TASK 7.2 REPORT

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Accurate design and yield assessment demonstration

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TRUSTPV
SOLAR PV, PERFORMANCE & RELIABILITY

Project Title: Increase Friendly Integration of Reliable PV plants considering different market segments.

Project Acronym: Trust-PV

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ABBREVIATIONS

AC	Alternating current
DC	Direct current
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
DT	Digital twin
EY	Energy yield
GCR	Ground coverage ratio
GM	Ground mount
GPOA	Global plan-of-array irradiance
HSAT	horizontal-single-axis tracker
LCoE	Levelized cost of energy
ML	Machine learning
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
O&M	Operation and maintenance
PR	Performance ratio
PV	Photovoltaic
SHJ	Silicon heterojunction
WP	Work package

ACCURATE DESIGN AND YIELD ASSESSMENT DEMONSTRATION

DELIVERABLE REPORT

1 INTRODUCTION

Designing a solar park and assessing its energy yield are fundamental aspects of a photovoltaic (PV) power plant project. Engineering factors, extending beyond mechanical structure and electrical layout to include topography, surroundings, and grid regulations, are critical inputs for any reliable yield assessment.

As competition increases, and profit margins narrow, optimizing project engineering and reaching accurate energy yield simulations are crucial for the commercial feasibility of a solar PV project.

This report demonstrates the impact of techniques used to optimize the digital twin design of a PV plant, and the energy yield (EY) tool developed within Trust PV.

The report comprises four types of energy yield analysis, for selected sites, in order to evaluate results in different scenarios. The analysis performed in this report are briefly summarized below.

- Validation of energy yield assessment tool

  Describes the developed yield tool, and the validation methodology and results from ground measured data from a lab-scale and a utility scale PV power plant.

- Benchmarking of energy yield assessment tool against a bankable software

  The EY tool is benchmarked against a bankable software (PVSyst), evaluating two utility-scale PV power plants, and a lab-scale power plant with unique system setup conditions, as well as 3rd party benchmarking, evaluating a set of PV power plants.

- Digital Twin topography evaluation

  This section evaluates the impact of topography on EY assessment, considering a satellite-based approach, in relation to a detailed drone assessment. It comprises results from two utility-scale power plants with unique topographies and surroundings.

- Financial analysis

  Based on the EY tool results, a detailed a financial analysis of the feasibility of a utility-scale PV power plant, considering various oversizing ratio conditions is provided.

2 STANDARDIZATION OF DATA FORMAT & PROVISION

Task 2.1 of the TRUST-PV project, titled "*Automated PV digital twin-based yield simulation framework*" [1] adopted the following definition for digital twins of solar PV assets:

> *A digital twin is a parametrized (2D/3D) model of a PV system that contains all the physical information needed to simulate the behavior and performance of the real PV plant it represents.*

Expanding the above definition according to [1] and respecting the merged requirements of all PV asset lifecycle stages, results in a digital twin that can enable collaboration between multiple platforms. The general digital twin needs to incorporate the following features:

- 3D model including all modules, nearby shading objects, and their optical properties
- Terrain topography
- Skyline description with increasing level of detail with decreasing distance from installation. Representation of far shading variations within PV plant. In certain cases, information regarding temporal changes is required (e.g., tree canopy)
- Complete electrical design and component characteristics. These need to be provided at delivery phase with the highest possible accuracy, because later discovery is challenging
- Component metadata, such as serial numbers and geolocation to uniquely identify otherwise identical components.
- Allow changes and their tracking using a versioning system
- Standardized, open format allowing different service providers to create compatible solutions. Thus, enabling the digital twin to act as an integration interface between multiple platforms

The purpose of the present report is to examine the validity of PV asset models created in-line with the above-stated requirements; and performance simulations carried out based on them, to demonstrate the benefits of the developed concepts.

3 DIGITAL TWIN BASED ENERGY YIELD ASSESMENT

The information contained in a PV digital twin can be fed to a PV performance model, allowing to simulate the performance and behaviour (e.g., yield, degradation, and reliability) of the PV plant that it represents. Such a performance model can facilitate optimal decision making throughout the lifetime of a PV plant. In the design & procurement phase, the PV system's design and component selection can be optimized and its lifetime energy yield can be accurately assessed. In the operational phase, the performance model can be used for performance monitoring and O&M decision making.

Transforming PV plant information into a PV performance model can be a challenging and time-consuming task, requiring specialist knowledge. This process may involve post-processing layouts to assign orientation groups, partitioning PV frames for shading calculations, manually selecting representative strings, choosing between mysterious modelling options, guessing and tweaking loss factors, and the list could be continued. One of the goals of the TRUST-PV project was to better streamline the design and performance assessment processes, to improve process efficiency, minimize human error and improve the transparency of estimated PV performance. This effort led to the development of PVcase Yield, a digital twin-based PV performance simulation software. PVcase Yield differs from other simulation software in its ability to ingest information directly from detailed PV asset digital twins and transform them into inputs to its physics-based models. This leads to a significant reduction in the number of tweakable simulation parameters, greatly reducing human effort required to prepare simulation runs, as well as the risk for errors. Thanks to the low number of simulation parameters, they can all be displayed on simulation reports, greatly improving the transparency and the reproducibility of performance assessments.

The basis of PVcase Yield is IMEC's patented bottom-up physics-based PV simulation framework [2]. One of its major advantages is that it uses a "grey-box" (physics-based) approach. Therefore, it can be easily adapted to various technologies, materials, and layouts without prior experimental calibration (as required by black-box modelling approaches mostly used in the PV sector), because all model parameters are physics-based. This gives the possibility to perform "what-if" simulations to optimize the system design and layout to the specific conditions of the sites.

The framework supports simulation of mono-/bifacial, fixed-tilt/tracked and integrated (e.g., BIPV) systems as well as Agri-PV and Floating PV systems. It applies advanced ray tracing techniques to calculate incident irradiance on the front and, in case of bifacial PV, the back side of the modules. Ray tracing allows to accurately resolve the effects of partial shading due to surrounding objects and the ground-reflected irradiance (albedo). The integrated electrical-optical-thermal model of the PV system can run at fine-grain temporal and spatial resolutions to include non-stationary and non-uniform effects. Precision in energy-yield modelling, even on short-time scales, is achieved in this model by coupling the thermal and electrical response, while resolving the impact of the micro-climate (affected by installation position, wind, etc.) [3]. It uses advanced computing solutions to ensure that high accuracy is paired with fast calculation times to meet the expectations in industrial applications [4], even for very large utility-scale PV plants. In particular, a machine learning algorithm analyses the layouts and captures repeated features, eliminating redundant calculations. This approach results in up to 10x reduction of computation time, without sacrificing simulation accuracy. The combination of these approaches brings PVcase Yield to the forefront of the current state of the art in precision, flexibility, and calculation speed.

Inconsistencies between the as-built documentation and the reality of a Solar PV plant are a recurrent problem in the PV industry. There is a general disconnection between fixes or changes made on site and the updates to the digital documentation. These documents are vital to assist with asset's health monitoring, using services like drone-based thermography, serial number scanning and digital twin. Throughout the use of drone-based CAD verification, an orthomosaic image of a solar PV plant is created. This orthomosaic can be geolocated, if required, using ground control points. Using it, CAD documents can be overlayed, immediately highlight any deviations in table placement and/or module amount. Further analysis and work can then provide up to date digital recreations of the plant. In addition, it is viable to analyse placement of transformers, inverters, and other components.

3.1 ENERGY YIELD SOFTWARE VALIDATION METHODOLOGY

The accuracy of PV performance simulation software can be assessed in multiple different ways.

The most applied methodology is comparison to other software, which we call “benchmarking”. Benchmarking is often chosen due to its simplicity, low associated costs, and the relatively good control over input and output variables. Despite these advantages, benchmarking results only provide a remote proxy to accuracy, since the only thing such studies assess is the delta between the compared software. In most cases it is impossible to determine which software comes closer to reality. Since benchmarking is a common industry practice, it cannot be ignored: results of benchmarking PVcase Yield with PVsyst are reported in Section 3.4.

The second most common accuracy assessment approach is comparison to data measured on a well-known and strictly controlled experimental setup. Such setups range from a single solar cell, up to few hundred kilowatts installations mimicking the components, design and structure of large-scale solar PV plants. Since such installations provide valuable insight into the capabilities and limitations of simulation software, the validation study performed on one such installation developed within the TRUST-PV project is described in Section 3.3.

Even the most realistic of such installations cannot be fully representative of large-scale plants, for 2 main reasons:

1. The plant needs to be heavily instrumented and well controlled, which sometimes leads to deviating from industrial design practices: very low DC-AC ratio to avoid inverter clipping modifying DC operating points, very low GCR to avoid row-to-row shading, special string design to allow string-level monitoring, are only a few examples.

2. The small size of such plants means that edge effects are emphasized, and topography undulation can be neglected. Additionally, such installations are typically developed in well-serviced areas, which often results in unusual (for large-scale PV) shading conditions.

The last, and least common accuracy assessment approach worth mentioning is the one with the highest relevance, but also the most challenging to carry out: comparing simulation results to data collected from operational, utility-scale PV plants – which the software in question is designed to simulate. It may seem ironic that this is the least common type of accuracy study performed, however, listing the main challenges helps to understand the cause of it.

a) Utility-scale PV plants operate with a minimum of instrumentation required to carry out the essential functions of Operation & Maintenance. These instruments are usually not carefully calibrated and not well maintained. As a result, data gaps and measurement errors affect the accuracy assessment

b) It is very challenging to re-create an accurate model of any real, large-scale PV installation in any PV performance simulation software.

c) Faults, degradation, equipment failures, outages all affect the recorded data. As such events are not deterministic in nature, PV performance simulation software cannot predict them. When such events affect the dataset, the scope of the accuracy assessment shifts from determining model accuracy, to examining how well one is aware of the evolution of these stochastic events.

Despite the challenges, the present report undertakes to use data recorded in a large-scale utility PV plant, in order to validate the performance predictions of PVcase Yield. A significant amount of effort has been invested into developing and executing a methodology that allows minimizing the impact of the above-listed challenges:

a) Additional instrumentation was deployed to measure the separate components of irradiance: GHI, DNI and DHI.

b) The study relies on the introduced Digital twin-based PV performance simulation software. Provided that the model of the site corresponds to reality, the software ensures that all of its characteristics influence the performance model. The 3D layout and the electrical connections of the plant have been meticulously digitalized, based on the provided as-built documentation. An additional CAD verification survey (drone-based) was performed to ensure that the real and modelled PV plant is in very close correspondence with each other.

c) The chosen plant has been designed and constructed to very high standards. The PV plant is practically new, under operation for less than a year. Thanks to this, degradation and equipment failures are not expected to impact the study. However, it is expected that some early-life issues might be encountered.

The results of validating PVcase Yield using data recorded in a real utility PV plant are presented in Section 3.2.

3.2 VALIDATING PVCASE YIELD ON A LARGE UTILITY-SCALE PV PLANT IN SPAIN

In this section, a description of the PV power plant will be given; followed by a detailed information on the dataset used and quality control applied. Finally, the validation results will be analyzed and discussed.

3.2.1 DESCRIPTION OF THE PV PLANT

The PV power plant is located in Spain. It`s a large-scale installation (>50MWp), with mono-Si PV modules and horizontal single-axis tracker (HSAT) setup (North-South axis at azimuth of 0 degrees). The plant is operating for less than a year. The topography is generally flat with undulations. Horizon shading is negligible, below 5° of sun height. The landscape is heavily populated by trees, which were taken in account for the system’s design, having a relevant impact in near shading. Tracker operation is enhanced through backtracking, however, without any diffuse sky optimization. There are three weather stations installed at the site. Measurements include plan-of-array irradiance (Gpoa), global horizontal irradiance (GHI), soiling ratio, relativity humidity, precipitation, module and ambient temperature, wind speed and direction, and finally one Razon+ which includes direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI).

The detailed model of the plant was created in PVcase Ground Mount (GM) by processing the as-built design files. Thanks to the CAD verification survey performed on the site by Above Surveying, it was guaranteed that the as-built design file accurately represents the reality. The as-built topography file was re-used, and the frame objects were converted into 3D objects effortlessly thanks to PVcase Ground Mount’s automated features. The as-built design file included LiDAR-based measurements of the surrounding trees: position, height and crown diameter. The latter data was also converted in an automated way into PVcase tree objects, preserving all major characteristics of these shading objects. The last and most laborious task was the re-creation of the complete electrical design of the plant.

Some impressions from the real asset and the digital model are shown below on Figure 1 and Figure 2.

