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Assessing tracker availability in 2 GW solar power plants

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Abstract. Single-axis trackers are key components to optimize utility-scale solar energy generation. As the overall electricity production share of PV is globally increasing at a significant pace, profitability margins narrowed and the industry is becoming more competitive. Ensuring high availability of all devices in a photovoltaic (PV) power plant is crucial for healthy asset life. Historically, specific key performance indicators (KPI) for single-axis trackers have been overlooked by both research and industry. This work proposes a KPI for trackers, with two alternative methods. Over 2GWp of PV power plants have been analyzed, mostly located in temperate climate zones. The median of results range from 66% to 88% availability, depending on data filtering considerations. These results are substantial, and alarming. Industry claims sometimes even as high as 99% availability, while the assessment of more than 2 GWp PV power plants tells us a different story. In addition, this work highlights and discusses multiple issues regarding tracker data quality, especially related to angle datasets, and identifies missing data as one of the main systematic issues when dealing with single-axis tracker data.

Keywords: Solar energy / photovoltaics / single-axis tracker / key performance indicator / availability / performance optimization

1 Introduction

Solar energy has seen exponential growth over the past decade, driven by geopolitical issues and a push for energy security in major countries. Photovoltaics (PV) have the one of the lowest Levelized Cost of Energy (LCOE) among all energy technologies [1]. However, constraints in the value chain and challenges in securing land have posed significant obstacles for power plant project financing. As technology has advanced, energy yield assessments and equipment reliability have improved substantially. Yet, as the market has evolved, competition has intensified, and profitability has diminished in many segments of the solar energy industry.

Even before the widespread adoption of bifacial photovoltaic (PV) modules, single-axis tracker systems were commonly used in power plants. Currently, trackers are used in many new developed PV projects. In high insolation conditions, PV plants equipped with trackers can increase energy yield by around 20–35%, depending on site conditions [2]. In addition, new technologies and tracking strategies have been introduced, with manufacturers claiming that tracking optimization strategies can enhance energy generation, in relation to standard backtracking operation, by up to 6%, depending on weather conditions [3–5]. Despite these promising figures, validating such information is challenging, especially when proprietary algorithms are used to manage tracker fleets.

Although single-axis trackers are common in PV power plants, and play a significant role in enhancing energy generation, there is a research gap on utility-scale tracker operation and reliability. Furthermore, single-axis trackers are rarely included in industry contracts as part of contractual guarantees. Contractual guarantees are measurable commitments defined in contracts to ensure that the plant meets specified performance requirements. For instance, the most common key performance indicator (KPI) is the Performance Ratio (PR) [6], used in Engineering, Procurement, Construction (EPC) [7] contracts with Asset Owners and Managers. Inverter availability is the primary KPI for Operation & Maintenance (O&M) contracts [8]. The International Energy Agency (IEA) PVPS Task 13 has recently issued a detailed report on Technical and Economic KPIs [9], highlighting common metrics and data quality control techniques. Notably, the report only briefly mentioned utilizing a KPI to evaluate single-axis trackers, without further description on its

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application. Similarly it is be mentioned as a best practice in other industry reports [10], however, without entering in detail about the metric.

Historically, trackers have not been included in contractual KPIs as they were considered optimization components, and manufacturers had no control over the EPC process and installation. However, technological advancements have made tracker operation more complex, generally requiring a separate communication system operated by the tracker manufacturer. Consequently, O&M personnel are not permitted to debug algorithms independently, nor is fully replacing a single-axis tracker feasible. Additionally, tighter profit margins have led to narrower safety margins for KPI guarantees, making any equipment malfunction on site to have a larger impact on potential bonuses or liabilities.

In summary, tracker system plays a substantial role in PV plant performance directly affecting contractual guarantees and generating liabilities for stakeholders who lack control and expertise over tracker algorithms and on-site troubleshooting capabilities. Therefore, it is crucial that equipment on site can be de-coupled from overall site performance and evaluated individually.

This paper proposes and evaluates a novel KPI methodology to assess tracker operation. The methodology aims to be simple and effective for use in contracts, facilitating the quantitative and qualitative evaluation of operational faults in single-axis trackers within utility-scale PV power plants. Reliable tracker operation is essential for the efficiency of existing PV power plants. Industry players generally claim operational availability, or uptime, over 99% [11,12], although detailed results and methodologies are not openly disclosed.

