PV|HARVESTER – A TOOL FOR PV POWER PLANT PERFORMANCE EVALUATION AND ECONOMIC OPTIMIZATION

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ABSTRACT: Experience shows that most solar PV power plants do not operate at their optimum. In particular, in locations with good solar irradiation and/or high feed-in-tariffs this can lead to significant losses in power and revenues for plant owners and investors, and thus implies an operational risk for lenders and operators. From another perspective harvesting maximum energy yields from solar PV power plants provides a tremendous upside potential. PV|Harvester is a software tool developed by the University of Applied Sciences Upper Austria together with deea Solutions GmbH, Germany with the aim to quickly assess the operational performance of solar PV systems. The tool, developed in Python, is a result of many years of experience in planning, designing, and data analysis of solar PV power plants. PV|Harvester delivers detailed and fast performance analysis on string level, a clear view on improvement potentials, and a thorough health check of the asset. It can also be applied to a due diligence analysis as part of an asset transfer, for calculation of liquidated damages, and a general failure analysis and localization.

Keywords: Solar PV, System Performance, Revenue collection, Asset valuation, Cost reduction, Cash flow improvement, Analysis, Modelling, Software

1 INTRODUCTION

After installation and commissioning, regular analysis of the operational parameters of a solar PV power plant is required to check how the measured performance meets expectations. Due to the large amount of operational data of PV power plants it is a challenge for project managers and operators to obtain a clear view of the health state of the asset. Moreover, the IEC 61724-1 standard focusses on the long-term performance of the asset [1], but for many applications such as due diligence analysis also the short-term state of the system can be relevant. Therefore, by gathering historical data of the power plant, the current performance of the asset can be determined [2,3]. The work presented in this paper describes how to evaluate the performance of existing photovoltaic power plants through data analysis acquired from different clients and collaborators' assets. Each power plant has a unique system layout, i.e. diverse combinations of inverters, maximum power point (MPP) trackers, strings and panels. Therefore, a complete understanding of the layout is assessed when a detailed cash flow evaluation up to the string level is desired. Acquired data is then analysed following data science criteria and the guideline of the IEC 61724 standard in order to increase its reliability and trust as a service. The software is programmed in Python due to its multiple advantages, such as open source, strong and reliable supported libraries and packages as well as its recognized use in data science.

2 APPROACH

2.1 PV|Harvester structure

The software is organized in different clusters in order to be easily adapted for each studied power plant. Among others, the PV|Harvester includes a data quality check, modelling, calculations, logging and graphic modules. This solid structure facilitates doing minor changes to the code without altering the overall automatic analysis. It also allows a precise analysis for a particular MPP or inverters that need further investigation to find out the reasons of underperformance. Though minor changes the generic workflow of the code runs from a data visualization that aids decision making, to a quality check and parameter calculation, and finishes with a metric rating and economic evaluation.

2.2 Data handling and quality check

The first step in data handling best practice is to have an overview of the data and a visualization of it. That is, once the structure of the investigated power plant is understood one needs to analyse how the acquired data correspond to its layout and which parts of the data can be quickly discarded, are missing or need special processing techniques.

The data quality check approach continues with a first overview of the data logs compared to the expected based on the frequency. This assessment sets the overall data availability and, in case expected logs are missing, duplicated or have logging errors (such as not numeric values) a reporting error in the acquisition system can already be flagged. The decision of using the rest of the available data is determined based on the quality of it, but which decision is taken has to be written down as the IEC 61724-1 standard states [1].

Next, the availability of the sensors of the power plant and the quality of the acquired data is analysed. To do so, data is divided in meteorological and electrical/power data; including any component of irradiance, ambient temperature, humidity, wind speed, etc. in the first category, while storing both DC and AC components of voltage, current and power in the latest.

To proceed with the quality of meteorological data assessment, first sensors that have incorrect readings and issues are discarded for the reporting period. The most cost-effective approach is using correlation of different sensors in order to correlate the data and discard those sensors that differ from the others. In a second step, data from these sensors is subject to a higher quality analysis and each log of each sensor is then studied. Among other measures, the quality check sets upper and lower physical limits (see Table 1), sensor data analysis and rate changes for each meteorological reading device [4].

Following the IEC 61724-1 criteria, quality issues are flagged and stored in parallel loggings as the automatic quality check proceeds.

Table 1: Thresholds set at the quality check module to detect out of range values.

