PRESCRIPTIVE SOLAR ANALYTICS & ADVANCED WORKFORCE MANAGEMENT

M2.2

„Routines to diagnose failures"

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EXECUTIVE SUMMARY

Within the PANAMA project, the milestone 2.2 is the outcome of the Task 2.2. Both are due at the 12th project month, which is the end of June 2021.

In the project proposal, the outcome was described as:

> In this task trend-based performance loss rate (degradation, PID, shading and soiling) algorithms will be developed in order to detect and predict underperforming conditions at early stages. In particular, regressive time series analysis techniques (ordinary least squares, classical seasonal decomposition, autoregressive moving average, etc.) will be investigated for the real-time calculation of the degradation rate of PV systems. Similarly, shading and soiling losses will be evaluated by comparing the loss trends of specific measured and calculated parameters (current, voltage, sun position) over daily and weekly periods and after specific events such as cleaning of arrays or rain. This will further include an estimation of the soiling of irradiation sensors based on previous rain and cleaning intervals. Time series analysis will be also applied to the captured voltage profiles of PV arrays in order to detect PID.

The promised methods were developed as intended.

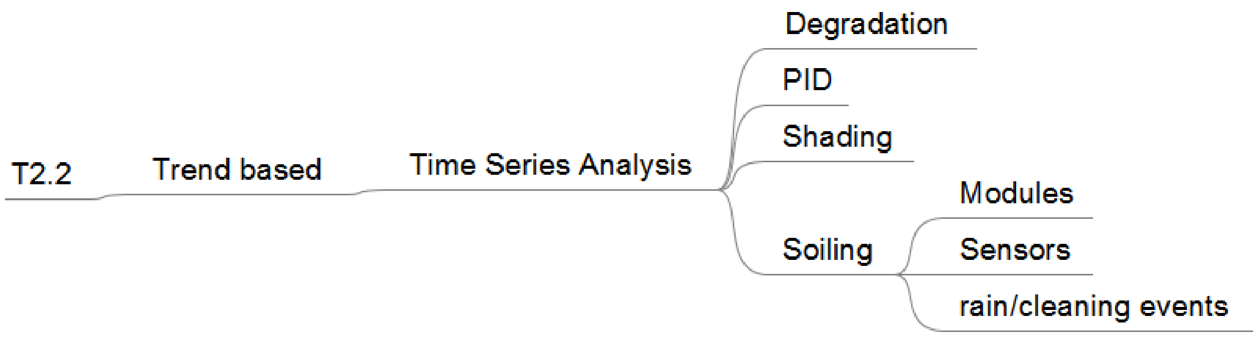

Figure 1: Mindmap representation of the content of Task 2.2.

1. Results of Milestone 2.2

While monitoring larger photovoltaic (PV) generators ("plants"), typically there are three different sources of data: data recorded by inverters, weather sensors, and finally the electric meters. Most commonly, data is uploaded to a web-based data aggregation platform.

From there, data can be downloaded for further analysis in text files larger than one gigabyte.

Typical data from inverters contains on the AC side: power, grid frequency and phase currents. On the module DC side, commonly the working point is recorded (U_mpp, I_mpp) for possibly multiple MPP trackers per inverter.

In the previous milestone document M2.1, analysis of the inverters efficiency behaviour were presented, as well as the behaviour of the inverters DC side, where the MPP tracking behaviour was analysed in combination with the modules string irradiation dependent MPP position. In the following chapters, we will build upon on this output.

1.1 Digital Twins

To analyze long-term degradation of PV modules, one could compare the production at similar environmental conditions between occasions that are distributed over multiple years. It is common to use clear-sky conditions, as the effects of clouds strongly depend on the clouds location on the sky. The problem with this approach is, that clearsky conditions at similar temperatures are hardly ever met, and hence the statistical relevance is very limited.

