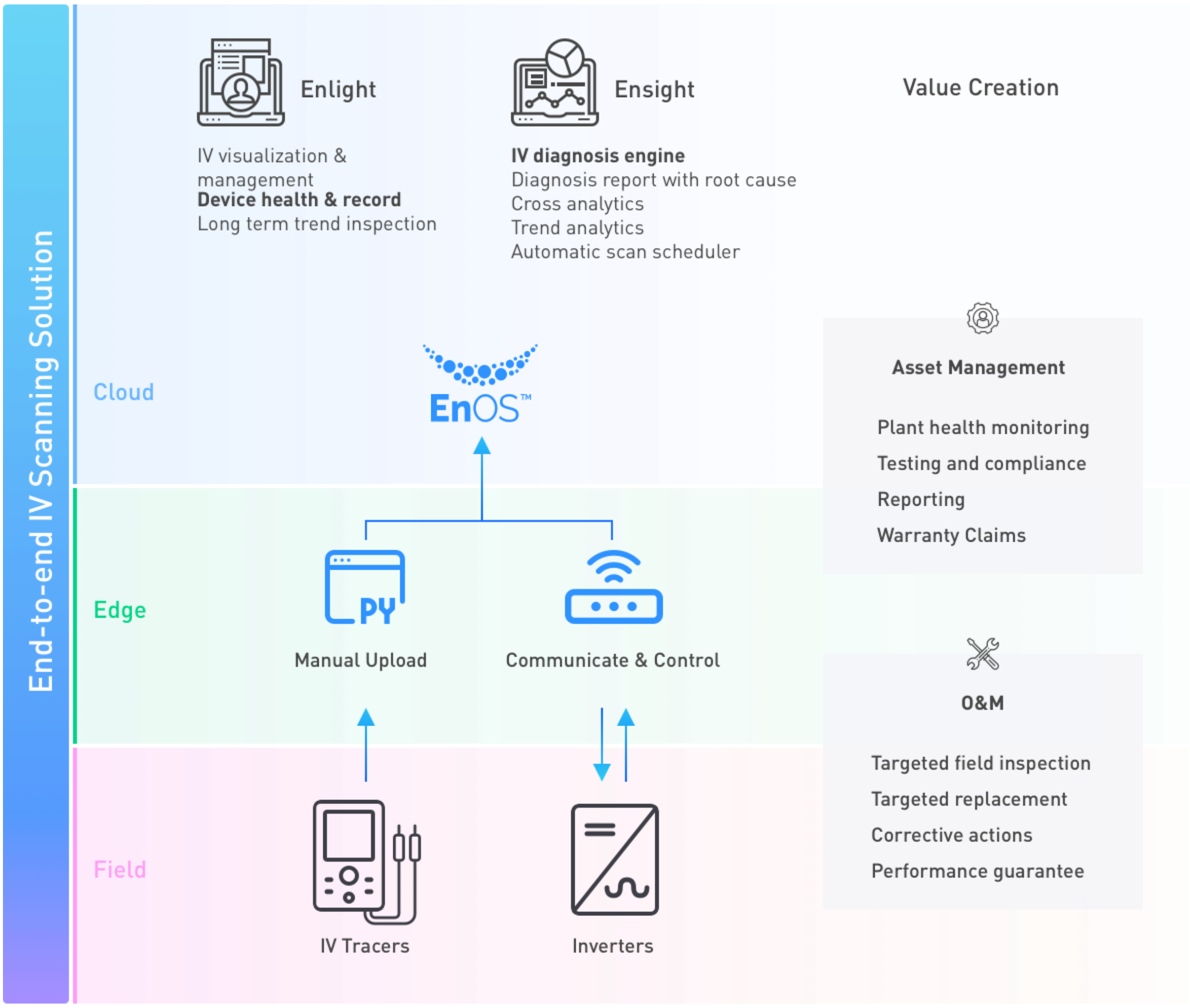


Figure 16. The architecture of Envision's IV curve diagnosis solution.