Variable	**Expected range**	**Dead sensor threshold**	**Abrupt change threshold**
DC current [A]	> 0 and <$I_{mppt} \cdot S^* \cdot 1.5$	<0.0001	-
DC voltage [V]	> 0 and <$V_{mppt} \cdot N^{**} \cdot 1.2$	<0.0001	-
AC Power [W]	> 0 and <$P_{mppt} \cdot N^{**} \cdot 1.2$	<0.0001	-
POA Irradiance [W/m^2]	> -6 and <1500	<0.0001	Depends on acquisition frequency
Ambient temperature [ºC]	Site specific	<0.0001	> 20
Module temperature [ºC]	> -30 and <90	<0.0001	> 20

S* is the number of strings per MPP tracker

N** is the number of modules per string

2.3 Performance evaluation

Present data analysis methods are often based on KPIs (Key Performance Indicators) that depend on the installed DC power, location, and varying weather conditions [5]. In order to estimate these KPI metrics that define the performance of the studied PV system, some parameters have to be calculated, both in the DC and AC side of the inverter. Among other parameters stated by the IEC 61724 standard, yields, losses and efficiencies are calculated with reliable data as shown in Table 2.

Table 2: Parameters calculated in PV|Harvester as stated by IEC 61724-1.

Parameters	**Units**
In-plane irradiation	kWh/m^2
Output DC energy	kWh
Output AC energy	kWh
PV energy yield (DC)	kWh/kW
Final system yield (AC)	kWh/kW
Array caputre loss	kWh/kW
Balance of the system [BOS] loss	kWh/kW
Array efficiency	-
System efficiency	-
BOS efficiency	-

Metrics, which rely on calculated parameters based on data of the power plant are unitless and are used to rate the overall performance of the studied asset. Among other metrics found in IEC 61724 PV|Harvester determines the ones shown in Table 3.

Table 3: Metrics calculated in PV|Harvester.

Metrics	**Units**
Performance Ratio [PR]	-
Annual PR	-
STC-temperature PR	-
Energy Performance Index	-

At this point, already underperforming inverters can be spotted due to their below-average yield, high DC or AC losses and poor efficiencies. Nevertheless, to spot the root of the problems, metrics and modelling must be done. As of the KPI metrics, performance ratios (PR) both with and without temperature correction are calculated and those PR that fall below the thresholds are further analysed. This approach ensures higher computational speed rather than analysing the whole power plant with good-performing inverters included. The thresholds set can either be statistically automatized or manually fixed.

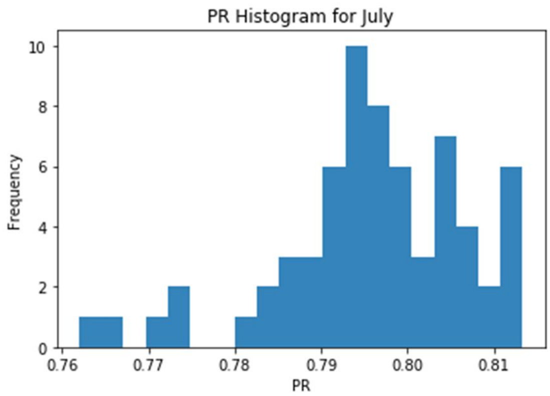

Figure 1: Exemplary histogram of all inverters of a large-scale PV power plant for the indicated reporting period.

While PR are metrics based on the system name-plate rating, other metrics such as energy performance index (EPI) offer a more detailed model of the system performance and are therefore included in the analysis.

In order to analyse the performance of the MPP trackers in detail the P1000 coefficient is calculated. The P1000 coefficient is the temperature-corrected normalised power at 1000 W/m² irradiation. Normalised power is defined as the generated DC power divided by the installed DC power capacity. Since the P1000 coefficient is the performance at STC condition it allows for comparison of the performance of all the strings not only within the same PV plant but also between different PV plants. P1000 coefficients are also analysed on MPP level, if more than one MPP per inverter is available.

2.4 Modelling

A core feature of PV|Harvester is to perform a modelling with on-site (checked) meteorological data in order to evaluate the difference between the real and the expected energy yield, and thus determine the cost opportunity for improvement. As mentioned, meteorological data is used to model the DC expected energy output based on module characteristics, and the layout and inverter configuration is later used to model the AC side. Both DC and AC sides are modelled using PV Lib.