To obtain better statistics, one creates a model of the PV production based on measured factors ("observables", e.g. air or module temperature, irradiation, wind speed) and derived features (solar sky position, clearsky irradiation). The ratio of the actual production to the predicted production then can be evaluated. While this can be done with the most fine grain time resolution, better statistical relevance can be obtained by temporal averaging over longer periods.

There exists the standard „IEC 61724-1", 14.3.2 „Temperature-corrected performance ratios", which defines a simple procedure. The digital twin in this case is a simple model: $P=G/1000*Wp*[1+\alpha(T-25)]$, with the predicted AC Power P, the in-plane irradiation G, the installed Module Peak Power at STC, and the temperature coefficient of the module MPP power (typically -0.42*0.01 /°). This is a very simple, linear digital twin of the PV production.

However, it does not include the decrease of PV power under lower loads, a combination of decreased inverter efficiency and the parallel resistance production power drop of the modules themselves. This effect can be included by three more fit variables. Thereby, the overprediction of standardized performance ratio can be decreased, leading decreased seasonality of the PR, see **Fehler! Verweisquelle konnte nicht gefunden werden.**.

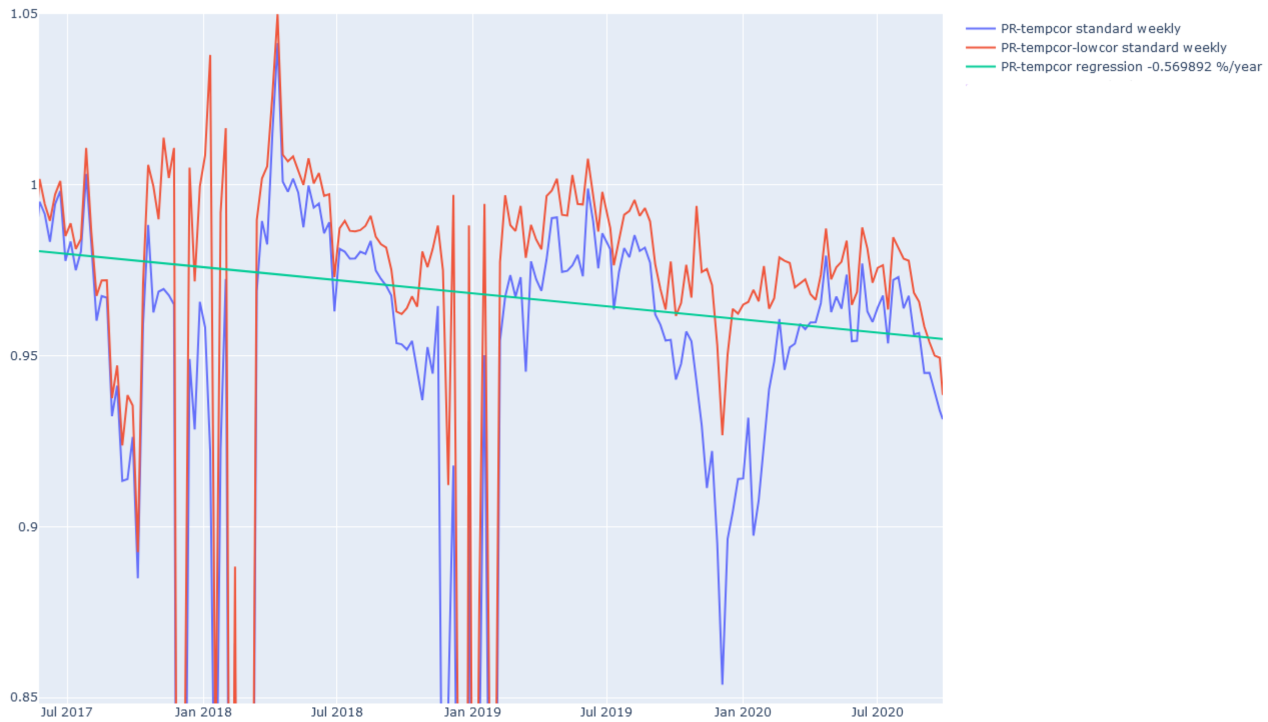

Figure 1:The monthly averaged PR of an Austrian PV-Plant according to standard (blue) and with improved low-light accuracy (red). Deviations occur mainly under snow conditions, if the modules are covered but the irradiation sensor is not. A robust linear fit exhibits the yearly power degradation.