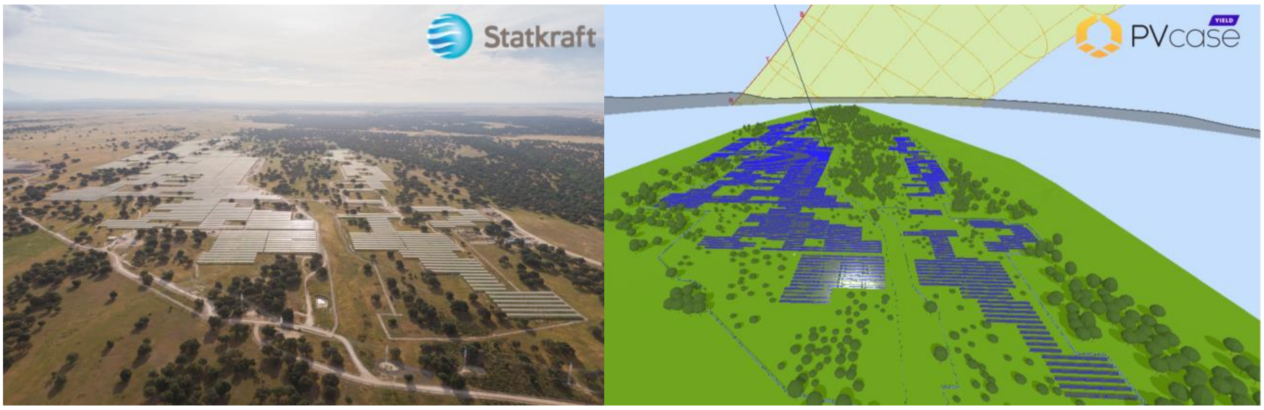

Figure 1 - Real PV plant (left) and its model in PVcase Yield (right) showing a high degree of similarity

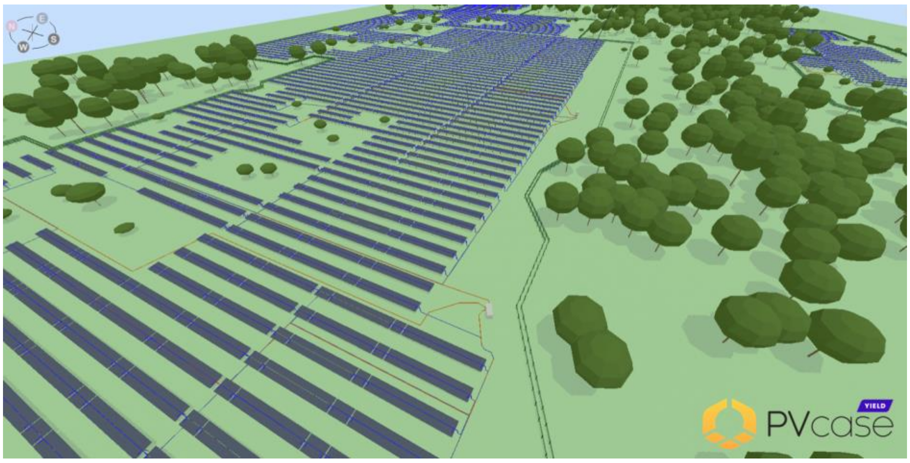

Figure 2 - Detail of the test plant's model showing trees, fences, transformer stations and underground cable runs (the terrain has been rendered transparent) in PVcase Yield

The developed model is directly suitable for PV performance simulations in the digital twin-based PVcase Yield.

3.2.2 INPUT AND VALIDATION DATA QUALITY CONTROL

The measurement campaign used in the validation ran from 27th Feb/24 until 7th Aug/24 measuring both input data (ambient temperature, wind speed, wind direction, DNI and DHI irradiance components – see Figure 3) and validation data (plane of array irradiance, module temperature and power). The data was measured at 15 minutes timestamp in UTC and no time zone correction was applied.

During the measurement period, most of the required variables as input for the yield model were complete with no need to apply any data imputation, except for a few timestamps of wind speed and direction had some missing values. In this case we applied a simple backfilling linear interpolation. Additionally, in a few cases the ambient temperature was zero. Since these appeared for only a few time steps, linear interpolation was also applied to fix these spurious values.

Note that, the ambient temperature, windspeed as well as wind direction, are measured at different substations. Given that the aim was to run a full PV plant, we averaged the different substations measurements of these input variables. The difference among the measurements at the different substations were minor. Figure 4 and Figure 5 show the mean and variations from the mean for ambient temperature and wind speed measurements at different substations.

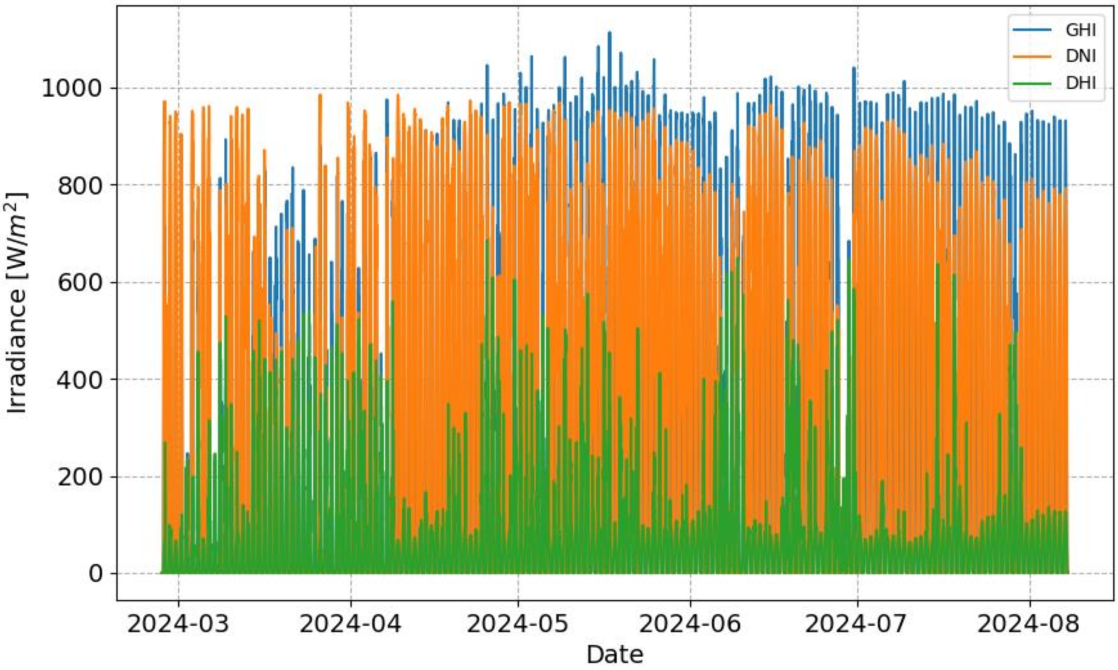

Figure 3 - Measured irradiance components; global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) used as input for yield simulation.

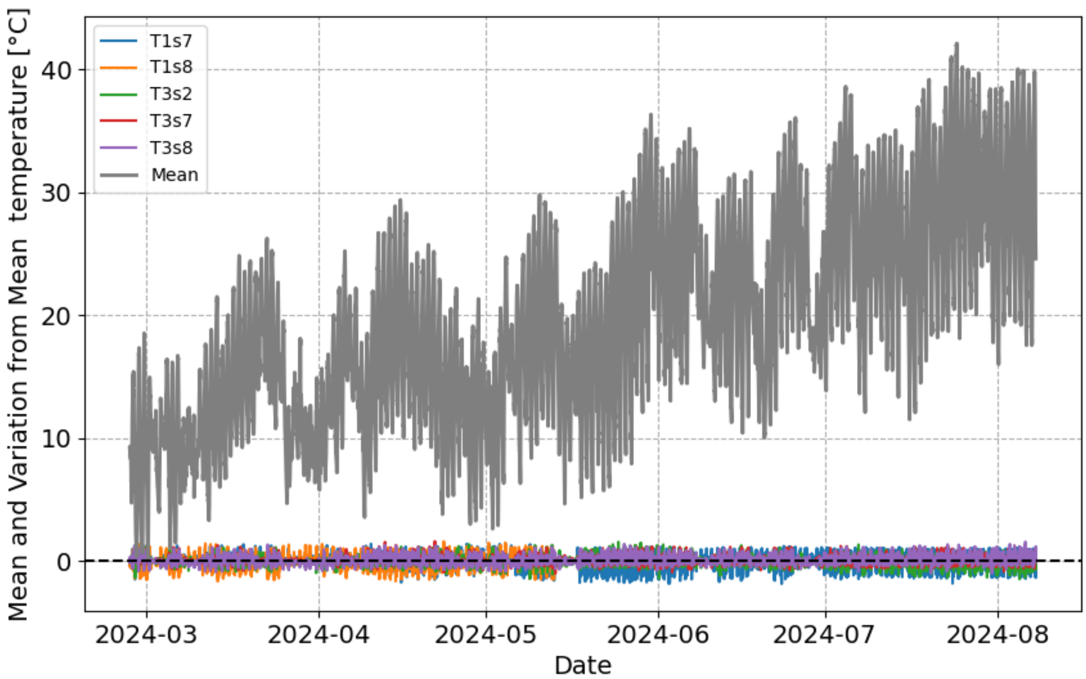

Figure 4 - The mean ambient temperature and the deviations from this mean temperature for various measurements across different substations.

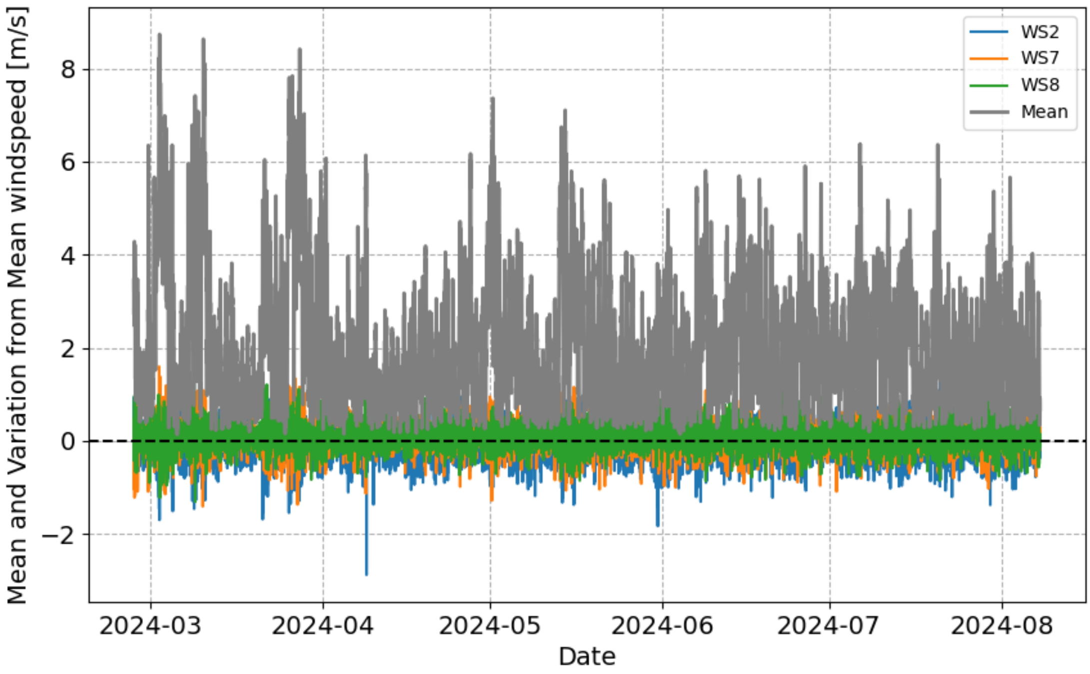

Figure 5 - The mean ambient temperature and the deviations from this mean temperature for various measurements across different substations (WS2, WS7 and WS8).

The validation data, (in this case the AC power), although didn't have missing values, it experienced curtailments, inverter clipping and inverter derating effects. The inverter setpoint signals were also provided, with values 100% indicating no curtailment for these timestamps or days, as shown in Figure 6.

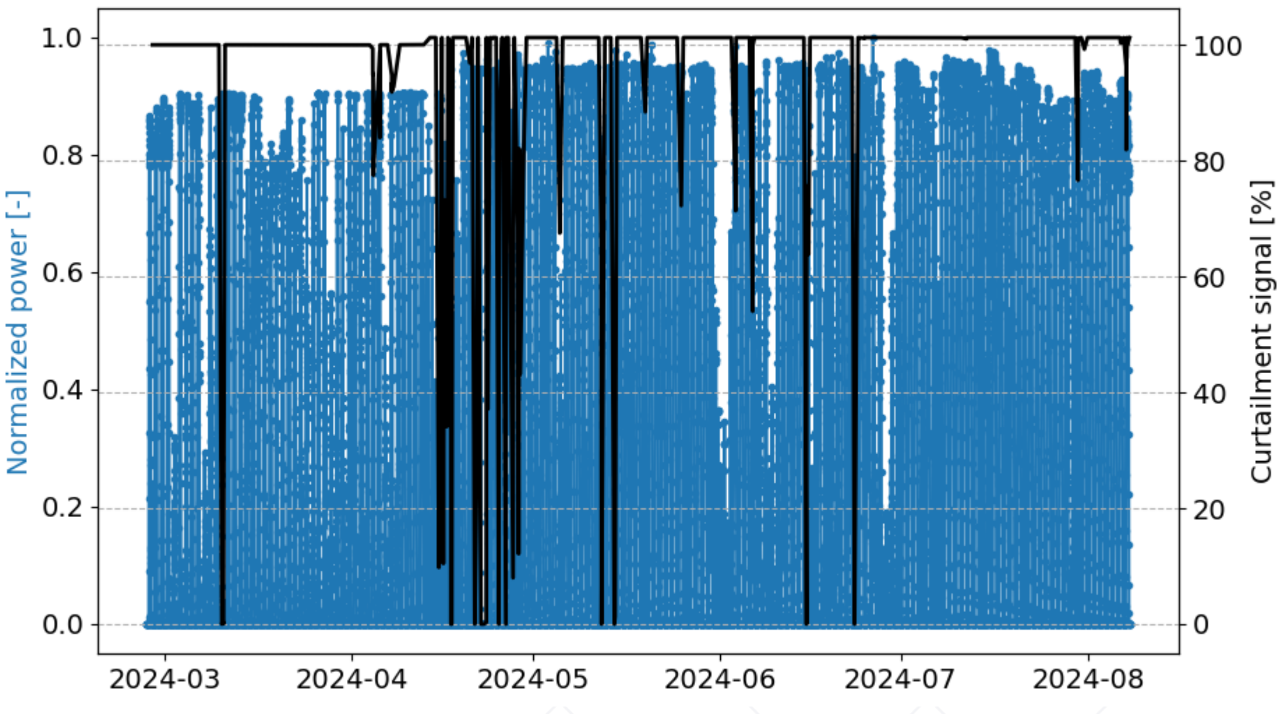

Figure 6 - Example of inverter AC power in blue with curtailment signals in black.