Operational issues in trackers are often embedded within other performance indicators, such as PR. It is crucial to decouple tracker performance and evaluate it individually. The industry requires such a KPI for future contractually binding agreements. This KPI has the potential to provide a better understanding of actual tracker losses that can be recovered or optimized (e.g. tracking misalignments, topography-related losses, etc.) and pure operational losses, which depend on equipment reliability.

2 Material and methods

This section discusses the proposed methodology and datasets utilized in this work.

2.1 Methodology

The proposed KPI is defined as *Tracker Availability*. The objective of this metric is to evaluate the time-based operation of the device, without any relation to its impact on energy generation. Analogous to inverter time-based availability [9], the reasoning is that the equipment must be fully functional as much as possible, to facilitate energy production regardless of sky conditions. As previously mentioned, optimization tracking algorithms may be hard to replicate; therefore, all PV plants used in this paper use a classic algorithm, with optimization only on backtracking period, which will be discussed later.

The KPI for single-axis tracker k will be:

$$Trk.Av._k = \frac{T_{Useful} - T_{Down}}{T_{Useful}} \quad (1)$$

Where:

T_{Useful}: Sum of all datapoints within the evaluated period.

T_{Down}: Sum of datapoints where single-axis tracker is deemed unavailable within the evaluated period.

For a datapoint to be deemed unavailable:

$$|\theta_{Trk.} - \theta_{Reference}| > \theta_{Threshold} \quad (2)$$

Where:

θ_{Trk}: Tracker actual operation angle.

$\theta_{Reference}$: Reference angle.

$\theta_{Threshold}$: Threshold angle.

Analogously, Tracker Availability for a PV plant with n tracker is defined as:

$$PVPlantTrk.Av. = \frac{\sum_{k=1}^{n} \left(T_{Useful} - T_{Down}\right)_k}{\sum_{k=1}^{n} \left(T_{Useful}\right)_k}. \quad (3)$$

Important considerations:

- Calculated only when Global plane-of-array (GPOA) irradiance > 0 (W/m^2).
- Wind stows, and other expected stows (i.e. maintenance) are considered available datapoints.

The threshold angle is empirically defined as 5°, using the available dataset. For plants with available information on actual and target tracker angles, provided by the manufacturer, it can be observed that the step angle, analysing a 15 min resolution dataset, is smaller than 0.5°. Therefore, a safety margin of ten times the expected operational behaviour is a fair assumption. Step angle is the fixed angular increment by which a solar tracker adjusts its position during each control action to approach the target angle. A detailed sensitivity analysis is much needed to identify the ideal threshold angle, however, given the complexity of the task, it is left for future work.

Essentially, a single-axis tracker operates by following the sun-path, which can be calculate through solar position equations. As power plants have become more complex, with thousands of concomitant operating trackers, manufacturers have developed in-house methods to mitigate energy loss due to self-shading by trackers, namely backtracking. Such behaviour is not simple to replicate, and the logic is generally not shared externally by tracker companies. Thus, operators need to rely on manufacturer data or machine learning techniques to replicate the backtracking behaviour at a designated PV plant, posing challenges for tracker operation evaluation during early-stage operations.

Figure 1 illustrates periods of core tracking and backtracking for a single-axis tracker in a PV power plant. As observed, the trackers gradually misalign during

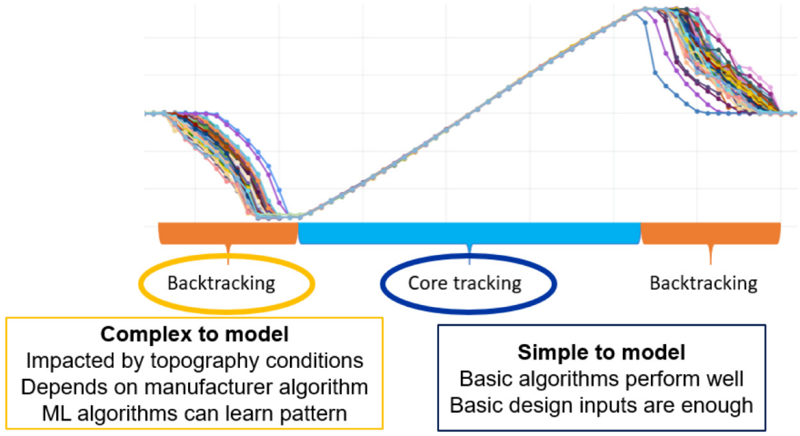

Fig. 1. Backtracking and Core tracking for a single-axis tracker.