Improved digital twins are necessary to exhibit smaller deviations of the PV production, see Figure 2. They require the tilted plane clearsky irradiation which can be calculated from the GPS location and the time of day using common radiation models such as "Perez"[1]. As typically neither the orientation nor the factual installed power is known, they need to obtained based on monitoring data.

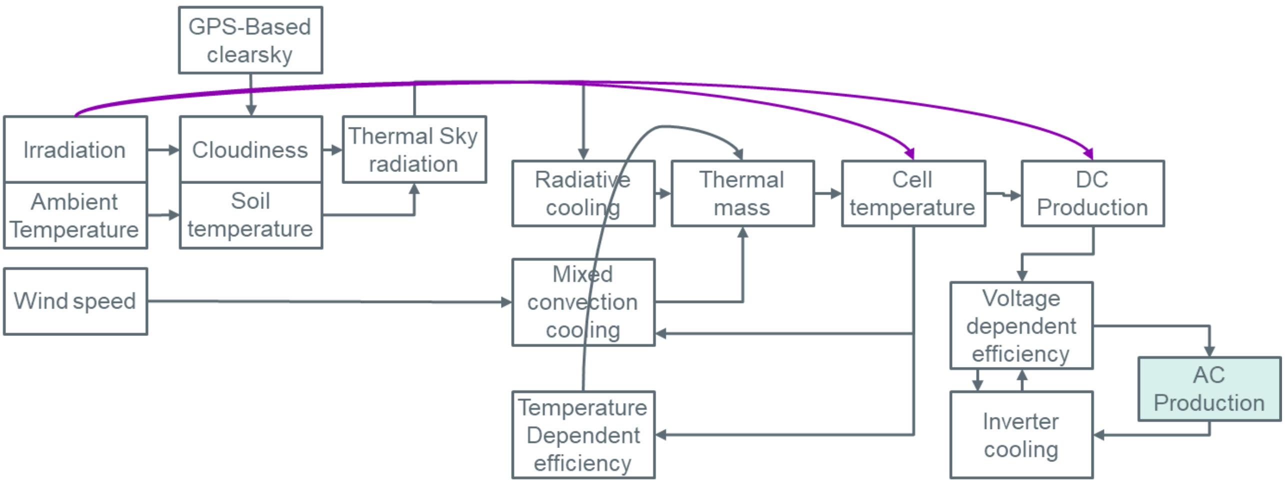

Figure 2: An analytic digital twin of PV production: From irradiation and the calculated tilted clearsky-irradiation the cloudiness can be estimated. This has impact on the infrared radiative balance that affects 50% of the modules cooling.

[1] Perez, R. et. al 1988. "The Development and Verification of the Perez Diffuse Radiation Model". SAND88-7030

The hysteretic cell temperature then influences the DC production, which by a simple inverter model creates the feed in power.

1.1.1 Timestamp validation and orientation estimation

Inverters typically have a quartz resonator as time source. This quartz is tuned to a specific operating temperature and is known to deviate of up to 30min/year in other climatic zones, if not regularly updated by online time servers. Additionally, problems with time zones and summer/winter time switching are fairly common.

By estimation of sunrise/sunset from the inverters data, and comparison to synthetic GPS-based values, the time system can be validated, and deviations be corrected. This can be done for each individual inverter, as well as the radiation sensors. In an observation interval, the values can be averaged over a period, or sampled at one instance. If this is done differently for the radiation sensor and the production, a timeshift of half the sampling period is observed.