The IV curves can be visualized, managed, compared, reported, and used for long-term trend inspection, alongside other performance data. More importantly, they can be passed into an advanced IV diagnosis engine for evaluation. Root causes are identified if there is a performance issue. All these insights can be conveniently consumed in downstream tasks such as targeted field inspection, replacement, cleaning, or warranty claims.

In addition to the unification and centralization of asset health data, it is important to highlight the essential role of an automatic IV diagnosis engine. It is one thing to provide rudimentary IV classification as guidance for users and a different thing to give refined and accurate diagnosis results with clear reasoning. The latter is only possible with deep domain knowledge, a huge volume of data, and the ability to correlate snapshots of IV curve and context from historical performance data. This is a unique capability of a full-fledged, mature TAM platform.

Based on deep knowledge of PV system behavior and rich experience with field phenomena, Envision's IV diagnosis engine greatly expands the list of detectable issues, a truly groundbreaking innovation that is not yet seen from any competitors in the industry. The rich diversity of problems that can be distinguished from IV characteristics are explained below in Table 4. For the shading scenario alone, the engine can discern the more innocuous type of shading from different subcategories such as vegetation overgrowth. Uneven soiling, snow cover, and mismatch issues can also be picked up. Most importantly, health issues related to panels and strings themselves are identified, hence giving timely warnings. These include resistance issues, electrical leakage, diode faults, cell cracks, certain types of hot spots, and degradation.

Table 4. Category of issues that can be discovered by IV curve scanning.

Category	Sub-category	Description
Shading	Local slight shading	A small fraction of string shaded. The shade amount is low. Possible causes: Trees, nearby objects, inter-row shade (under diffuse irradiance) IV curve symptoms: Knees (steps) near MPP.
	Widespread slight shading	A large fraction of string shaded. The shade amount is low. Possible causes: Trees, vegetation, thin objects, inter-row shade IV curve symptoms: Knees (steps) near Isc, or increased slope for the horizontal section.
	Local near shading	A small fraction of string shaded. The shaded part has very low irradiance (direct sunlight blocked). The shading amount has a little variation (clean cut). Possible causes: Building, nearby objects/structures, inter-row shade IV curve symptoms: Clear Knees (steps) near Voc.
	Widespread near shading	A large fraction of string is shaded. The shaded part has very low irradiance. The shading amount has a little variation (clean cut). Possible causes: Trees, buildings, inter-row shade IV curve symptoms: Clear knees (steps) in the middle part.
	Distributed/irregular shades	Small to a large fraction of string shaded. The shade amount varies significantly. Possible causes: Trees, vegetation, fence IV curve symptoms: Many small and irregular knees (steps).

Surface coverage	Bird dropping / leaves / debris	Small to a large fraction of string soiled. The soiling amount varies significantly. IV curve symptoms: Many small and irregular knees (steps).
	Melting snow	Some modules may be covered extensively while others are clear. Coverage may not be uniform. IV curve symptoms: Several irregular knees (steps).
	Inhomogeneous soiling	Soiling on module surface is not uniform, sometimes with a gradient along a certain direction. Usually affects a large portion of PV string. IV curve symptoms: Knees (steps) near Isc, or increased slope for the horizontal section.
	Bottom row soiling/dirt dam	Regular soiling affects only a small fraction of modules. IV curve symptoms: Knees (steps) near Isc, increased slope for the horizontal section, or sometimes very pointy knee at MPP.
Electrical issues	Excessive series resistance	Large parasitic series resistance dissipates heat and reduces useful output power. Possible causes: Connector/wiring issue, solder-bond/ribbon failure, undersized conductor, moisture ingress in the junction box, corrosion. IV curve symptoms: The reduced slope of the vertical leg.
	Electrical leakage (shunt)	Excessively small shunt resistance in the circuit due to leakage pathways in cells or modules. Possible causes: Internal shorts, junction box issues. IV curve symptoms: The increased slope of the horizontal section.
	Shorted diodes	Diodes are shorted, as a result, sub-strings in parallel with the diodes are bypassed and do not contribute to power generation.