Table 1. Information on methods utilized and approach utilized per tracker condition.

Method	Backtracking	Core Tracking
ALL Trk	Compare Actual angle provided by manufacturer vs Modelled angle	Compare Actual angle provided by manufacturer vs Modelled angle
Core Trk	Disregarded	

Constituents are expressed as percent of seed wet weight.

backtracking periods to avoid self-shading and improve energy yield. During core tracking periods, all equipment aligns to maximize solar energy utilization.

In this work, the authors will evaluate the metric, based on two different methodologies. Outlined in Table 1.

Both methods will utilize single-axis tracker modelled angle as reference, using PVLIB open-source model [13]. The inputs of the model are based on as-built information from the PV Power plants. In some cases, tracker manufacturers provide the tracker target angle information within the SCADA system; however, to ensure fair comparison throughout the dataset, a standard modelling algorithm was selected as the approach. The actual tracker angle is retrieved via the SCADA system, for each individual tracker. The data is available in 1 min and 15 min resolutions, thus the highest available time resolution was utilized for the calculations relating to each PV power plant.

2.2 Dataset

The authors analyzed sixty-four PV power plants, mostly installed in mediterranean and temperate climate regions. Approximately 80% of these installation are installed in European countries, with a combined installed DC capacity of approximately 2.1 GWp. The datasets from each power plant range from 6 months to 4.9 yr of data. Figure 2 illustrates the overall capacity and data length of the analyzed power plants. Due to confidentiality reasons, the exact capacities and locations of the power plants cannot be disclosed.

3 Results & discussion

The dataset was analyzed considering additional information from status and error logs available for each device. Thus, deviations due to preventive maintenance and safety measures, such as stowing caused by high wind, were considered as available behavior, see formula (1). As mentioned previously, the objective is to evaluate the sole operation of single-axis trackers, regardless of sky conditions or energy contribution. Therefore, the following results assume that missing data for actual tracker angles relates to equipment unavailability. The caveats of this assumption and its impact on the results will be discussed in detail in section 3.2.

The plot below illustrates the results regarding both *Core* & *ALL* Tracker conditions. From the initial dataset analyzed, fifteen out of the original PV power plants were considered to have insufficient data quality for the analysis. The reasons for poor data vary and include:
- Significant amount of stalling and missing data;
- Inconsistent scaling and offsets from the data coming from the SCADA system;
- Deviation between tracker angles and generation profile;
- Mismatch between available data and provided as-built inputs to be used in tracker angle modelling.

As a matter of fact, the authors have identified data quality to be one of the main challenges when working with utility-scale single-axis tracker datasets; section 3.1 will address in detail issues encountered and related difficulties in addressing these data anomalies.