In Figure 7(A) we see the typical "M-shape" of the trackers in both Gpoa and power data at the beginning of the measurement period. However, a deviation from this 'M-shape' is visible in Figure 7(B) and(C) due to inverter clipping and derating, respectively. The inverter clipping was more frequent from the 13th of April through June and the derating was more frequent in July through the end of the measurement period.

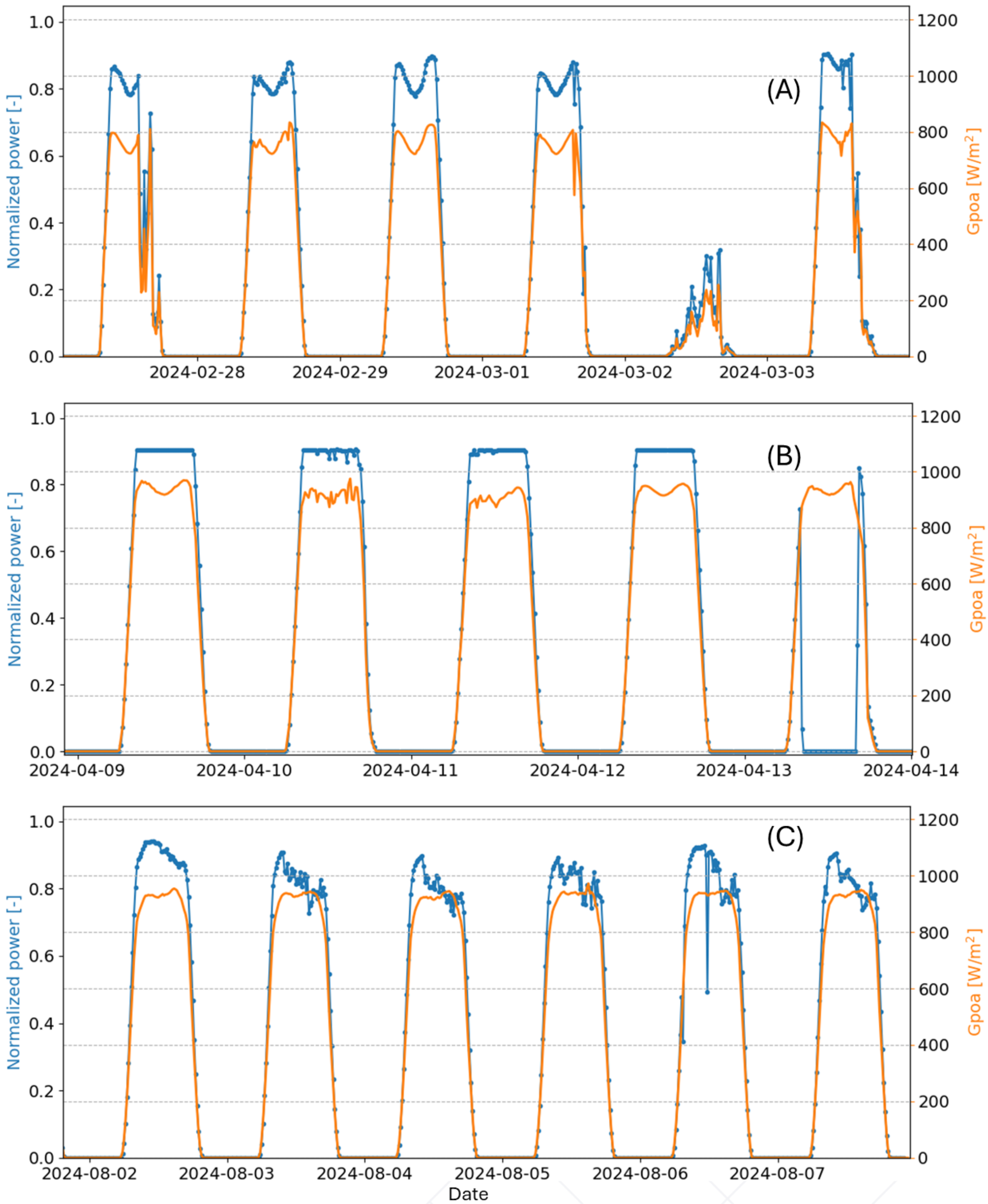

Figure 7 - Typical “M shape” of the tracker visible in Gpoa and power (A) and figure (B) and (C) shows the deviation of power from the ‘M shape” due to inverter clipping and derating respectively. The last day of (B) shows curtailment.

3.2.3 VALIDATION ASSUMPTIONS, RESULTS AND ANALYSIS

Simulations, and the comparison of simulated and measured data were performed using the same 15 minutes time resolution as used in the on-site meteorological and performance data. System losses were set identically to the as-built PVsyst report used for benchmarking purposes in Section 3.4.1. The PV plant model used in the simulation is described in Section 3.2.1. Additionally, to the accurate 3D and electrical reconstruction of the plant, care has been taken to assign module power classes to strings in accordance with reality. Therefore, the simulation considered the fact that some inverters combine strings built with different module types.

The comparison was performed using the inverter output AC power data, a dataset that excludes effects of AC cabling and transformer losses. While it was made possible to compare results inverter-by-inverter, here only the aggregated results summing all inverter contributions are reported.

The validation period was limited to the range 27th Feb/24 until 13th April/24. The reason of this is well visible on Figure 6: the way the plant was operated substantially changed, which is something performance simulation software cannot forecast and model. There were two major changes in the way of operation. First, the curtailment signal representing “no curtailment” changed from 100% to 101.25%, allowing inverters to export more power. Second, it also appears that the inverter clipping setpoint changed from the inverter nominal capacity to a value about 4,4% higher. The underlying reason was an issue with the Power Plant Controller, which the plant operator managed to resolve through these adjustments. However, after these adjustments the way the plant operates no longer aligns with the assumptions employed in the simulation model. This is why the decision was taken to limit the validation period.

The different statistical comparison measures are shown by Table 1. The simulations reproduced measurements with a very small bias of only -0.5%, meaning that simulation results generally underestimated the measured inverter AC output.

Table 1 - Statistical results of comparing simulated data to measured data, at 15 minutes resolution. A negative bias means that simulations under-estimated measurements

Mean Bias Error (MBE) [kW]	-119.5
Normalized Mean Bias Error (nMBE) [%]	-0.5
Mean Absolute Error (MAE) [kW]	1317.8
Normalized Mean Absolute Error (nMAE) [%]	5.6
Root Mean Square Error (RMSE) [kW]	2153.2
Normalized Root Mean Square Error (nRMSE) [%]	9.2

In order to provide a deeper understanding of what lies behind the above statistical measures, the following graphs illustrate the quality of comparison in more detail. For data protection reasons the vertical axis (Inverter AC power output) values have been hidden.

Figure 8 shows a good general agreement between simulation and measurement, even if a few days with missing data and larger discrepancies can be spotted.

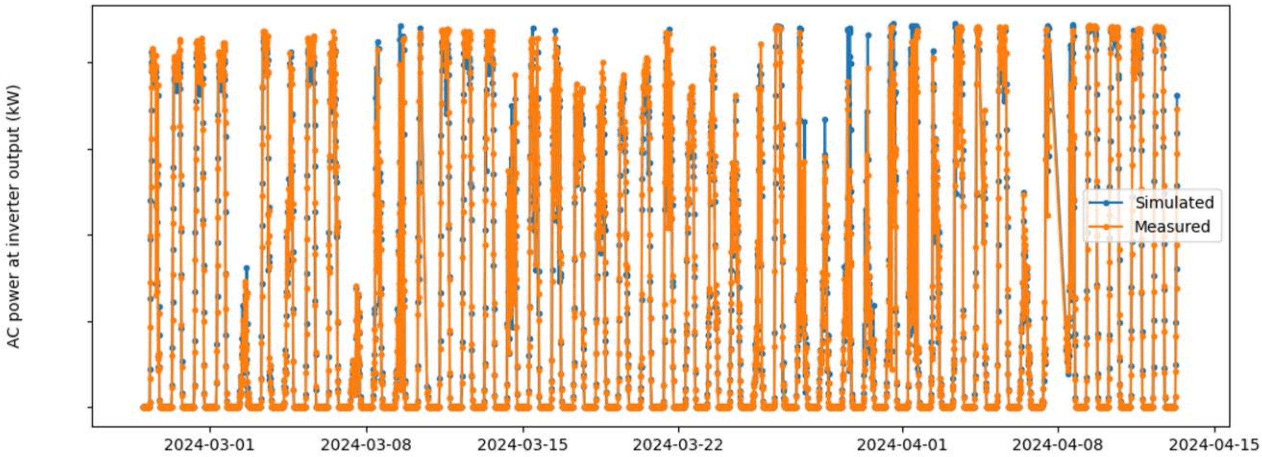

Figure 8 - Comparison of simulated and measured total inverter AC power output for the complete period used for calculating statistical measures

It is worth noting that some of the analyzed days were affected by inverter clipping (examples shown on Figure 9). On such days the near-perfect agreement of simulated and measured data significantly improves the validation measures.

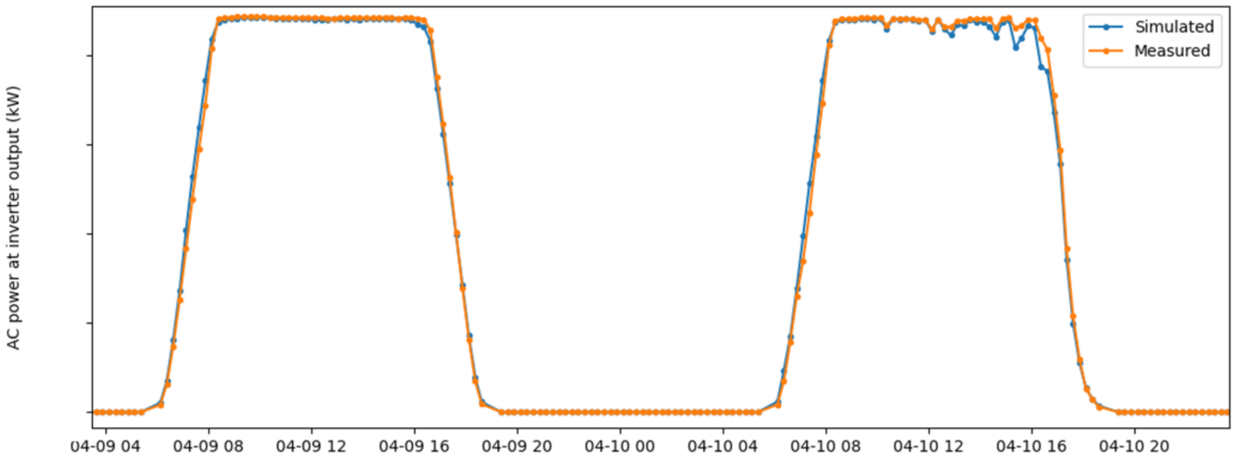

Figure 9 - Comparison of simulated and measured total inverter AC power output for clear-sky days, when inverter clipping occurs.

On clear-sky days that were not affected by inverter clipping, the comparison generally looks as shown by Figure 10, where simulations under-estimated measurements.

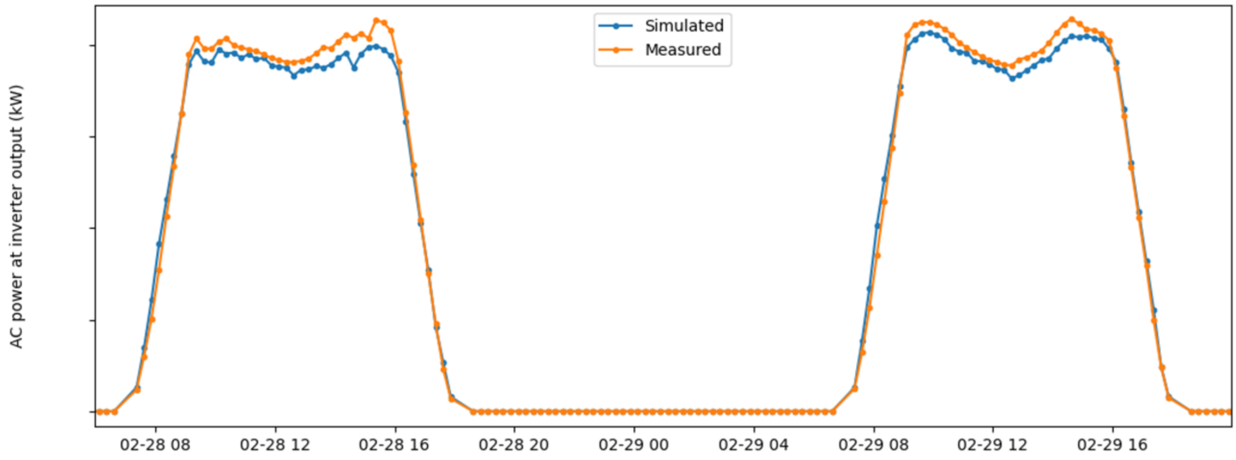

Figure 10 - Comparison of simulated and measured total inverter AC power output for clear-sky days not affected by inverter clipping

Finally, the good general agreement obtained for the (low number of) cloudy days is shown by Figure 11.