		Possible causes: Diodes may be undersized, damaged by electrical transients, or failed from electrical and thermal stresses. IV curve symptoms: Quantum drops in voltages or steps along the vertical leg of the IV curve (when several strings are connected in parallel).
	Open diodes	Open diodes are unable to bypass shaded strings. The shaded part may become severely reverse biased and dissipates heat. This is a rare but dangerous failure mode. Possible causes: Diodes may be undersized, damaged by electrical transients, or failed from electrical and thermal stresses. IV curve symptoms: Reduced Isc or an abnormally steep slope in the horizontal section when shading happens.
	Hot spot	Localized heat accumulation resulting in regions much hotter than usual. Possible causes: Spot shading or local shunts. IV curve symptoms: May exhibit similar patterns as that of local shading or open diodes, but in many cases do not lead to an observable change in IV curve as the spots are usually small or string is bypassed.
	Short-circuited cells	Cells may be shorted so do not contribute to power generation. Possible causes: Cells shunted by poor interconnections, pinholes or corroded/damaged cell material. IV curve symptoms: Drop-in output voltage.
	Line-to-line fault	Accidental low-resistance connection established between two points within the same string or between strings. Possible causes: Water ingress, animal chewing, mechanical damage, junction box corrosion. IV curve symptoms: Clear steps at distinctive current levels, or excessively low voltage (depends

		on fault type, location, string configuration, and presence of blocking diodes).
Module quality / degradation	Major cell/glass cracks	Major cracks result in large inactive cell areas, which lead to a mismatch of current. Possible causes: Mechanical damage during transportation/installation, hail, vandalism. IV curve symptoms: Knees (steps) at currents near Isc, or increased slope for the horizontal section.
	Round knee	Round knee near MPP is a signal of module aging with reduced FF. Possible causes: Nonuniform aging within modules. IV curve symptoms: The major knee appears rounded.
	PID	PID typically results in reduced shunt resistance and voltage drop at its advanced stage. Possible causes: Voltage, humidity, poor cell / encapsulation quality. IV curve symptoms: The increased slope of the horizontal section and/or drop in output voltage.
	Degraded junction	Degraded cells with increased reverse saturation current can lead to a significant drop in voltage. Possible causes: Cell degradation, moisture ingress, backsheet problems. IV curve symptoms: Drop-in output voltage.