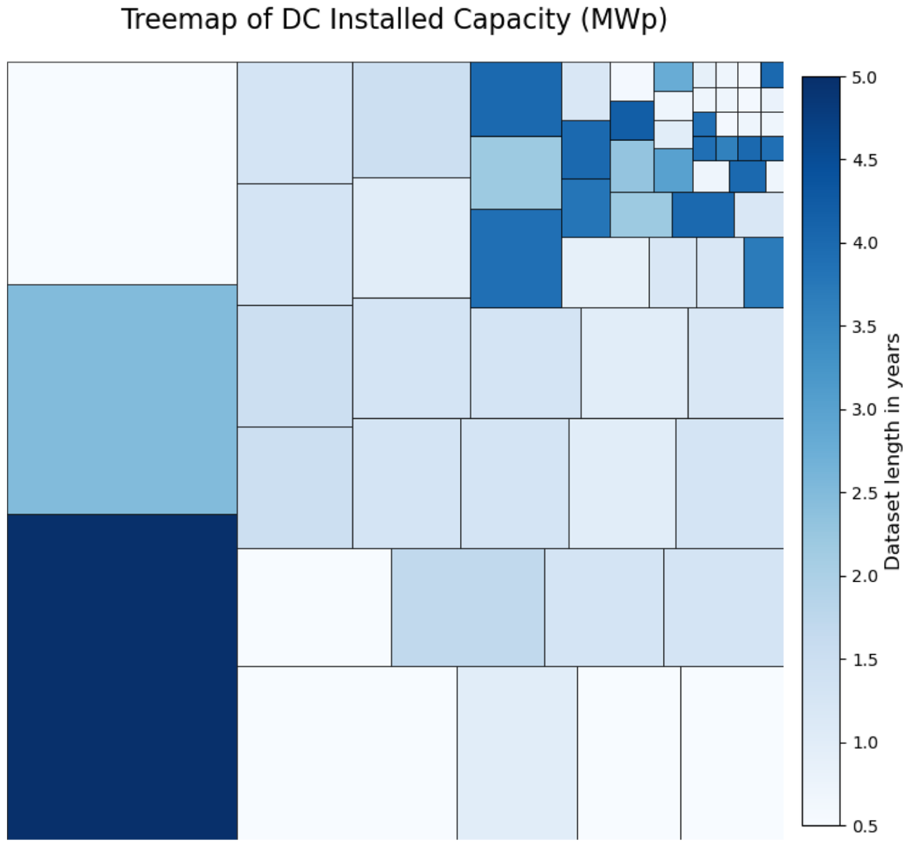

Fig. 2. Treemap sized by installed capacity per PV power plant, in MWp, where smallest one is rounded to the nearest 2. Colormap illustrating dataset length, in years, per PV plant.

Figure 3 summarizes the distribution of results observed throughout the analyzed power plants. The *ALL Trk* has availability distributed more evenly throughout the assets, without a clear concentration in any of the bins. The highest availability was 96%, whether the lowest is at 22%, having an average and median distribution of 64% and 66%, respectively.

Furthermore, the *Core Trk* results highlight a higher uptime, being the 85%–90% availability bin the one with larger number of plants, and the distribution has an average and median of 76% and 83%, respectively. There's a +17 percentage point difference between *Core* and *ALL Trk* medians, demonstrating aspects such as more robust operation at key sunlight hours, but also intrinsic difficulties in modelling backtracking. *Core Trk* has only two plants above 99%, illustrating a systematically poor availability of single-axis tracker throughout the power plants, which may significantly impact energy generation.

As can be observed, the *ALL Trk* has systematically lower availability than the *Core Trk*, mainly due to the conditions discussed in the following paragraphs.

Firstly, data investigation shows that early morning tends to represent poorer operation conditions, as unidentified operational issue can be carried overnight and unstable connections may impact equipment turning on. As a result, these events will only be observed by O&M teams during the early hours of the day, who may reboot devices or replace tracker control units; thereby resolving minor operational issues. Consequently, this minimizes the availability impact during the core tracking period, where devices remain unavailable only if the problem is not easily solvable and requires expert troubleshooting. Complex issues, which may refer to interconnection between devices and data stream limitations, are generally handled by the single-axis tracker manufacturers. In modern PV power plants, these manufacturers are responsible for ensuring that the trackers function smoothly, as on-site O&M teams commonly do not have access nor expertise to debug tracker control systems and related issues.

Another aspect refers to the backtracking period. The algorithms and software utilized in this period are generally proprietary, and utilize spatial information to calculate the tracker position, taking into account topographic conditions and related positions between devices. Thus, the utilization of PVLib's algorithm, even ensuring correct information on ground coverage ratio (GCR) and pitch conditions, will not identically replicate the real behavior of trackers in a PV power plant, as this depends on proprietary strategies. However, due to the complexity of these strategies, the control logic may be more prone to errors. This makes it challenging for other stakeholders to determine whether the tracker is functioning as expected without physical proof. Consequently, the higher figures, in *ALL Trk*, can be partially attributed to modeling errors stemming from the lack of transparency in the control logic.