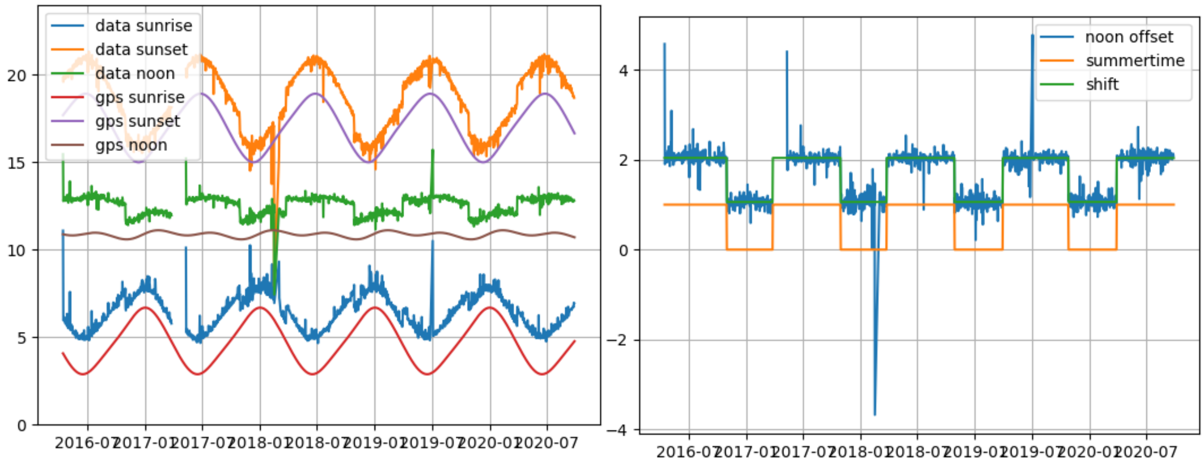

Figure 3: Validation of time stamps. Horizontally the days of multiple years, vertically the dayhour/hour difference.

Once the timezone and summer/wintertime behavior of the monitoring data is established, the orientation of the section of the PV plant can be found by numerical optimization. The comparison of the directional clearsky radiation to the observed peak irradiation, see Figure 4, can be used to create a shadow map in Figure 5:

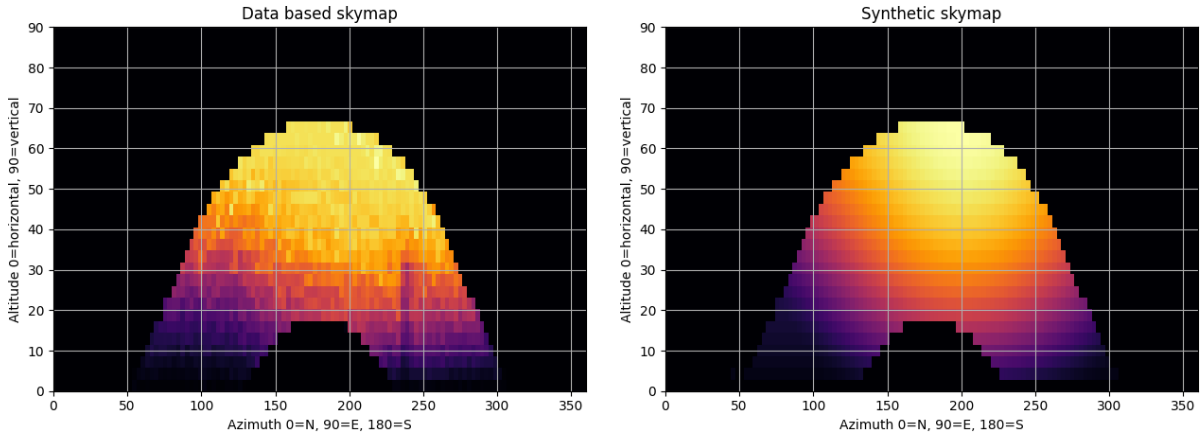

Figure 4: Comparison of data based clearksy irradiation plotted over the hemisphere, to synthetically clearsky irradiation for the fitted optimal orientation.