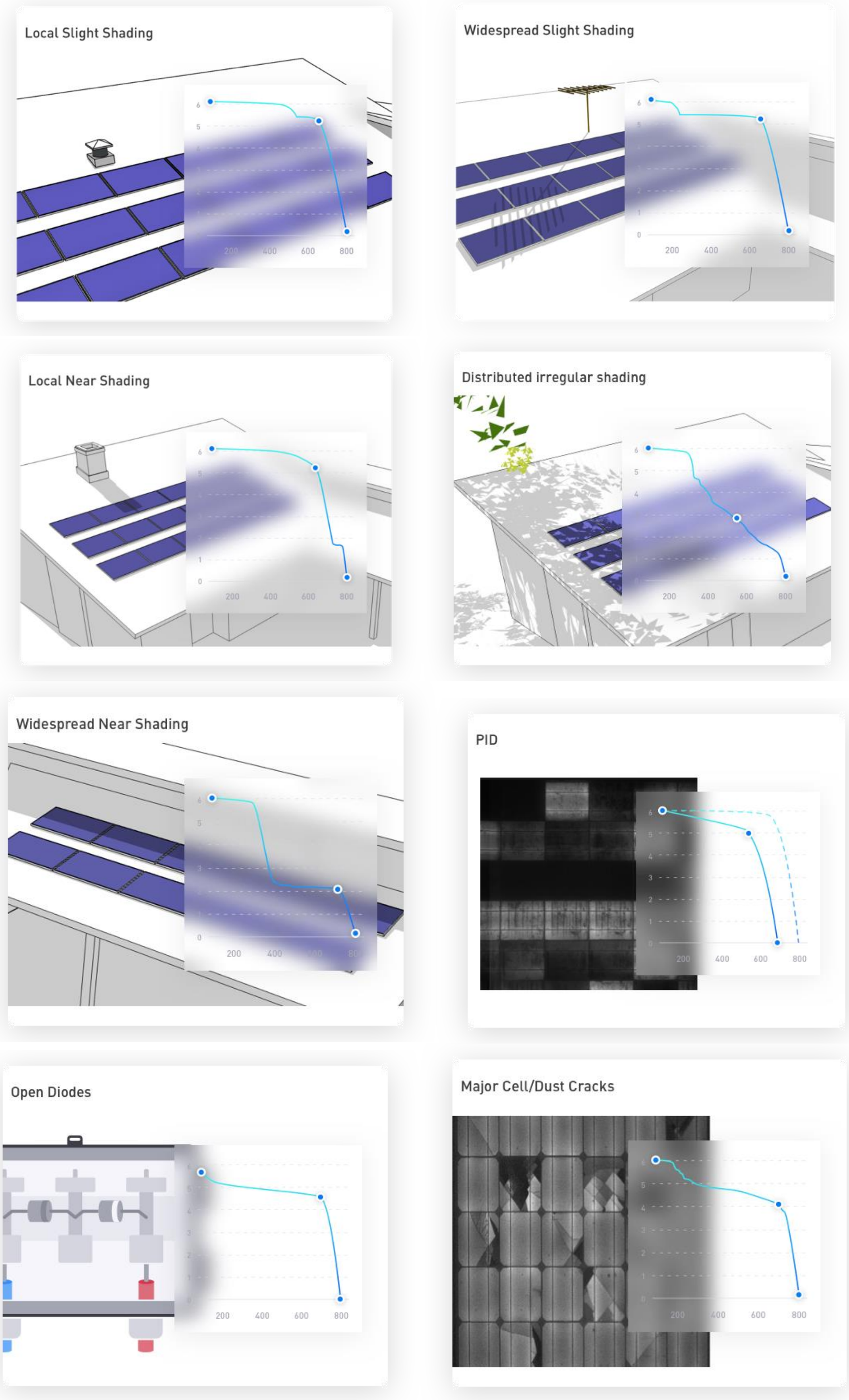


Figure 17. Illustration of IV curve patterns under several common underperformance scenarios.

The accuracy of diagnosis is constantly improved with more and more data. However, even with the most adequately trained AI model, there are still cases where it is impossible to pinpoint the root cause from a single glance of the IV curve, as different causes may result in very similar IV characteristics. Therefore, a technique we called **"triangulation"** is required. What this means is to take observations from different "angles" to help rule out some possibilities and determine the most probable one. This step can further enhance the diagnosis preciseness of the engine. The different "angles" available are:

- Time-series performance data.
- Performance analytics results and KPIs.
- Alarm history.
- Weather information from an onsite weather station or satellite sources.
- Cross comparison with peer neighboring devices.
- Multiple scans under different times and conditions.
- Others, such as equipment specification and system configurations.