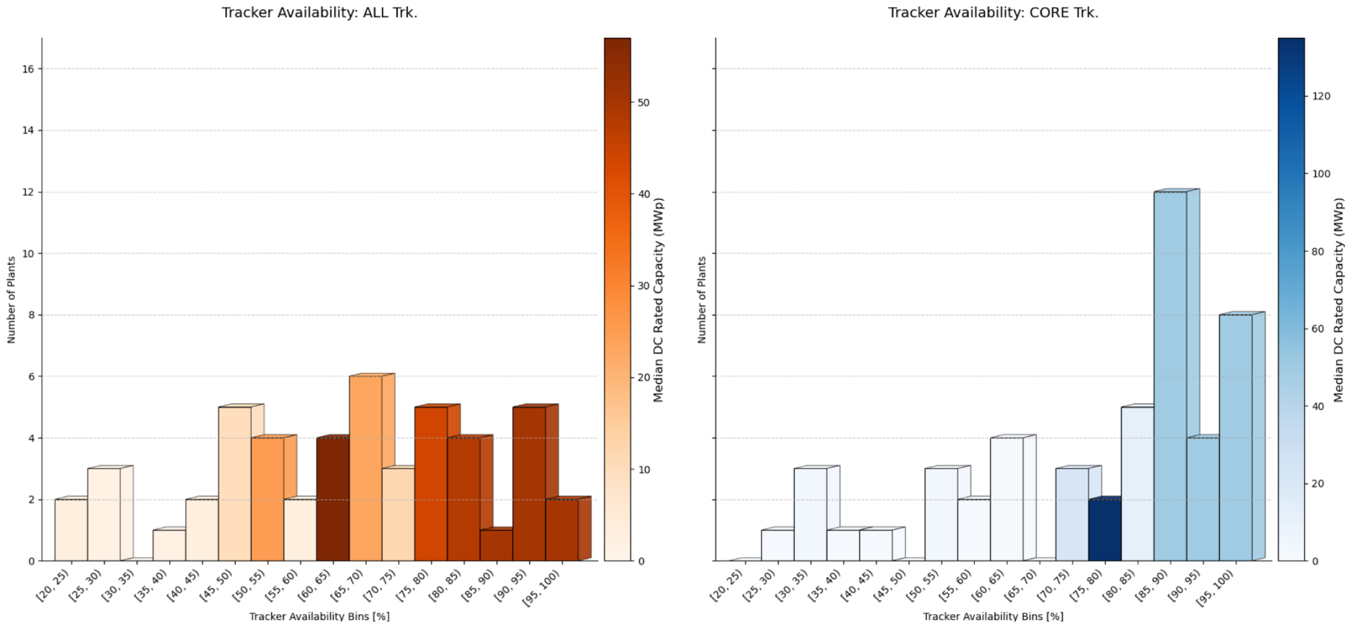

Fig. 3. Histogram of tracker availability results for both ALL and Core Tracking results. Subplots have same scale in left-hand side y-axis.

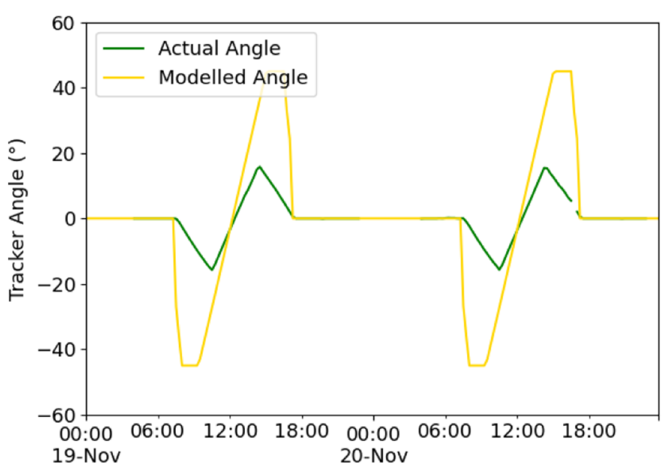

Fig. 4. Example of scaling issue in single-axis tracker actual angle.

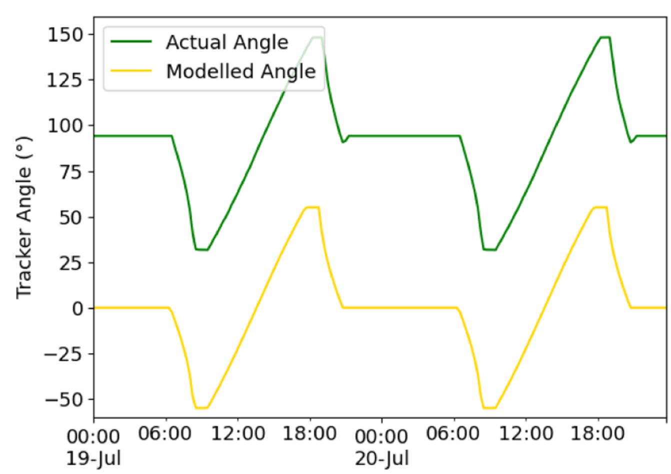

Fig. 5. Example of wrong offset applied to single-axis tracker angle.