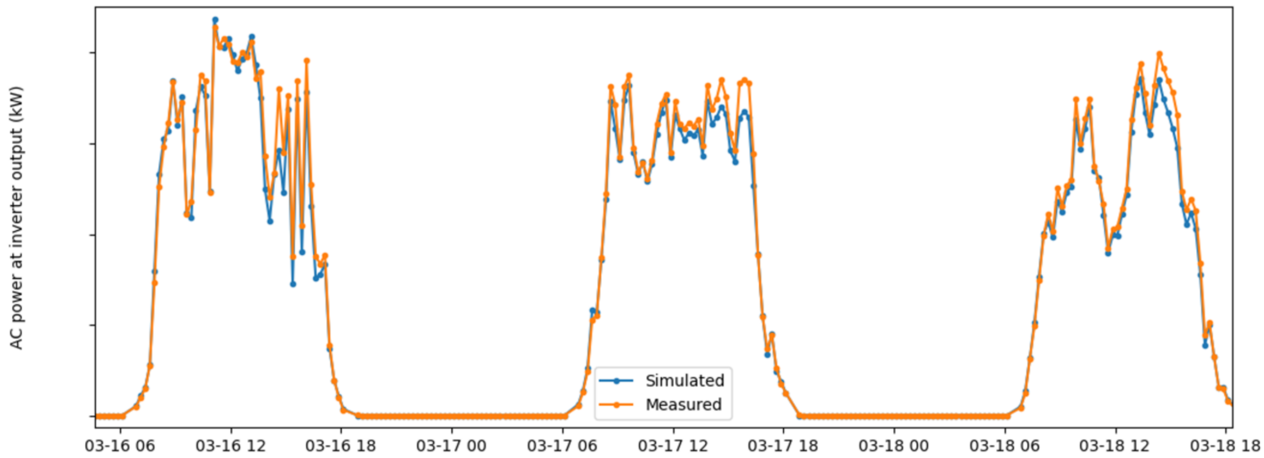

Figure 11 - Comparison of simulated and measured total inverter AC power output for cloudy days

In conclusion, the general agreement between simulation and measurement was found to be satisfactory, for the modelled complex, utility-scale HSAT, bifacial PV plant. The high detail of the available simulated and measured data leaves a lot more room for further analysis, which will be exploited in the future.

3.3 VALIDATING PVCASE YIELD ON OUTDOOR LAB-SCALE INSTALLATION

In this section, a description of the lab-scale PV installation will be given. Followed by a detailed information on dataset and considerations applied in the analysis, further on validation of results, using measured data, and its related discussions.

3.3.1 DESCRIPTION OF THE PLANT

In Bolzano (Italy), Eurac installed a horizontal single-axis tracking system (North-South axis at azimuth of 198 degrees) with bifacial silicon heterojunction (SHJ) PV modules from TRUST-PV partner Enel Green Power. The system has four separate rows of trackers, 12 modules each, with a total of 48 modules. The system is organised in two strings of 24 modules. One string has 24 modules with a nameplate capacity of 375 W, while the other strings have 24 modules with a nameplate capacity of 360 W. The system is installed on a surface of concrete and asphalt, and for testing purposes the ground underneath one of the strings was painted white to enhance the albedo and backside irradiance on the PV modules above it (Figure 12). One tracker is equipped with a pyranometer on the front and on the backside of the module plane. In addition to the plane of array irradiance, a full set of meteorological data is measured, including the irradiance components DNI, DHI, and GHI. The system as implemented in PVcase Ground Mount is shown in Figure 13. In Figure 14 we show how the torque tube is implemented in the 3D model, while in Figure 15 we visualize the shading scene as imported in PVsyst using a PVC file generated using PVsyst Ground Mount.

Figure 12 - Photos of the TRUSTPV system at Eurac in Bolzano, Italy. Left: String #1. Right: String #2. Clearly visible are the differently colored ground surfaces with the white-painted ground underneath String #1 (two tracker rows) and the unpainted mixed ground surface under String #2.

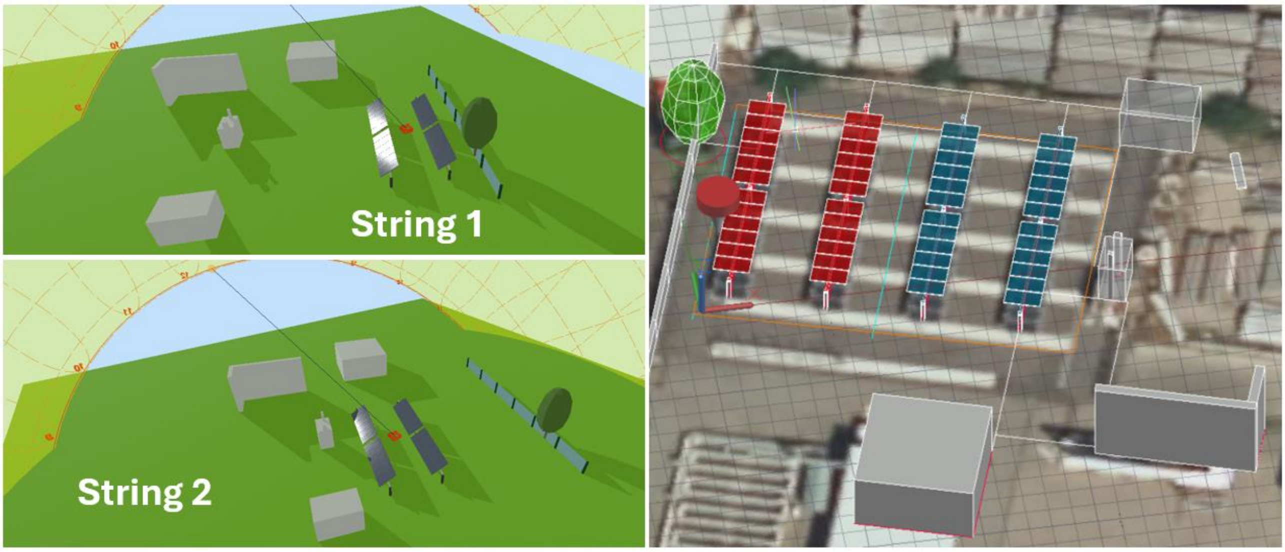

Figure 13 - Visualisation of the TRUST PV plant in Bolzano, Italy, as modelled in PVcase GroundMount. Right: screenshot of the system design as implemented in AutoCAD using the PVcase GroundMount plugin. Top left: layout visualization of String 1 in PVcase Yield. Bottom left: layout visualization of String 2 in PVcase Yield.

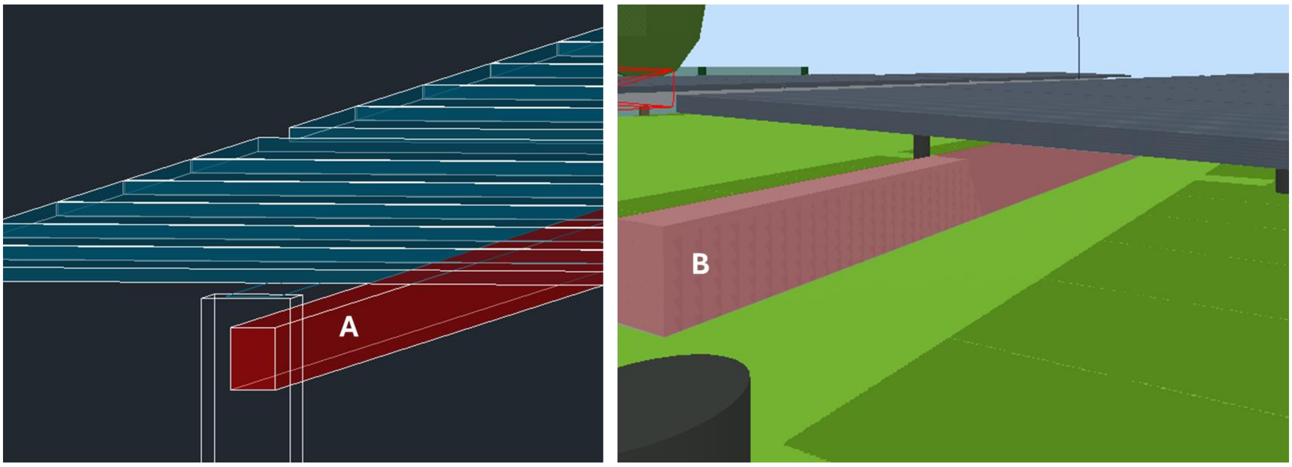

Figure 14 - Screenshots from PVcase Ground Mount (A) and PVcase Yield (B) showing the modelled torque tube underneath one of the tracker rows.

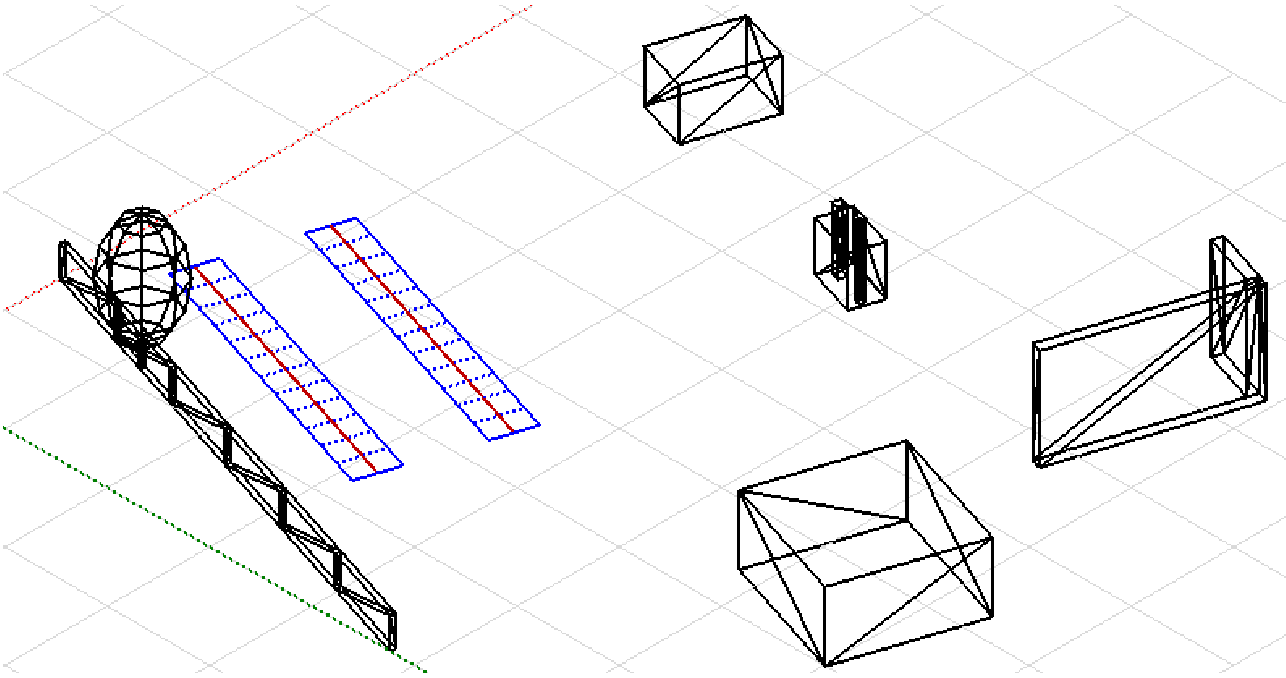

Figure 15 - Shading scene as modelled in PVsyst, using a PVC file exported using PVcase Ground Mount.

3.3.2 VALIDATION: ASSUMPTIONS, RESULTS AND ANALYSIS

For the validation activity, the TRUST-PV bifacial single-axis tracking system in Bolzano (Italy) was recreated in PVcase Ground Mount. Using onsite measurements, the tracking systems, including the torque tube, as well as several nearby shading objects (cabins, trees, fences) were implemented in the 3D design. The created AutoCAD model was subsequently exported to PVcase Yield and PVsyst for modelling the system energy yield. The system consists of two strings, each divided over two trackers. Since the ground surface is painted white under one of these strings, the yield modelling was performed for the two strings separately both in PVcase Yield and in PVsyst. PV module specifications were taken from the manufacturer's datasheets, but were updated using indoor flash-test results that were performed for all modules.

For the required meteo-data input, the onsite measured data for the year 2023 were used. Since some gaps were present in these data, Eurac used a machine learning model trained on local weather data from multiple weather stations to estimate the missing data to be able to run the simulations (both tools require a full year of input data).

Finally, PV system yields were modelled using both PVcase Yield and PVsyst, and the modelled data were compared to each other and to the measured data. For the final model comparison, the timestamps with missing data were excluded. Additionally, the data was filtered to exclude timestamps with obvious outliers in the measured data, nighttime values, and values with measured power of less than 50 W_{DC}. For our comparison, we focus on modelled DC power output.

At the time of writing, PVcase GM does not yet include the functionality of including a torque tube automatically, but rather PVcase suggests a workaround to place the torque tubes manually. The inclusion of the torque tube in the rear shading scene is important, to more accurately model the effect of the torque tube on the backside shading.

It must be noted that the system's tracker axes are rotated by 18 degrees from south, but the tracking algorithm of the physical system does not account for this. Rather, it is tracking as if the system's trackers were installed at 0 degrees from south, and also for the backtracking algorithm a perfectly south-facing orientation is assumed. The modelling tools, however, both *do* take into account the axis azimuth, and hence have different tracker angles at each timestep. The result of this discrepancy becomes apparent in Figure 20, where we can observe that for both tools there is a trend of negative bias in the morning hours, and positive bias in the afternoon hours.

In Figure 16 we show scatterplots of modelled vs measured DC power for the two modelling tools. Here we see that both tools have similar performance and have larger outliers mainly at low measured power values. It must be noted that the largest outliers were already filtered, for instances where we could clearly identify issues based on a comparison of measured DC power vs. measured plane-of-array irradiance. These cases reflect the experimental character of the power plant, which is occasionally disconnected from the inverter to conduct different kinds of inspections and other analyses for the TRUST-PV project.