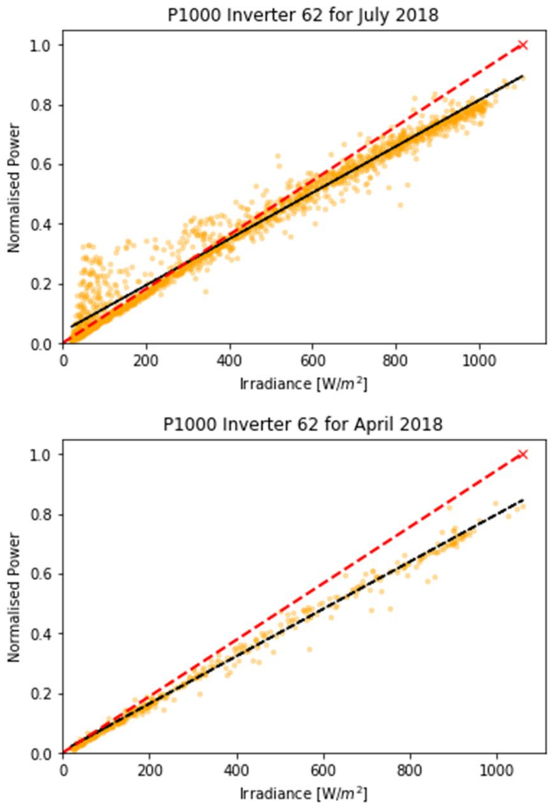

Figure 2: P1000 values for a specific inverter that is underperforming along the year. While in April the data acquisition failed for an extensive period, during July shading of the pyranometer at early morning and late afternoon hours happened.

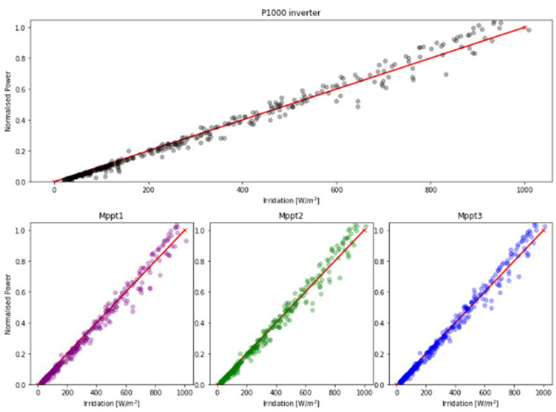

Figure 3: P1000 values for an inverter with three MPP trackers per inverter.

Once the expected data at the MPP, inverter and power plant level is modelled, underperforming issues or failures can be spotted and further evaluated. If enough data is available, a correction can be then determined to find a solution to these spotted issues such as soiling and shading as well as other module or inverter failures, and a detailed analysis can be carried out in PV|Harvester.

2.5 Economic evaluation

The main goal of performance evaluation of PV power plants is to evaluate the yield losses during the reported period. Figure 4 shows a flowchart of the economic evaluation as performed in PV|Harvester. The final assessment, based on the analysed yield losses is an economic evaluation. The determined energy loss is extrapolated until the end of the contract or life-time of the PV power plant. This follows a conservative approach, since current errors might get worse and increase the overall system underperformance. The result will be even higher losses.

In addition, the remuneration and/or the power sales clause is studied in order to calculate the overall capital loss until the contract expires, based on the conservatively extrapolated energy yield losses. Although most power plants have a base remuneration scheme, such as a feed-in-tariff, each PV power plant has to be individually assessed by studying its contract clauses.

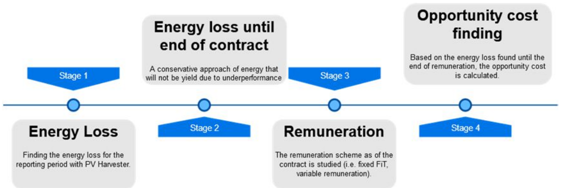

Figure 4: Flowchart of the economic evaluation done at the end of the study in order to find out opportunity costs.

3 RESULTS AND DISCUSSION

PV|Harvester analyses data acquisition issues that can bias the overall system performance calculation. As an example, in 5 one can see that the DC PR is far greater than 1 in late afternoon hours (green peaks in third graph). The reason for this is that while the pyranometer has a good data quality for most of the year, during summer months it receives shading during the last hours of the day, resulting in an incorrect calculation of the PR. This issue can also be seen in the lower irradiance values of Figure 2 for the month of July.