3.1 Data quality

Throughout this work, the authors have analyzed hundreds of thousands of single-axis trackers datasets, representing a significant volume of data. In fact, single-axis trackers are one of the most numerous components in utility-scale PV power plants. Tracker data quality, mainly inclination angles and logs, are not the object of much focus in research nor in the industry; as O&M and Asset Mangers commonly would have KPI guarantees tied to inverter, or more recently, string availability.

Tracker angles are the most effective way of identifying tracker stows, however, it is sometimes necessary to utilize power profiles to identify stow conditions [14]. It is technically challenging to use power profiles to identify malfunctions during overcast and cloudy conditions. In this section, the authors discuss data quality issues encountered, and potential routes to facilitate data quality automation.

The Figure 4 demonstrate recurrent issues encountered in tracker datasets across the power plants. Figure 5 refers to a wrong offset being applied to the original data, while Figure 4 relates to wrong scaling of the actual tracker angles. Whether the problem arises from actual wrong data or incorrect mapping of the data signals in the SCADA platform, these simple mistakes highlight a common problem when automating analysis for tracker datasets. Since these datasets are generally overseen by key stakeholders, a simple corrective measure may be postponed, making data curation a cumbersome task and potentially unfeasible if these effects are random or inconsistent.

Data quality does not depend only on single-axis tracker manufacturer data streaming set-up or to SCADA systems configurations. Figure 6 highlights a case where tracker's maximum and minimum angles, available in as-built documentation, represented by the *Modelled Angle*,

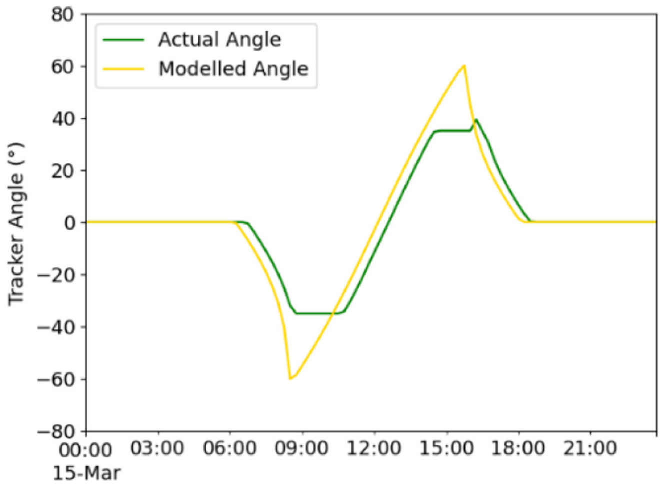

Fig. 6. Example of wrong maximum and minimum angle information.

do not match the actual path performed by the tracker. The analysed dataset showed multiples of such case. The root-cause can vary, ranging from incorrect as-built information, alternative backtracking strategies, and incorrect inputs provided at the single-axis tracker configuration level.

Another interesting example lies in Figure 7. From left to right, it represents two subsequent years for the same single-axis tracker. A minor leftward shift in the actual angle curve can be observed from 1 yr to the next. Although the investigation was not conclusive, the authors suggest this may be caused by specific tracker geolocation, however other sources of tracker malfunctions may be possible, e.g. calibration drift, mechanical wear, etc. Industry practice generally uses plant-level latitude and longitude information, as device-level information is rarely available and difficult to validate. Therefore, inconsistencies in the model input affect the generated model, which does not accurately reflect the inputs within the tracker configurations.

Using modelled tracker angle is the most effective way to identify whether a specific single-axis tracker is following its path. However, as shown in this section, the data can be inconsistent, raising concerns of the veracity of the information. Therefore, coupling this method with alternative ones may mitigate the existence of both false positives and false negatives in tracker availability. Due to the nature of PV plants electrical and mechanical topology, string intercomparison is a simple but effective way of veryfying whether the equipment was functional. Figure 8 highlights strings all connected to the same inverter, showing two underperforming strings connected to the respective tracker. On the other hand, it is important to emphasize that this method, or even utilizing inverter's power profile, is not effective at overcast or cloudy sky conditions. Thus, being significantly difficult to prove the tracker status without a physical evidence.