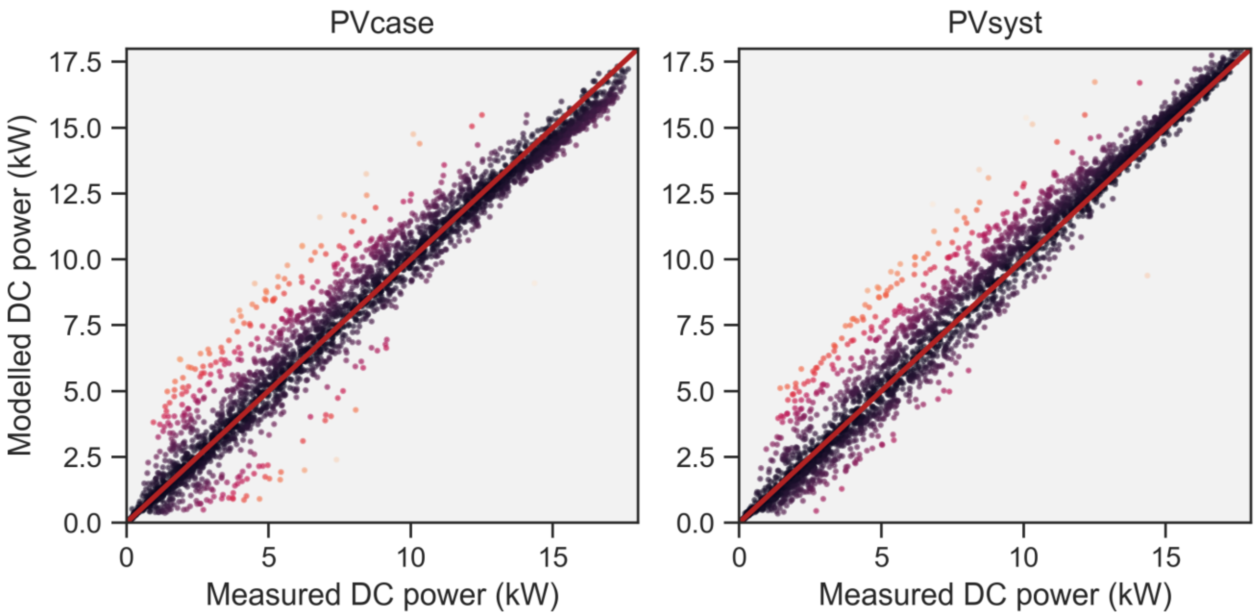

Figure 16 - Scatterplot of modelled vs. measured PV system DC yield. Left: PVcase, right: PVsyst. The datapoints' colors indicate the relative error magnitude.

For this section, we evaluate both the normalized root mean square error (nRMSE) and the normalized mean bias error (nMBE). The nRMSE is defined as:

$$nRMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(P_{\mathrm{mod};i} - P_{\mathrm{meas};i}\right)^2}{n}} \times \frac{1}{P_{\mathrm{meas;max}} - P_{\mathrm{meas;min}}}$$

Where $P_{\text{mod};i}$ is the modelled power and $P_{\text{meas};i}$ is the measured power a timestamp i, n is the number of observations, and $P_{\text{meas;max}}$ and $P_{\text{meas;min}}$ are the maximum and minimum measured power, respectively.

The nMBE evaluated here is defined as:

$$nMBE = \frac{\sum_{i=1}^{n}\left(P_{\text{mod};i} - P_{\text{meas};i}\right)}{n} \times (\overline{P_{\text{meas}}})^{-1}$$

Here, the MBE was normalized using the mean of the measured values, $\overline{P_{\text{meas}}}$. As can be seen from this equation, the MBE will be negative when the modelled values are lower than the measured values, and positive if the models overestimate the system's actual power output.

In Figure 17, we show the distribution of model errors. Here we can observe that for PVcase Yield, the distribution peaks at a slightly negative model error, while for PVsyst, the distribution peaks at a slightly positive model error. However, due to the asymmetrical distribution, the mean bias error is positive for both models, as indicated with the dashed lines in the following graph.

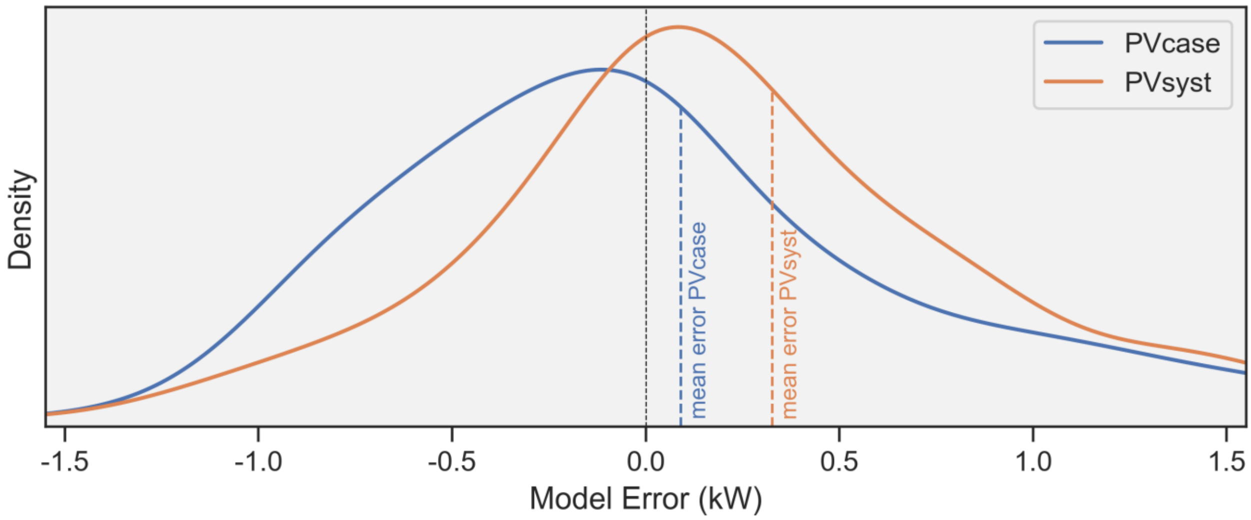

Figure 17 - Kernel density estimation showing the distribution of model errors for the two yield modelling tools compared. The mean errors for each model are indicated using dashed lines.

A comparison of the model error metrics is shown in Figure 18. Here we can observe that for most time aggregation levels, the normalised RMSE for PVcase Yield is slightly smaller than that of PVsyst. For the raw, 1-hour data outputs however, the normalised RMSE is essentially equal for both tools, at 4.66% for PVcase Yield, vs 4.68% for PVsyst. The MBE, shown in Figure 18 on the right, amounts to 1.13% for PVcase, vs 4.04% for PVsyst, e.g., both models slightly overestimate the energy yield of the TRUST-PV plant at Eurac Research.

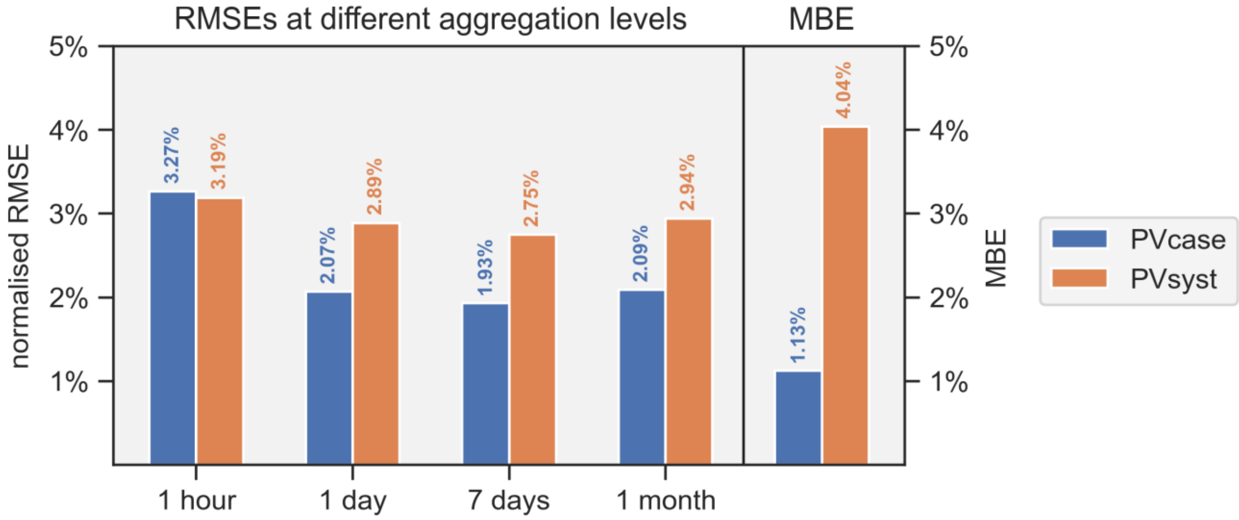

Figure 18: Overview of the model errors for the two yield modelling tools compared. Left: normalized RMSE for different levels of time aggregation. Right: normalized mean bias error.

In Figure 19 and Figure 20 we show how the error metrics vary by month of the year and by hour of the day. In Figure 19 we see that for both models, the MBE and RMSE is especially large in the winter months. These months are characterized by heavy shading of the system, and the large errors indicate potential user error with the recreation of the physical design of the PV system using PVcase Ground Mount, especially related to the shading objects. In these months, both models overestimate the PV system power, as evidenced by the large positive normalized MBE values.

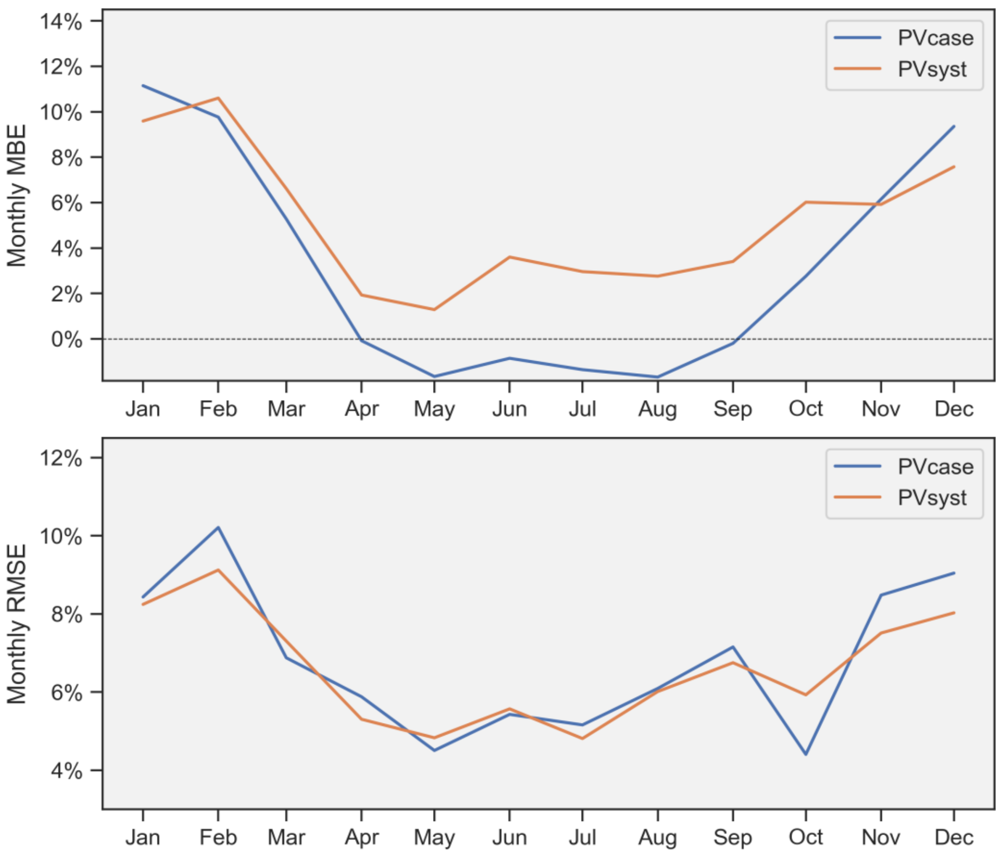

Figure 19: Plots showing the model error metrics per month of the year, for the two yield modelling tools compared. Top: Monthly mean bias error. Bottom: monthly normalized RMSE.

The process of recreating the shading scene accurately was complex, due to the presence of a tree with varying height and denseness of foliage throughout the seasons. Another complicating factor, as mentioned above, is the fact that the tracker axes are rotated by 18 degrees from south, but the tracking and backtracking algorithms of the physical trackers assume the axis is on a perfect north-south line. In addition, the system features two strings, each string consisting of two tracker rows connected in series. The shading for each row is likely very different, and this type of string layout is uncommon in commercial systems, so the modelling tools are not necessarily very well adapted to modelling these particular circumstances. These factors combined could at least partially explain the large modelling errors, as row to row shading due to faulty backtracking, and suboptimal orientation would especially affect the power generation in the winter months, with low sun elevation and large angles-of-incidence.

In Figure 20, we present the model errors by hour of day, for a selected range of hours. As before, we see that the model errors at low sun elevation, at the beginning and end of the day, are considerably larger than at higher sun elevation. Also, we see an asymmetric behaviour of the MBE, which is negative/lower before noon and higher/positive after noon, further indicating a relation with the offset of the tracker axes and the tracking algorithms that do not account for this in the physical PV plant.