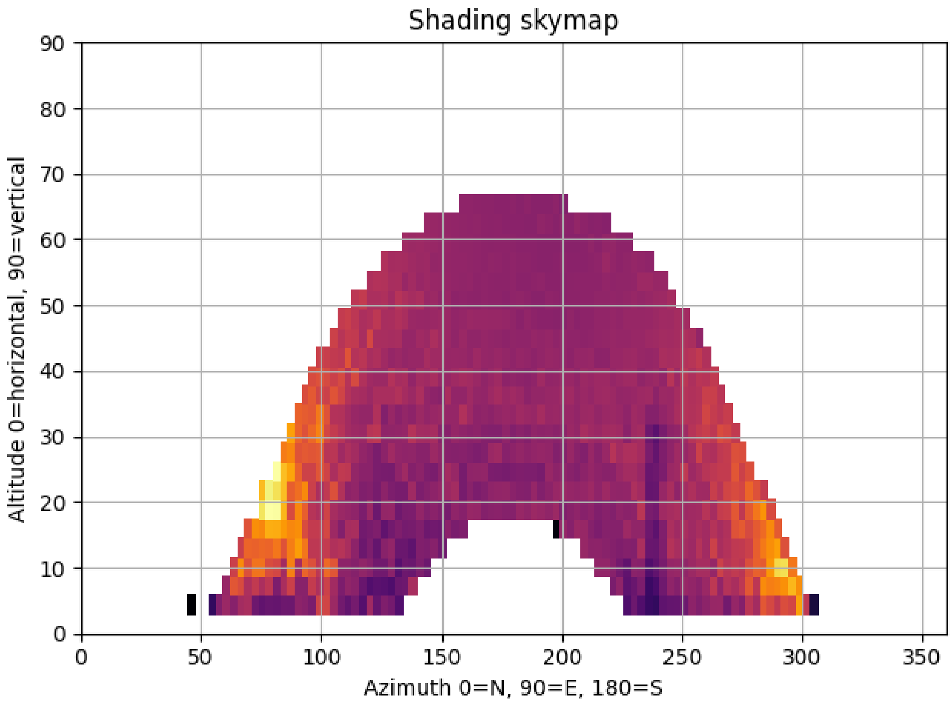

Figure 5: The ratio of the synthetic and databased irradiation skymap shows directional shading, in this case a tower in the west of the system.

As soon the orientation of the plant is known, the tilted clearsky irradiation can be calculated using common radiation models, e.g. “Perez”. As the majority of large PV systems have an irradiation sensor (typical accuracy 5%, typically worse below 200W/m^2), the ratio of the measured irradiance and the calculated clearsky irradiance can be estimated. The value named “cloudiness” is typically ranged between 0 and 1.2, where values above 1 are caused by unhindered direct irradiation and bright clouds outside of the suns direct trajectory.
Typical weather forecasts contain a value representing the amount of cloud cover, but as the location of the clouds matter, there is only a week correlation between the meteorological cloud cover and the cloudiness as defined before.

1.1.2 Data reduction for model fitting

Rapid changing ambient conditions, i.e. a compact cloud moving in front of the sun, can create changes in the modules current-voltage curves, and hence in the MPP point. The inverter sometimes needs some time to regulate to a new ideal setpoint, and while the tracking is performed will create deviations of the production that cannot be explained by a simplified digital twin. Hence, it is useful to decrease the importance of such data points while numerically fitting system parameters of a simple digital twin, see Figure 6. During the fit, one can either give each point a weight/importance that is defined the stability of the conditions, or remove points with insufficient stability altogether.