3.2 Missing data & related issues

Missing data has been identified as one of the main issues when analyzing tracker data, based on the findings from over 2 GWp of installed PV power plants. The missing data

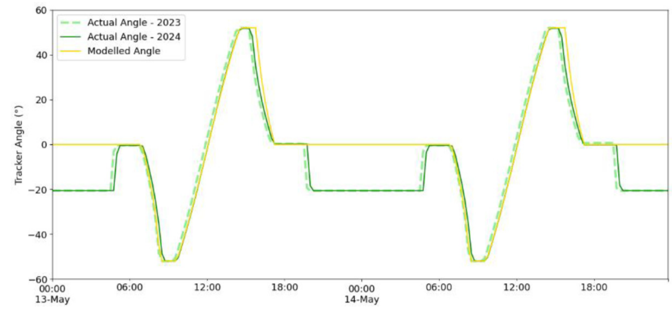

Fig. 7. Example of actual angle time shift between subsequential years.

was identified through communication gaps, where data is not collected and is lost, as well by stalled or frozen data being retrieved in the SCADA system. PV plants use a range of communication interconnections, such as physical connections (i.e. cable) and wireless. The issues can be traced back to several reasons, such as poorly dimensioned systems and significant signal interference within the power plant. Although identifying root causes is important, this paper will not focus on this aspect, as it is an engineering problem and generally project specific.

This section will discuss how the lack of data may impact Tracker Availability KPI. It is important to highlight that communication gaps do not necessarily indicate tracker unavailability or equipment downtime. However, discretizing what happened may not be viable without physical evidence. Hence assuming unavailability may be conservative but still a reasonable assumption, considering the lack of evidence through alternative analysis routes.

Figure 9 shows the distribution of missing data throughout the analyzed dataset. It can be inferred that the majority of PV plants have up to 15% of data missing, where the plant with least lost data is 0.5%, while the one with most missing data reaches 70%, at ALL Trk period; besides the median of distribution is at 11% and 5%, and averages of 18% and 9% for ALL & Core tracking, respectively. This skewness in the distribution illustrates that some power plants are more prone to issues than others. On the other hand, even though the extreme cases exist, it is important to notice that a significant portion of the power plants have data losses around 10%. Although the related energy impact of the communication gaps will depend heavily on sky conditions, the referred figures are quite remarkable, especially when compared to other equipment such as inverters, where contractual availability is generally around 99%, and substantial communication gaps could create significant manual work for O&M teams trying to prove the equipment was operational. Thus, even though missing data is expected in utility-scale environments, due to its unpredictability, the figures found in this work highlight a systematic problem in transferring data from single-axis tracker to monitoring systems.

On Tracker Availability KPI, the authors re-visit the initial results, now considering missing data as if the equipment was available. The purpose of this exercise is to illustrate possible best- and worst-case scenario for single-axis tracker availability, as observed in the presented