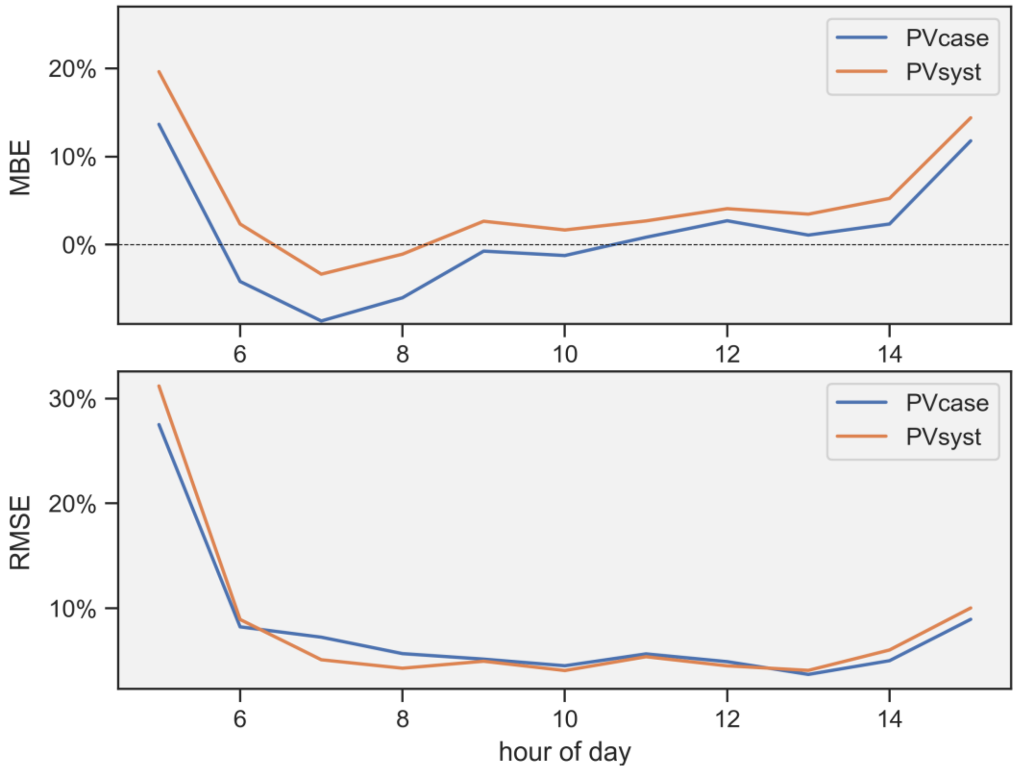

Figure 20: Plots showing the model error metrics per hour of day, for the two yield modelling tools compared. Top: Hourly mean bias error. Bottom: hourly normalized RMSE.

3.4 BENCHMARKING PVCASE YIELD VS PVSYST

Benchmarking energy yield simulation software against bankable software is a vital step in ensuring accuracy, reliability, and transparency in the PV industry. As the solar sector continues to expand, developers, investors, and operators rely heavily on energy yield software tools to estimate project performance and financial returns. However, different software platforms, such as PVSyst and other used tools, may produce varying results due to differences in underlying algorithms, inputs, assumptions, and methodologies. Without a clear understanding of these discrepancies, stakeholders risk over-reliance on a single tool, potentially leading to misinformed decisions and suboptimal project outcomes. As its widely understood in the industry sector, sole reliance on a unique provider may lead to products with lack of transparency, vendor lock-in, and limited innovation, while also potentially increasing costs and risks from disruption.

By conducting benchmarking studies across multiple energy yield software tools, the industry gains deeper insights into how different providers perform under virtually identical conditions. Such comparisons foster greater transparency in the evaluation process and encourage competition among software developers to improve user experience and innovation. This, in turn, helps stakeholders make more informed decisions, minimizing the risks associated to simulation uncertainties. Ultimately, benchmarking promotes a healthier, more competitive marketplace, ensuring that solar PV projects are developed with the best possible solution, enhancing overall industry confidence and performance.

3.4.1 BENCHMARKING PVCASE YIELD ON THE MODEL OF A LARGE UTILITY-SCALE PV PLANT IN SPAIN

The purpose of this benchmarking analysis is to compare the PV performance simulation performed in PVcase Yield and the one performed in PVSyst, using as-built documentation as inputs for both software. The goal of this study is to assess potential differences between the results calculated by PVcase Yield and the yield report accepted by financing institutions (i.e. bankable).

The utility-scale PV plant used for this study is the same as the one used in the previously described validation study. Its detailed description is provided in Section 3.2.1. In order to facilitate reading this report, it is recalled that the large-scale PV plant is a >50MW bifacial, HSAT plant, surrounded by a large number of trees.

To ensure a fair comparison of results, care has been taken to align all software inputs as much as possible. Nevertheless, some differences were inevitable. First, different shading scenes were used because none of the software support importing shading scenes from the other software. The used shading scenes can be visually compared with the help of Figure 21. Second, the input meteorological data is different by a small amount, since the original source files were not available. Third, the inverter model of PVcase Yield imposes clipping at the nominal inverter power, while PVsyst has different options to adapt the inverter's behaviour. In the current PVsyst simulation inverter over-power was enabled, and temperature de-rating was applied, causing the two inverter models to not yield the same results.

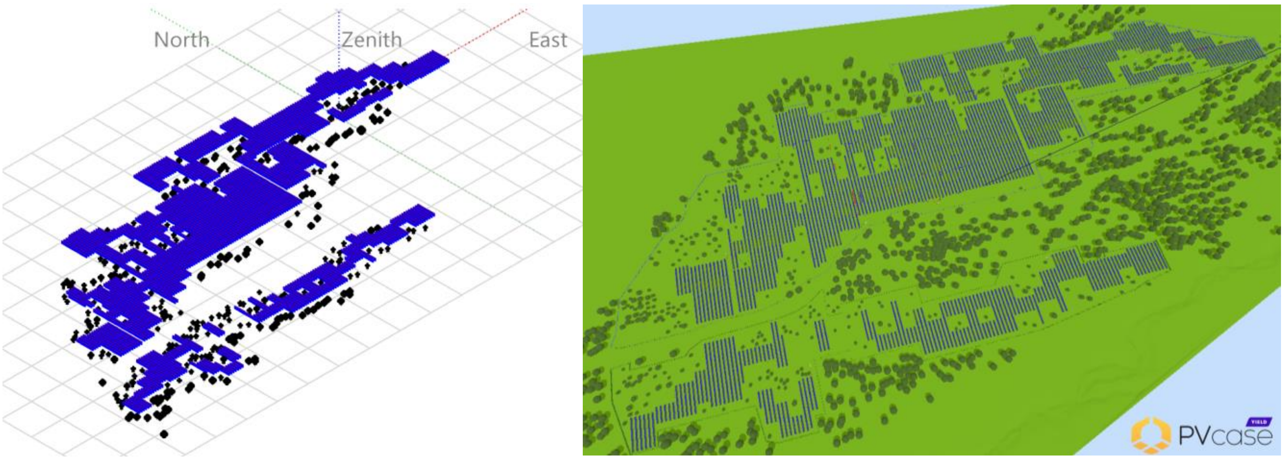

Figure 21 - Comparing shading scenes from PVsyst (left) and PVcase Yield (right).

From both simulation reports the loss breakdown charts were used to extract the main points where simulation results differ. This analysis is summarized in Table 2. Loss factors with identical values are not listed.

Table 2 - Differing loss factors between PVsyst and PVcase Yield simulations, their difference in % and the cumulative difference they contribute to.

Simulation step	Difference (PVsyst – Yield) [%]	Approx. cumulative difference [%]
GHI	0.2	0.2
Transposition gain	1.0	1.2
Far shading loss	-0.3	0.9
Near shading (front)	1.8	2.7
IAM loss	0.5	3.2
Low irradiance loss	0.6	3.8
Operating temperature loss	-0.5	3.3
DC cabling loss	0.4	3.7
Inverter efficiency loss	0.3	4.0
Inverter clipping loss	1.2	5.2
AC ohmic loss	-0.6	4.6
Transformer loss	-0.3	4.3
Grid limitation loss	-0.6	3.7

The difference of Energy injected into the grid is 3.8%, confirming that the approximate cumulative difference of Table 2 (3.7%) is relatively accurate. In order to provide more insight into the cause of these differences, Table 3 summarizes the known model differences for each impacted loss category.

Table 3 - Explanation of differences between the PVsyst and PVcase Yield simulations

Differing loss category	Explanation of difference
GHI	Different meteo data input file
Transposition gain	PVsyst's 2D view factor model and PVcase Yield's 3D ray tracing model represent different simulation techniques, providing two independent answers to the same question.
Far shading loss	The horizon profile used is slightly different. PVsyst: unknown source, PVcase Yield: PVGIS 5.2
Near shading (front)	Different 3D site model was used in both software
IAM loss	PVcase Yield reports combined IAM losses from both the front and rear side of the modules, assuming that the rear side glass is not AR-coated. PVsyst reports only the front-side IAM loss in this category.
Low irradiance loss	If the PAN file specifies it, PVsyst uses the low-illumination relative efficiency data. PVcase Yield does not rely on this input, instead, it uses default values obtained from the laboratory characterization of commercial c-Si PV modules.
Operating temperature loss	PVsyst's module cooling model relies on the Uc and Uv heat transfer coefficients, whose values need to be chosen by the user. PVcase Yield implements a physical cooling model, resolving the combination of

	conductive, radiative and convective heat transfer modes, without requiring any user input. The two models are very different and represent two independent answers to the same question.
DC cabling loss	Defined by the user as a loss factor in PVsyst (0.8% at STC), but calculated from the electrical topology, 3D cable lengths and a user-defined average cable resistance value of 4 Ω/km in PVcase Yield.
Inverter efficiency loss	Small difference likely due to slightly different operating points due to different power levels
Inverter clipping loss	The inverter model in PVsyst was configured to process power above the nominal inverter capacity and to apply temperature de-rating. In PVcase Yield, the inverter model is set up to start limiting at the nominal inverter capacity.
AC ohmic loss	Difference of loss factor input definitions
Transformer loss	Difference of loss factor input definitions
Grid limitation loss	Direct consequence of the different inverter clipping configurations

Finally, the Performance Ratios (PR) obtained from the 2 simulations are compared in Table 4. The PR formula used is the following:

$$PR = \frac{AC\ energy\ output}{\frac{Front\ Global\ Irradiance\ in\ plane\ of\ array}{1000} * Total\ module\ DC\ capacity}$$

, which is an equivalent of the monofacial PR definition, but considers the total bifacial production in the numerator. The absolute difference between the two PR results is only 2.27%, which is likely caused by the fact that simulation differences impact both the numerator and the denominator of the PR formula.

Table 4 - Comparison of final AC Performance Ratio results.

	PVsyst [%]	**PVcase Yield [%]**
AC PR monofacial	86.02	83.75

3.4.2 3RD PARTY BENCHMARKING ANALYSIS OF PVCASE YIELD

PV performance simulation software is widely used to forecast the financial potential of PV projects. Due to the key role of such software in financial decision making, it is of the utmost importance that new software entering the market be benchmarked against established, industry standard software. To this end, PVcase commissioned a 3rd party consulting firm to produce a benchmarking report. The executive summary stating the main conditions and findings of the report is cited below[1].

3.4.2.1 EXECUTIVE SUMMARY

Black & Veatch Management Consulting LLC ("Black & Veatch") was retained by PVcase UAB ("PVcase") to provide a conceptual level benchmark analysis of PVcase Yield ("Yield") and PVsyst© ("PVsyst") on four separate design/technology cases. The results of these analyses are summarized below. Additional details are provided in the body of the report.

Information on the location and photovoltaic (PV) module array type in the four cases for which Black & Veatch compared Yield and PVsyst simulation results are shown in Table 1-1. These cases include fixed tilt and single axis tracker configurations and monofacial and bifacial modules deployed on level sites in Germany, Texas (United States), and Spain. In addition, Yield and PVsyst simulations were run on sloped terrain for the case in Germany and the Texas case with the bifacial array. In Germany, the array was laid out on a three percent northward slope. The eastern half of the array with bifacial modules in Texas sloped five percent to the east and the western half of the array sloped five percent to the west. The four modeled cases had DC capacities of approximately 100 MWdc. Black & Veatch paid particular attention to match the inputs of the Yield and PVsyst simulations.

Table 1-1 Simulation Cases

Site Location	Coordinates	Array Type
Germany	48.931°N, 10.379°E	Fixed tilt, monofacial
Texas	31.736°N, -98.214°E	Single-axis tracker, monofacial
Texas	31.736°N, -98.214°E	Single-axis tracker, bifacial
Spain	39.619°N, -3.501°E	Single-axis tracker, bifacial

Table 1-2 summarizes the simulation results. The differences between the energy injected into the grid for the first year of operation, including the appropriate module degradation, computed by Yield and PVsyst ranged from 0.24% to 2.4%. The differences between the Yield and PVsyst simulation results were smaller for the cases using monofacial modules (0.24 to 0.41%) than for the cases using bifacial modules (0.76 to 2.4%). In

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every case, the net energy output computed by Yield was lower than that computed by PVsyst. Black & Veatch compared the individual loss terms in the Yield and PVsyst simulations. The differences in loss terms are described in detail in Section 2 of this (Edit: “the original”) report.

Table 1-2 First-year Energy Injected into the Grid

Design Cases	PVsyst	Yield	Difference (Yield – PVsyst)
Germany fixed tilt monofacial	115.81 GWh	115.47 GWh	-0.35 GWh (-0.30%)
Germany fixed tilt monofacial 3% N slope	114.96 GWh	114.49 GWh	-0.47 GWh (-0.41%)
Texas SAT monofacial	190.50 GWh	190.05 GWh	-0.45 GWh (-0.24%)
Texas SAT bifacial	196.99 GWh	195.49 GWh	-1.50 GWh (-0.76%)
Texas SAT bifacial 5% E & W slopes	195.68 GWh	194.08 GWh	-1.60 GWh (-0.82%)
Spain SAT bifacial	207.93 GWh	202.94 GWh	-4.99 GWh (-2.40%)

3.5 DIGITAL TWIN TOPOGRAPHY EVALUATION

During the past years the PV industry has recognized the importance of designing PV plants in 3 dimensions, using topographic data. 3D design software such as PVcase Ground Mount greatly facilitated the implementation and adoption of 3D design processes. The way topographic data is sourced depends on the project stage. In early stages, it is common to rely on data available from online repositories. As the project advances towards detailed design and construction, it is relevant to update the model with more accurate data obtained from LiDAR databases, or on-site surveys. Such data not only has higher spatial resolution and accuracy, in addition, a higher level of detail, representing both natural and man-made objects such as trees, buildings, electricity pylons, etc. While the impact of accurate 3D context on correct PV plant design is relatively well understood, its impact on PV performance simulation results is much less studied. Of particular interest is to investigate how the estimated performance of an asset changes when its model (and Digital Twin) is updated with an accurate 3D topography and shading scene.