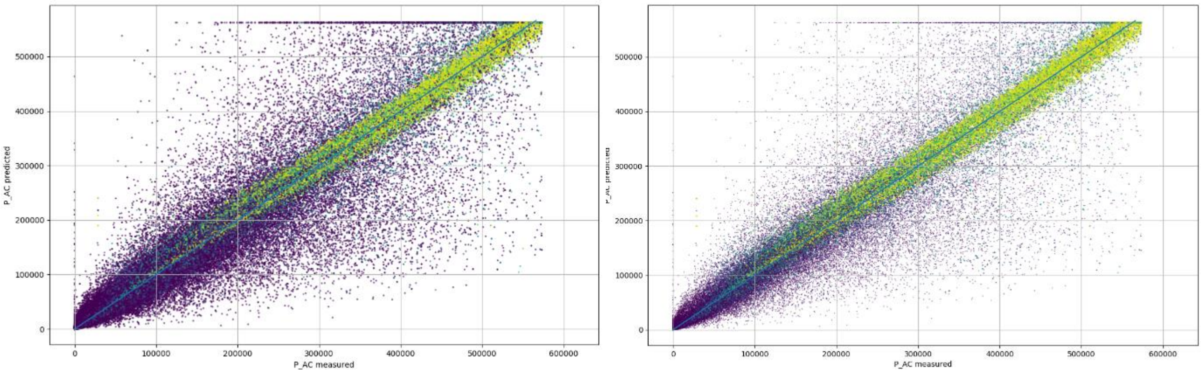

Figure 6: The correlation between the production predicted by a digital twin (vertical) over the measured production (horizontally). Left, the points are drawn with equal weight/dot size. Right: with a decreased point size for instable conditions.

1.1.3 Evaluation of the digital twin

After the fitting, the historical environmental data can evaluated using the twin, and from the predicted production the observed production can be subtracted. This can be normalized to a peak production, e.g. found by a 99% percentil of the AC production, to obtains relative deviations.

In a next step create bins of ambient conditions (e.g. five ranges of irradiation) are defined and used to create histograms of the relative predictor deviations for each of the bins, see Figure 7. For each bin, the mean (systematic under/overestimation) as well as the standard-deviation (typical prediction error) can be calculated. Furthermore, the binning can not only be done in one dimension but be performed two-dimensionally using both irradiation and ambient temperature. This classified expected error enable to not only predict the production, but also the uncertainty of the digital twin, see Figure 8.

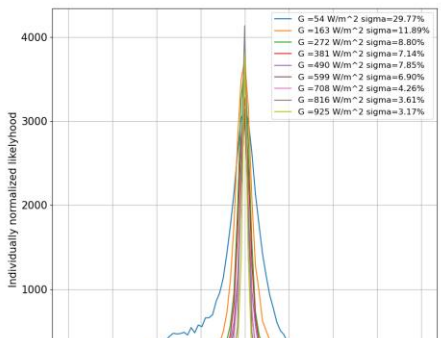

Figure 7: The histograms of relative deviations between digital twin and actual overserved production, depending on a one-dimensional binning of the irradiance. The larger the irradiation, the lower the deviation.