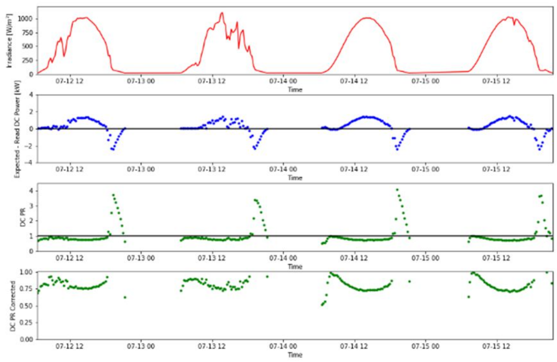

Figure 5: Irradiance, difference in DC power (expected-real), DC PR (both corrected and non-corrected) are plotted to determine modelling misbehaviour.

Nevertheless, the corrected PR shows the characteristic bath-shaped curve expected of an inverter, as the temperature rises over noon-time in clear irradiation days and the PR drops at that time.

For other studied power plants, the underperformance is found at their respective inverters and, consequently, at the overall power plant level. The magnitude of the underperformance varies with the power plant and the inverter configuration (i.e. number of MPP, strings per MPP, modules per string, etc.). To obtain an overview of the whole PV power plant and the statistical distribution of values, a box plot of all data on inverters level is very useful (Fig. 6).

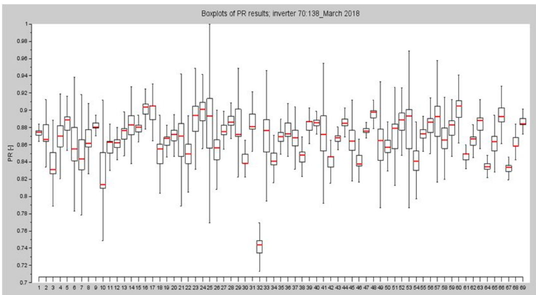

Figure 6: Box plot of PR values of parts of a large PV power plant with string inverter concept.

In Figure 7, selected parameters of a studied inverter are plotted in order to spot underperforming issues.

From the upper left corner to the right, the following parameters are plotted: AC over DC power, inverter efficiency over irradiance, DC voltage over module temperature, module temperature over irradiance, PR DC over irradiance and PR AC over irradiance.

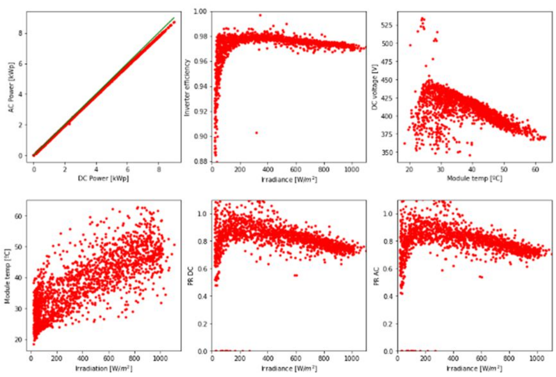

Figure 7: Detailed analysis for a specific inverter, following the guidelines of IEA PVPS [4].

For one studied power plant with an installed capacity of 700 kWp that has been operating for 9 years, the annual energy yield loss was of 161.292 kWh. This deficit, extrapolated with a conservative approach until the expiration of the contract, results in total energy losses of 861.406 kWh. Economically, taking into account the respective feed-in-tariff scheme, this amounts to losses of 172.300 €.

4 CONCLUSIONS

PV|Harvester is a state-of-the-art tool that offers a thorough analysis of solar PV power plant performance. It quantifies energy and economic losses, determines the opportunity cost, and spots issues that need to be correct or mitigated.

In order to evaluate the performance of the power plant a diligent data quality check is a core task. Although PV|Harvester does evaluate the raw quality of the data to mould it into useful information, a good acquisition system and good quality data is the key to outperform an excellent calculation and modelling. Therefore, it is recommended that the power plants operate under ISO and IEC standards (from collecting and logging data to O&M practices) in order have useful information to solve potential issues and problems found in the PV power plant industry.

PV|Harvester is a continuously improved tool and will be adapted and extended as new insights are gathered while building up experience in the industry.

5 REFERENCES

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