3.5.1 METHODOLOGY

In order to maximize the relevance of this study, only real, existing, operating assets are used as study cases.

The first step is to re-create the investigated PV plant in digital domain, using the methodologies developed in the TRUST-PV project and described in [1]. The digital twin creation process uses the most accurate available 3D scene information, which includes topography, may include drone-based 3D model of the surroundings and LiDAR-based model of nearby shading objects. This high-fidelity model serves as the basis for comparison.

In the next step the model is simplified to the topography and level of detail that is commonly used in early project development stages. The topography layer is switched to the one obtained from Google’s Global Terrain Database, and further shading objects are ignored. This modification is very easily achieved in PVcase Ground Mount: the topography layer can easily be changed, the 3D PV frame and cable models adapted with one click of a button.

Finally, both models are transferred to PVcase Yield where simulations are set up (using identical assumptions), ran and compared. Since PVcase Yield implements the concept of a “Digital twin-based PV performance simulation software”, its performance model automatically takes any relevant 3D model difference into account, ensuring maximum objectivity and user-independence throughout this comparative study.

3.5.2 HILLY UTILITY-SCALE PV PLANT IN ITALY

This section describes the PV power plant in Italy, and analyses the differences between online vs drone-based topographic.

3.5.2.1 DESCRIPTION OF THE PLANT

Situated in the picturesque landscape of the Comune di Campli, within the Province of Teramo in central Italy, the hilly PV Plant represents a key renewable energy asset for the region. With an installed capacity of 850.08 kWp, this free-field solar power plant harnesses the abundant sunlight of the Italian countryside to generate clean and sustainable energy. Built on irregular terrain with diverse and rolling landscapes, the site was carefully selected for its solar potential and serves as a model for integrating renewable energy installations into challenging environments. The plant, which has been operational since 2011, employs a fixed-structure design. This means that the photovoltaic modules are installed at a permanent inclination of 25° with a 180° azimuth, directly facing south to maximize sun exposure throughout the year. While some modern solar plants utilize advanced tracking systems that adjust panel orientation based on the sun's movement, the plant relies on the simplicity and durability of fixed installations. This design reduces maintenance needs and operational complexity, ensuring a long-term, reliable energy output.

The plant is equipped with 3,696 photovoltaic modules, each one having a peak power of 230 Wp, which convert sunlight into electrical power. These modules are connected to three central inverters: 1 with a nominal capacity of 150 kW and the other 2 with a nominal capacity of 300 kWp. The inverters play a critical role in converting the direct current (DC) produced by the solar panels into alternating current (AC), which is then fed into the Italian national grid. The entire system is efficiently integrated to ensure that the energy produced is distributed directly into the grid, contributing to Italy's renewable energy targets.

One of the unique aspects of this PV plant is its use of irregular terrain, which has made it an ideal candidate for various advanced solar technologies and research initiatives. Drone surveys have been conducted to analyze the topography and improve understanding of how the landscape affects solar production. In addition, terrain and production simulations are being used to further optimize the plant’s performance, ensuring that energy output remains high despite the challenges posed by the uneven ground.

3.5.2.2 ONLINE VS DIGITAL TWIN TOPOGRAPHY EVALUATION

The hilly test plant in Italy is a fixed-tilt, South-oriented PV plant, with a capacity slightly less than 1MW. It is characterized by a steep South-facing slope, which tilts slightly towards East on the East half of the layout, and slightly towards West on the West half of the layout. Vegetation surrounds the PV plant from multiple directions, and industrial / agricultural buildings are found just North of it. The detailed model was created in PVcase Ground Mount by first performing a drone-based photogrammetry survey and subsequent 3D modelling (by Above Surveying), followed by re-creating the plant’s electrical design based on as-built documentation. Some impressions from the real asset and the digital model are shown below on Figure 22 - Figure 25.

Figure 22 – Real plant(left) vs. digital plant (right): view towards North, up the slope.

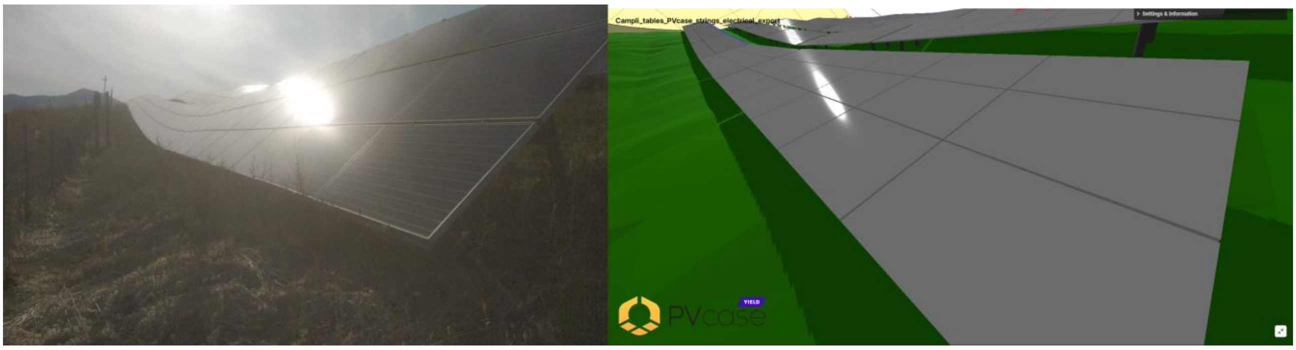

Figure 23 - Real plant(left) vs. digital plant (right): view along the front row of the East part of the array.

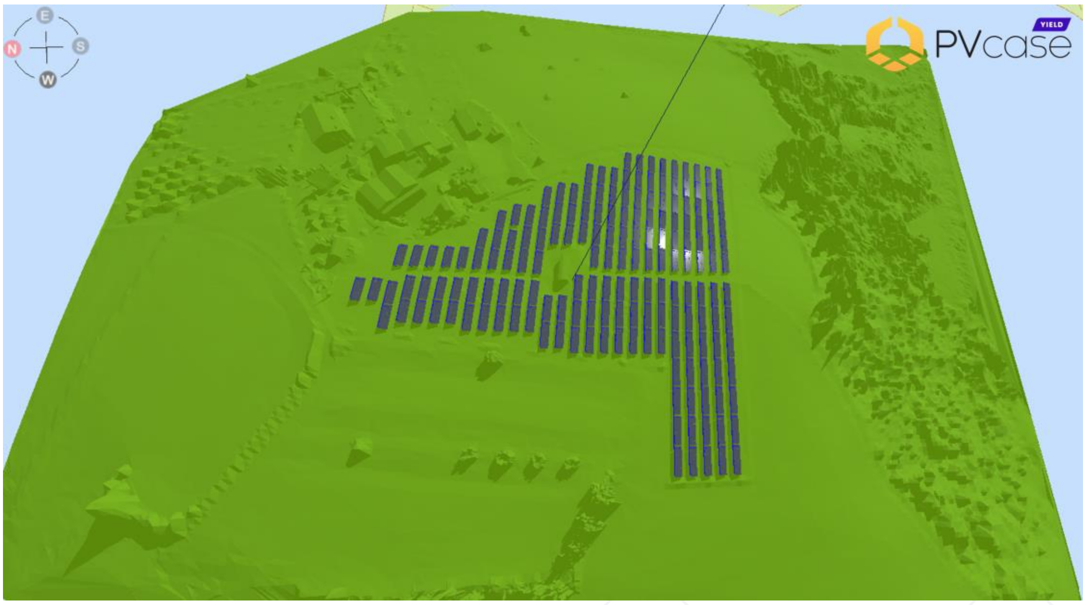

Figure 24 - Overview of the Italy test plant's layout and surroundings, as seen from the West.

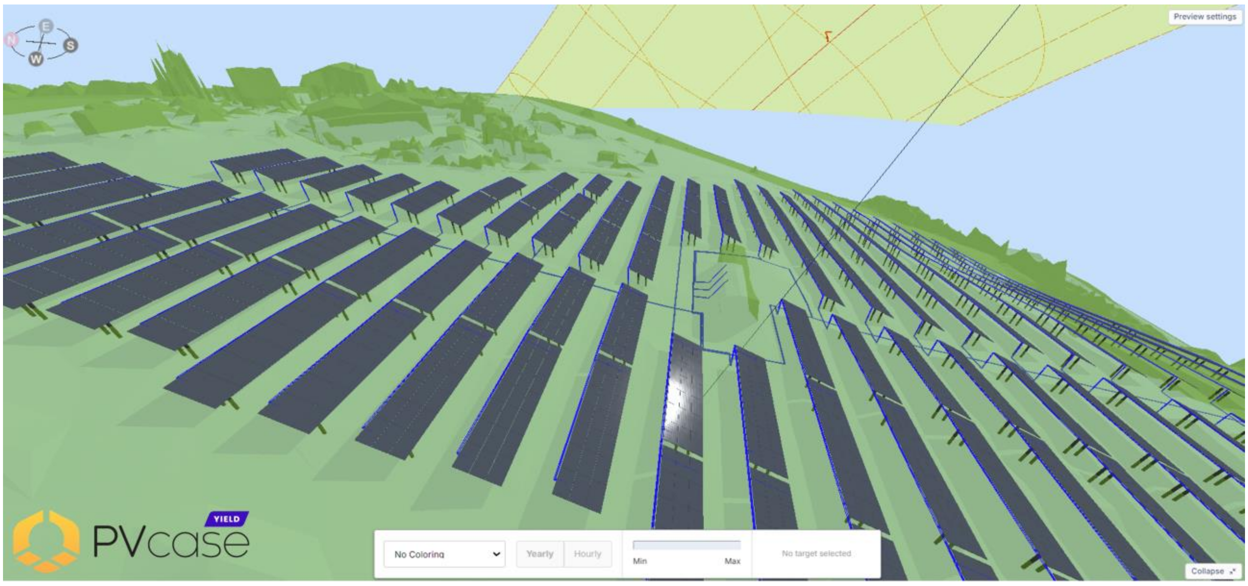

Figure 25 - Underground electrical cable (blue) runs visualized by rendering the terrain transparent, near the central inverter station (located in the centre).

After running performance simulations in PVcase Yield on both the high-fidelity and early-stage models, the distribution of string shading losses reveals some important terrain topography differences (Figure 26):

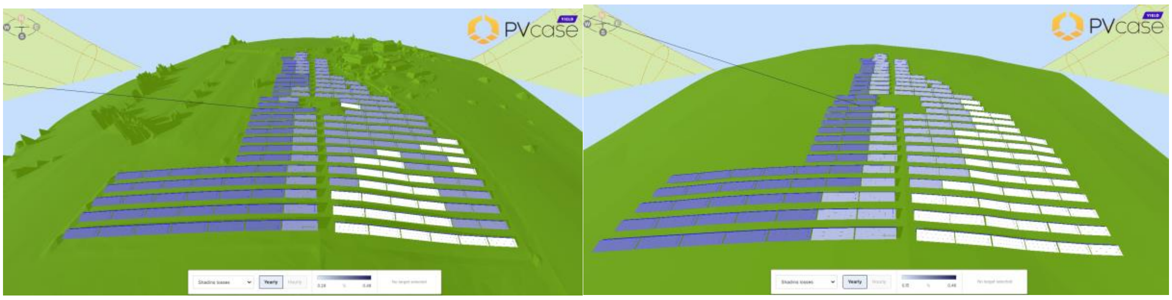

Figure 26 - Shading loss distribution on the high-fidelity model (left) and on the model using the online topography data (right).

The average slope of the site is well-captured by the online terrain model; however, further, localized details – such as the recess in the middle of the East-side block – are clearly lost.

Comparing high-level simulation results in terms of specific yield, energy output, transposition gain and shading losses in Table 5, however, reveals only minor differences. This finding suggests that in some cases capturing the main site slope tendencies might be sufficiently representative in order to reasonably estimate the high-level performance measures of a PV plant.

Table 5 - Comparison of high-level simulation results between the two models.

	AC yield [kWh/kWp]	Energy injected [MWh]	Transposition gain [%]	Near shading loss [%]
Drone survey	1419.63	1183.88	16.2	0.43
Online topography	1420.56	1184.66	16.23	0.34

Zooming in, on the strings mostly affected by the topography difference, we can observe significant differences in hourly string DC energy output, of 2.35kWh (drone survey) vs. 2.2kWh (online topography), or 6.8%. This is shown by Figure 27.

Figure 27 - DC string output during a specific hour: high-fidelity model (left), online topography (right).

String performance differences occur in both directions but average out during a years' span. The results suggest that the deviation of respective strings performance between the 2 layouts might be significant. This suggests that using accurate topography, in conjunction with digital twin-based PV performance simulations might enable more robust performance benchmarks for monitoring and fault identification purposes.

3.5.3 LARGE UTILITY-SCALE PV PLANT IN SPAIN

The PV plant used for this study is the same as the one used in the previously described validation study. Its detailed description is provided in Section 3.2.1. In order to facilitate reading this report, it is recalled that the PV plant is a >50MW HSAT plant, which is surrounded by a large number of trees.