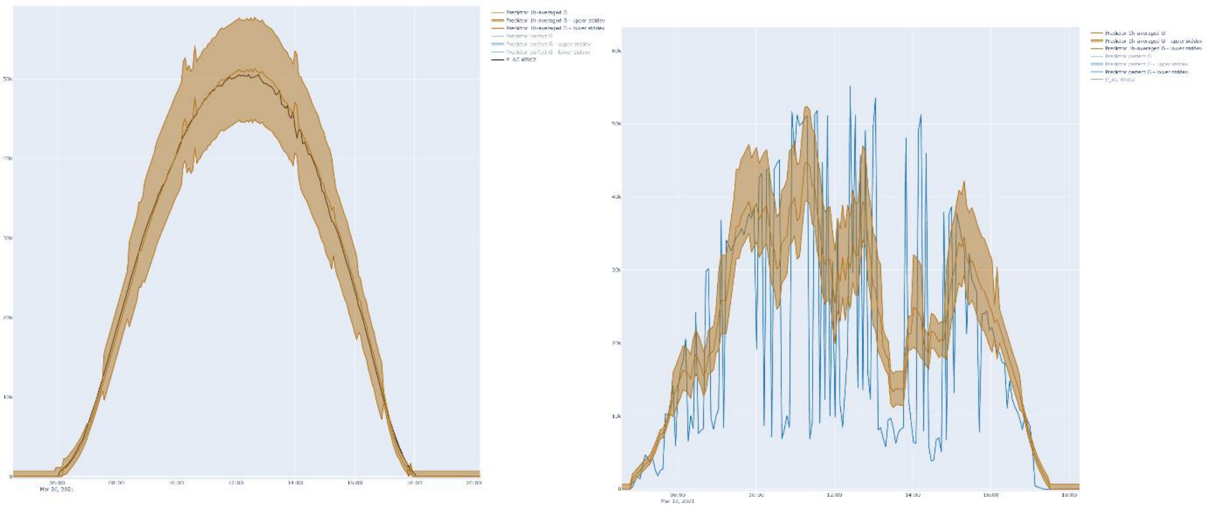

Figure 8: Comparison between measured production (left: black, right: blue) and expected deviations (brown band). Left: on a clear day, right on a day with volatile cloud cover.

1.2 PID

Potential induced degradation is caused by a voltage applied between the frame of the module and the interconnected cells. If the voltage is larger at the frame, it creates an electrostatic field that can cause galvanic drift of Na+ ions out of the glass onto the cell surface. There, microscopic spikes might be created that pierce through the PN junction, ultimately causing a short circuit. As the field is stronger close to the edges of the module, initially outer cells are damaged first. Also, this only happens if the cells voltage is more negative then the frame, and increases in intensity with the voltage difference. Hence, most often, only the most negative modules are affected.

Electrically, both a healthy and a short-circuited cell can be described within the framework of the diode model, where the defect is represented by a decreased parallel resistance.

The effect of a varying number of cells damaged by decreased parallel resistance can be simulation, see Figure 9. Thereby it is visible, that PID causes a voltage decrease, initially only at low light settings. With increasing PID, larger and larger currents are affected, until in later stages a general voltage decrease is noticeable.

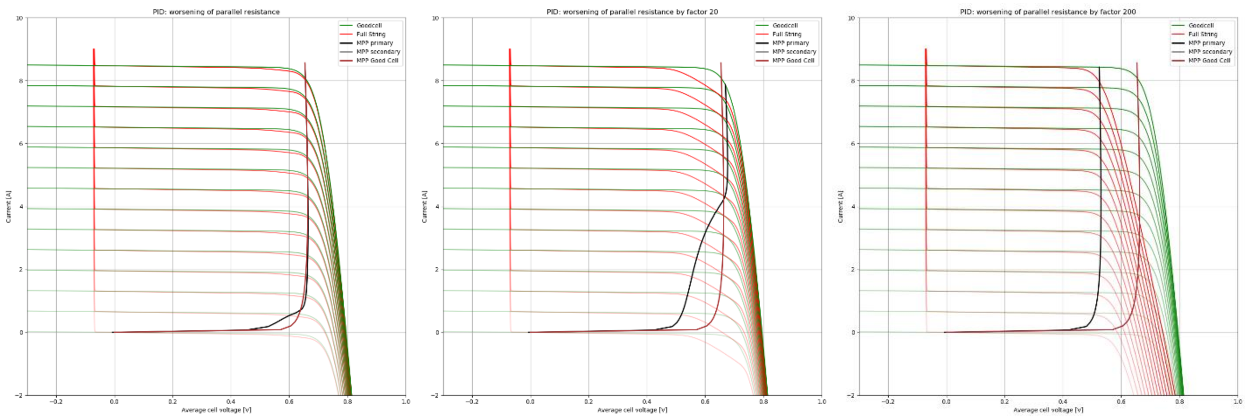

Figure 9: Simulation of the effect of PID on module strings. Bright voltage (horizontal) and current (vertical) characteristics are shown for damaged (red) and undamaged (green) modules, with varying irradiation. The Black curve describes the position of the MPP point of the damaged string, while the brown curve shows the same of the undamaged string.