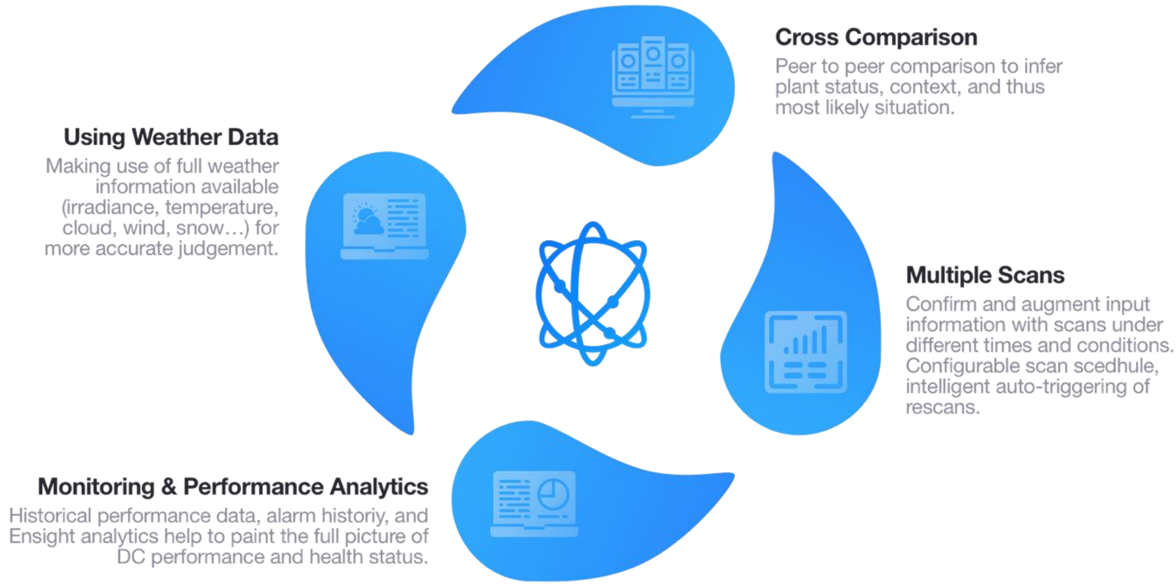


Figure 18. Refining IV curve diagnosis accuracy by "triangulation", which means taking into account various information together in an automatic fashion.

The ability to relate various sources of data demonstrates the technical prowess of a holistic solution. Furthermore, operationally, this enables greater room for automation. For instance, the engine can automatically schedule and trigger a rescan (given user authorization) at a suitable condition similar or different from the first scan based on weather forecast information. According to requirements, the system can also auto-generate reports suitable for O&M or warranty claims.

3.3 Enabling a unified flow

As asset management is a rich collection of tasks and processes, it is no doubt desirable for the digital tool to encompass as wide a spectrum as possible. The benefits are obvious: breaking the silos of different work items and enabling digital transformation across the board so that business flow can be optimized. This puts great pressure not only on the software applications but also on the underlying digital platform.

As already seen in the discussion of the asset health record, one key enabling factor is **interoperability and unification of data**. This must go beyond a central deposit to achieve an organic integration of information, which ranges from digital twin models (reflecting information about equipment parameters, string layouts, and system configuration), to time-series performance data, IV curve, imaging data, alarms, and work history. These building blocks, all seamlessly integrated with analytics and the decision-making process, allows for quick adaptation to various practices of managing a solar asset.

Communication to various stakeholders matters. Information on the ground is available to technical personnel in the form of dashboard displays, data visualization, and notifications, but it eventually needs to be communicated to other stakeholders, usually via reports. The platform should help users summarize information in various ways, generate insights, then formulate reports with clear presentation, low technical barrier for interpretation, as well as results that are trustworthy and auditable. Polishing this process may mean years of experience, total understanding of solar assets, and credibility.

Interface to other applications is another important feature. As most monitoring solutions do not provide adequate functions to suit all the complex business needs outside TAM, asset managers may also use an additional system for non-TAM processes. Tight integration is necessary to convert outcomes from TAM into real business values.