Performing energy yield simulations in PVcase Yield revealed that the trees significantly impact the performance of certain strings. This is visualized on Figure 28, where the performance difference of the East and West module rows can be clearly distinguished from the difference caused by shading due to trees.

Figure 28 - Simulated DC string power timeseries result rendered on the 3D model in PVcase Yield, showing the impact of row-to-row and tree shading.

Next, the simulation was repeated on a simplified version of the model, which aims at representing the level of detail available during the early development stage. The topography data was swapped to the one from Google's database and the accurate tree models were ignored.

The AC specific yield, and the system losses mainly responsible for the difference are listed in Table 6.

Table 6 - AC specific yield and the most differing system losses between simulations using the detailed plant model and online topography data

	AC yield [kWh/kWp]	Front shade loss [%]	Back shade loss [%]	Mismatch loss [%]
Detailed model	1946.7	3.1	8.12	0.18
Online topography	1957.06	2.66	7.97	0.08

Ignoring the presence of the trees leads to over-estimating the plant's performance by ~0.5% due to under-estimating the front-side shading losses. Since the plant has been designed by considering a buffer zone between the tree-covered areas and the module areas, this affects only a low number of strings. However, it could be speculated that if the tree locations and the shading losses would have been precisely known in the early design stage, module placement could have been further optimized, potentially enabling to place more modules on the available land, without compromising on shading losses.

It is apparent that the minor topography differences did not affect the plant's performance, usually the case for predominantly flat sites.

3.6 FINANCIAL ANALYSIS

Financial analysis is critical in determining the viability and profitability of solar photovoltaic (PV) projects, with the Levelized Cost of Energy (LCOE) serving as a key metric. One of the most influential design factors affecting LCOE is the DC/AC ratio, which refers to the relationship between the DC capacity of PV modules and the AC capacity of inverters. Optimizing this ratio can significantly impact energy yield, system efficiency, and overall project costs.

This analysis leverages on a digital twin verified plant, applying the analysis into an operational asset. By understanding the financial impact of different configurations, the study aims to provide practical insights that can help developers and investors optimize system design for maximum cost-effectiveness. These findings are critical for advancing solar energy's competitiveness in the energy market and driving further cost reductions.

3.6.1 PROBLEM STATEMENT

This analysis explores how the DC/AC ratio affects the economic assessment, particularly the levelized cost of electricity (LCoE). The DC/AC ratio is "the ratio of installed DC capacity to the inverter's AC power rating" [5]. The LCoE is "the cost per kWh of electricity produced by a power generation facility" [6]. It considers the whole lifetime of the system n and can be calculated with the equation below for a PV farm:

$$LCoE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

The investment costs I_t and O&M costs M_t as well as the electricity yield E_t of each year t are considered in the calculation. The discount rate r translates future costs into the present value.

3.6.2 INPUTS

Statkraft's PV plant located in Spain will be employed for this study, described in Section 3.2.1. The plant has a nominal DC power of >50 MWp and multi-MPPT string inverters with ~250 kVA nominal power each. Hence, the plant has a DC/AC ratio of 1.1. Of the originally installed inverters, ~90% are connected to 14 strings each, while the remaining are connected to 12 strings each. Each inverter has 12 MPPT inputs. Some inverters are connected to a higher number of strings than available MPPT inputs. In these cases, the strings are connected in parallel.

PVcase Yield was used to provide simulated data for the electricity generated by the plant. The provided data is effective DC power output (kW) and average string MPP voltage (V). Ideally, the study should employ the power and voltage of each string of the plant to consider shading effects and other local phenomena. However, such data was unavailable. Statkraft has provided the financial inputs for this calculation.

3.6.3 METHODOLOGY

The DC/AC ratio of the plant will be altered by changing the number of inverters in the PV plant while preserving the original count of 2728 strings. This will affect the AC capacity and the generated electricity yield for the LCoE calculations while keeping the DC capacity of the plant.

The input DC power and voltage to each inverter must be determined to model the generated electricity yield. Since all strings are connected in parallel to the inverter, the input voltage is the average string MPP voltage. The input power, on the other hand, is the average string MPP power multiplied by the number of strings connected to the inverter. Therefore, we need to determine the number of strings connected to each inverter. This value depends on the total number of inverters. For example, if a DC/AC ratio of 1.2 is aimed for, 185 inverters are needed, and 14.8 strings should be connected to each inverter. Since this is not physically possible, 47 inverters will contain 14 strings each while the remainder will contain 15 strings each. Considering this, one can determine the DC inputs to each inverter in the plant.

The next step consists of the conversion from DC to AC power. For that, the inverter efficiency needs to be modeled. The study intended to employ the inverter model developed by the Sandia National Laboratories (SNL) [7] which parametrizes the efficiency curves for its ease of use. However, the inverter is not available in the CEC database. Its SNL parameters could have been extracted from the efficiency curves of the inverter's datasheet. However, given that the inputs are already approximations, the marginal gain in accuracy from using the SNL model does not justify the time invested in finding the parameters. Instead, the digitalized efficiency curves are employed for the assessment (see figure below).

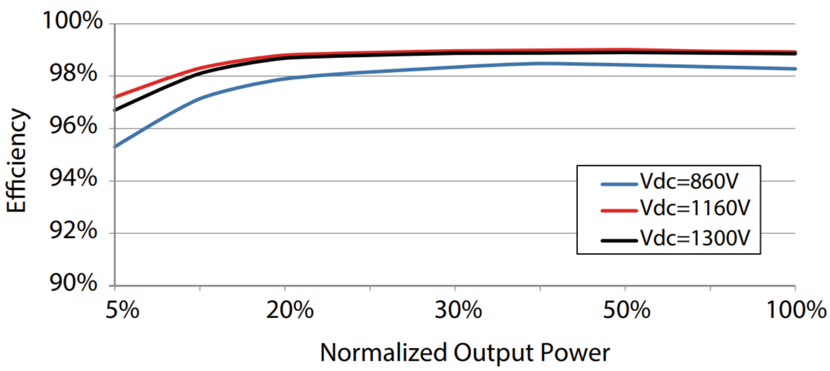

Figure 29 - Inverter efficiency curves for three input voltages. Figure extracted from the inverter's datasheet.

To use these curves, one needs the DC power and voltage at every instant of time. The DC power determines the efficiency value of each curve, while the DC voltage decides which curves to employ. A linear interpolation between the efficiency curves of the two closest voltages is performed. If the DC voltage exceeds 1300 V or is below 860 V, the efficiency of the 1300 V curve and 860 V curve are used, respectively.

Additionally, if the normalized output power is below 5%, the inverter is not operating and consumes 0.2 kW. The maximum that the inverter can output is 100% of its nominal power. If the input DC voltage or DC current is outside their operating ranges, the inverter does not operate either. Additionally, the grid limits the AC capacity of the farm at the connection point at ~75% of the installed DC capacity so the output AC power is trimmed to this value.

Once the annual electricity yield is obtained, the LCoE can be calculated by adjusting the financial inputs to the number of inverters.

3.6.4 RESULTS AND DISCUSSION

A range of DC/AC ratios between 0.9 and 1.35 was explored. For each combination, the AC yield and LCoE were computed. The figure below shows the main results. The values for the original layout of the 1.1 DC/AC ratio are highlighted with a filled dot.

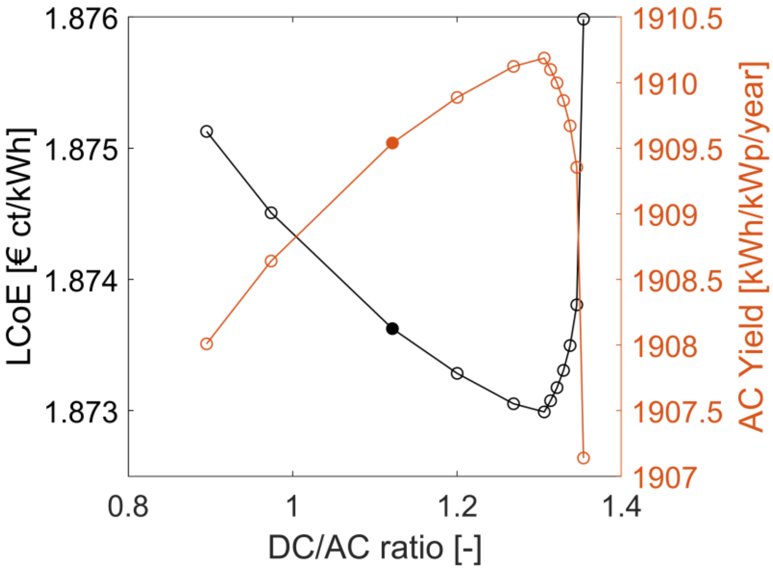

Figure 30 - Levelized Cost of Electricity (LCoE) and annual AC energy yield as a function of the DC/AC ratio altered by changing the number of inverters.

The lowest LCoE (and highest AC yield) was obtained for a DC/AC ratio of 1.3 by using 170 inverters. For ratios below 1.3 the LCoE decreases steadily while for values higher than 1.3, it increases abruptly. The optimum DC/AC ratio optimizes the inverter operation. Looking at the efficiency curves, the inverter works optimally for normalized output powers between 30 and 100%. For powers below 30%, the efficiency decreases. For powers higher than 100%, the inverter power is clipped. The optimum DC/AC ratio ensures operation mostly in the range of 30 to 100%. Additionally, a reduced number of inverters decreases the overall losses during downtime. The inverters' cost is not affected since they are represented in €/kWp.

Looking at the whole picture, the impact of the DC/AC ratio on the LCoE and the AC yield is minimal. At least when such a ratio is altered by varying the number of inverters. The maximum difference in LCoE is well below 1 Euro cent when altering the DC/AC ratio between 0.9 and 1.35, which is a wide range. Similarly, the impact on AC yield is below 0.2%. A higher impact may be observed if the string values were not approximated, and the local effects could be considered. Additionally, the inverter costs for this plant were independent of the number of inverters and relatively low, both in comparison to other expenses and to the inverter costs of other PV farms. These two aspects caused the LCoE to be altered only through the AC yield, which is a small contribution. In addition, other aspects may have contributed to the original decision of DC/AC ratio, for example paid reactive power ingestion into the grid, and potential future integration with other technologies (wind and BESS).

4 CONCLUSIONS

This report demonstrates key methodologies and results for the validation of the digital twin-based PV energy yield simulation software. A laboratory-scale system, two complex utility-scale PV power plants, and a number of hypothetical PV plants were evaluated under different accuracy evaluation scenarios. Trustworthy data is vital for energy yield accuracy investigations, thus drone-based CAD verifications were performed on the utility-scale assets, ensuring simulation inputs are accurate.

Validation of PVcase yield showed satisfactory performance with an nMBE of -0.5% (underestimation) and nRMSE of 9.2% at 15-minute resolution for the utility-scale plant, and a nMBE of 1.13% (overestimation) and nRMSE of 3.27% at 1 hour resolution for the lab-scale system. The main causes of differences between measurements and simulations have been identified for both cases. These generally point towards the simulation tool's lack of flexibility in modelling unusual operating conditions that we encountered in these real, operational assets. However, observing the utility-scale, and the summer months results for the lab-scale system, it can be inferred that PVcase Yield tends to underestimate generation, however, generally within a reasonable uncertainty range.

The benchmarking results obtained relative to PVSyst illustrate the importance of software documentation and user understanding of simulation inputs. Variations in results had root-causes in hidden-layers of inputs, which are not necessarily present in the final report, such as the inverter's temperature de-rating behaviour, or the module's low illumination behaviour. In addition, fundamental methodological differences also exist between PVcase Yield and PVsyst; particularly in module temperature and irradiance modelling. Results obtained from the two software hence represent two independent answers to the same question and carry complementary value.

The benchmarking analysis not only included results obtained by the TRUST-PV consortium, but also a summary of a 3rd party benchmarking study carried out by Black & Veatch. Including all mentioned studies, it can be inferred that PVcase Yield predicts energy yield more conservatively relative to PVSyst. Moreover, it is important to highlight its capabilities such as 3D modelling and 3D ray tracing, which likely enables PVcase Yield results to be more realistic, especially when evaluating complex topographies and surroundings.

Due to increasing competition, PV power plant developers are struggling to secure suitable land, often opting for sites with complex topography. The report compares online available topographic data with drone-based surveys, revealing that while high-level simulation outputs may show negligible differences, string performance can vary by up to 6.8%. Therefore, showing that critical aspects can be overseen in the early stages, impacting stakeholders later in the process. Energy yield simulation is the basis for solar project's finance and performance guarantees, it is the key information for O&M and technical asset managers to identify expected performance. Therefore, if simulated string information is not available, inaccurate data may lead to misdirected efforts, rather than addressing more meaningful and productive work.

Finally, a financial analysis was performed, using PVcase Yield simulation outputs, focusing on DC/AC ratio variations. The study explored a range of DC/AC ratios between 0.9 and 1.35, assessing their impact on AC yield and Levelized Cost of Energy (LCoE). The optimal DC/AC ratio was found to be 1.3, which maximized AC yield and minimized LCoE by optimizing inverter performance between 30% and 100% of output power.

In summary, this report executed several simulation, benchmarking and validation studies based on the outlined digital twin-based simulation methodology. The results demonstrate the feasibility of modelling PV power plants in great detail at a variety of scales, and the possibility of harnessing the potential unlocked by a high level of detail for accurate and detailed PV performance simulations. Simulation results obtained on highly realistic models offer a new, more conservative look at estimated asset performance, relative to the status quo. This work involved the collaboration of many partners, from across the PV value chain, which was essential to identify and address the key challenges within a digital twin-based energy yield simulation workflow, meant to support the complete PV system lifecycle.

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