Similar to the results of Milestone 2.1, the effects can be found in the clouds of MPP-tracking points, based on the DC voltage and current of individual module strings, see Figure 10.

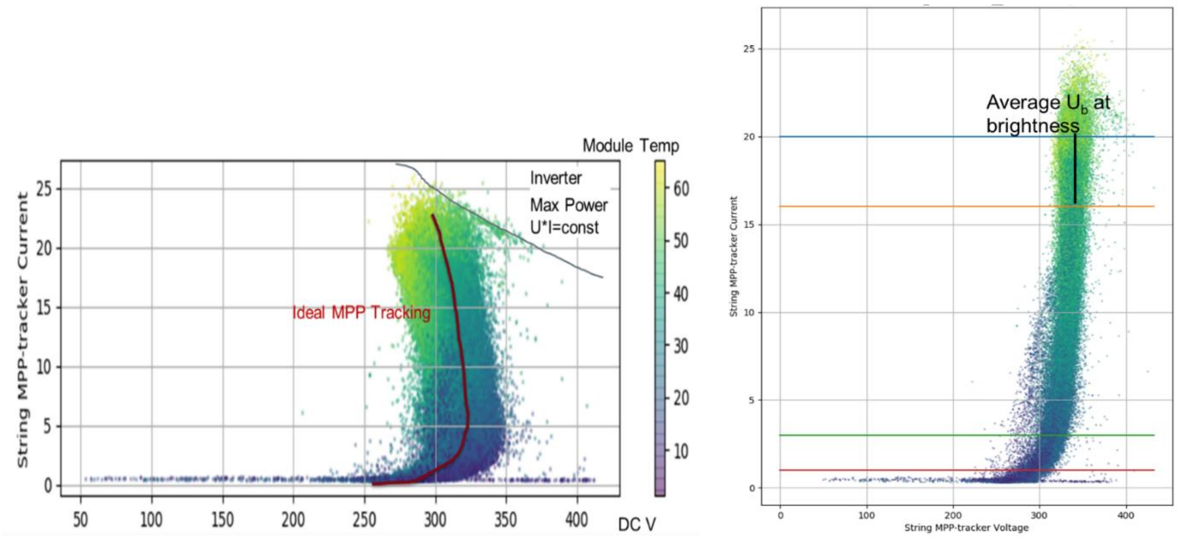

Figure 10: To detect PID, in the MPP clouds (left) described in Milestone 2.1, two current ranges can be defined (right): one at relatively large current (blue-orange) and one at low current/irradiation (red-blue). Within each band, an average voltage can be defined (bright: Ub, dark Ud).

In the onset of PID, a decrease of the ratio Ud/Ub is expected to be observed. For strong PID Ub will decrease over the course of more than six months.

1.3 Soiling

To detect soiling, a naïve approach would be to look at a performance ratio based on a well fitted digital twin. However, in most natural cases the soiling onto the modules will be of similar extend as the soiling onto the irradiation sensor. Hence, it is a good practice to clean such sensors every second week with non-abrasive methods. This is however hardly performed even in multi-gigawatt plants.

There exist dedicated sensors to measure in-field soiling, typically based on the amount of total reflected light within a backlit glass plane. Any dirt would cause external leaking of light and decrease the internal back reflection. Such sensors are part of the current established standard IEC for monitoring PV systems. However, practical application is lacking, because of the sensors price and the low impact in plant performance.

Purely based on monitoring data, the options to analyze soiling are limited. One approach however is to filter for clearsky day conditions and observe the ratio of the digital twin’s production based on the simulated irradiation and the observed production. While this signal will be noisy, the typical 1-6% performance loss might be visible. Typically, one assumes that the soiling absorption is constantly increasing by the so-called soiling rate. During precipitation, the soiling absorption is decreased proportionally to the water amount. These parameters can be fitted to the measured ratios, to obtain a digital twin. As however a strong seasonality is to be expected, e.g. due to pollen, the practical application was found to be limited.