TAM should be **closed-looped**. Issues discovered should have follow-up and rectification whenever cost is justified. The management should have easy visibility to the efficacy of the process, manifested in the performance level recovery or revenue increase. Therefore, the TAM platform should possess some capability to enable O&M evaluation. For instance, in EnOS Analytics, wash event detection aims to automatically discover drops in soiling levels to verify washing events. More generally, EnOS Analytics's Corrective Actions function allows users to track follow-up activities on detected issues by modifying their status to acknowledged, dispatched, resolved, or simply ignored. EnOS Analytics will continue to monitor and see if the issue is indeed closed or remains. Action statistics then summarizes this information to give an overview. On a higher level, this information provides feedback to system design, which helps improve future projects.

TAM needs to be ready for the next wave of revolution, namely hybrid power plant, smart grid, and virtual power plant (VPP). Apart from digitalizing and breaking the data silos, new applications will need to be developed in a fast and efficient way to cater to diverse use cases. There might also be a need for adapting to new processes should the owner expands business to new domains. These are all challenges for being future-ready, which should be best solved by having a good AIoT platform as the digital backbone.

Envision's solar solution leverages on the versatile EnOS platform capabilities to address all these needs. On the bottom, EnOS provides the infrastructure to manage connectivity and *data assets* from myriads of devices. Abstracted models for many different device types, including inverters, combiner boxes, weather stations, etc., are natively available on EnOS, and digital twin representations are instantiated based on these models, providing lifecycle management for *device assets*. On top of this, the AIoT platform powers the applications with flexible, configurable, and versatile modules such as visualization, notification/alarms, reporting, work order management, business process management, interface with external platforms, etc. These building blocks help businesses put together their unified TAM flow easily, with low-code or even no-code experience. The solution is therefore highly expandable, enabling new applications to be added, meeting the needs of potential future scenarios such as hybrid plants and VPP.

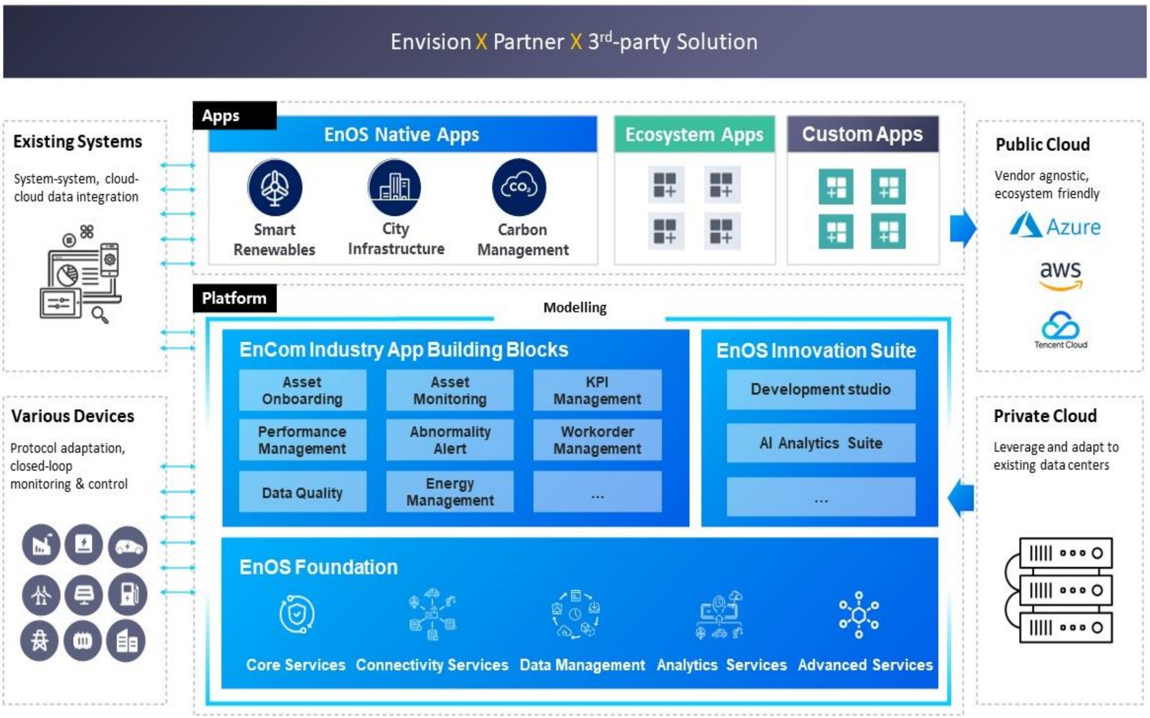


Figure 19. Architecture overview of EnOS, the AIoT operating system.

4. Conclusions

In this technical white paper, we have analyzed the needs and trends of technical asset management (TAM) for solar assets. As solar continues to grow, a leading foreseeable problem is the *scale-manpower conflict*, which calls for digitalization in every aspect of TAM. To do so, one needs to embrace the AIoT framework, software tools as well as state-of-the-art techniques, and build them into the TAM framework from the very beginning.

Among all the TAM items, the ability to monitor the condition of the electrical generator is key to understanding asset health status and performance level. This is not an easy task, as a PV system is quite complex.

As the industry matures, the business processes and O&M management will become more streamlined – this is the lower hanging fruit – but optimization of asset performance and reliability will be more difficult, requiring advanced technological solutions and a high level of expertise.

In chapter 2, we performed a deep dive into the tools and technologies available for facilitating TAM. With remote monitoring forming the foundation, advanced performance analytics, IV curve scanning coupled with automatic AI diagnosis, and drone-based IR/EL imaging coupled with computer vision intelligence are technologies that have the greatest potential. Moving forward, embracing technical sophistication is a must to cope with the scale and cost competitiveness requirements of the PV industry. An optimum combination of these techniques can bring great value at reasonable costs, but this is not always straightforward to achieve. Hence, a good digital solution should supply the relevant ingredients needed to synergize the use of advanced technologies.

These technologies will generate a large volume of data. The data should form part of the digital solution too. IV curves, images, and results from performance analytics are all valuable components for an asset health record. Gathering data from multiple sources and managing it coherently in a single platform opens new possibilities, such as detecting hidden issues, increasing diagnosis accuracy, mining useful insights, and automating decision making. This point is well illustrated in Envision's advanced IV curve solution, which optimally leverages the same digital infrastructure and combines the advantages of time-series performance monitoring, analytics, and IV curve diagnosis.

Moreover, the advanced technologies should be organically integrated with other elements of TAM as well as non-technical processes to generate a highly valuable data for all the stakeholders. This calls for powerful and versatile digital platforms such as EnOS that can unify data, manage communication among stakeholders, easily interface between software applications, enable close looped processes, and adapt to future scenarios of the hybrid power plant, smart grid, and virtual power plant.

Digitalization is becoming a reality in the solar industry today, with more players adopting remote monitoring and software solutions. However, digitalization is not a one-step transformation. It is a continuous journey of breaking silos and embracing technologies.

A mediocre digital platform merely facilitates traditional TAM processes, a good digital platform contains advanced domain know-how to help achieve new heights.

That is why Envision's innovation in solar asset management solutions goes beyond providing monitoring software. Instead, the solution strives to evolve into more than just a tool, but also a solution partner to solve problems alongside users, condense learnings, and help to shape the best practices for a holistic TAM of the new era.

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Envision Digital owns EnOS™ – the world-class AIoT operating system which currently connects and manages over 63 million smart devices and 120GW of energy assets globally. Its monitoring, advanced analytics, forecasting and optimising applications provide insights to help clients better manage their assets and portfolio performance. Its offering extends to: Smart Renewables (Hydro, Solar, Wind); Smart Cities; Smart Buildings; Connected Energy; Smart Plants; and Smart Networks; partnering companies and governments in their digital transformation journey.

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