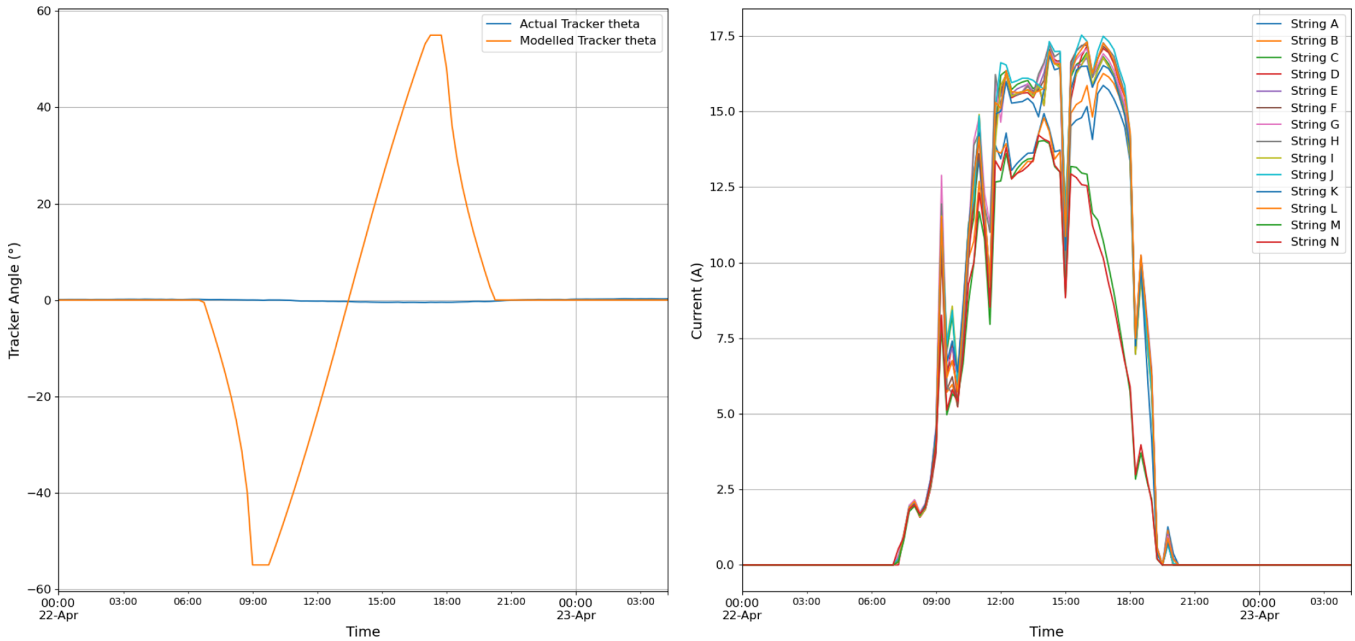

Fig. 8. Example of single-axis tracker unavailable, or stowed, and its related string-level generation profile.

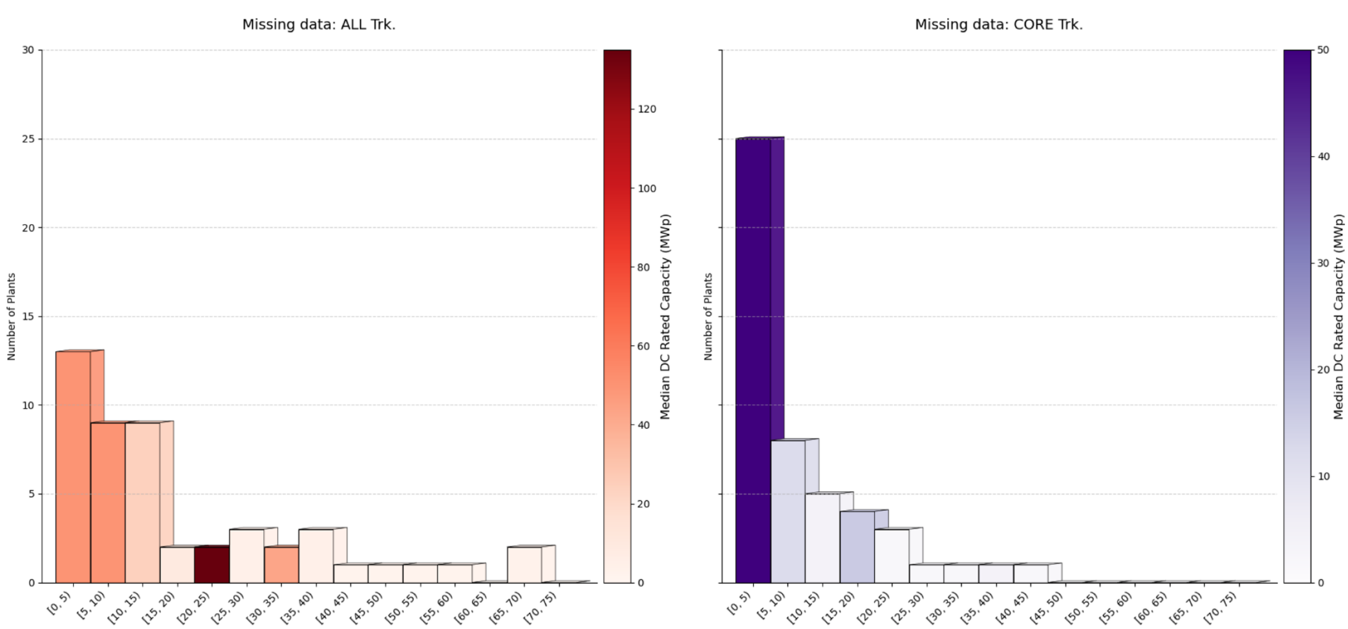

Fig. 9. Distribution of missing data for both Core and ALL Trk instances. Subplots have same scale in left-hand side y-axis.

figures the amount of missing data is significative and simply disregarding such values would have created a bias in the KPI results. The Figure 10 illustrates the distribution of results. The median of the distributionshifts from 66% to 87%, and from 83% to 89% in *All Trk* and *Core Trk* scenario respectively; while the average shifts from 64% to 83%, and from 76% to 85% in *All Trk* and *Core Trk* scenario respectively. Thus, approximately 21 percentual point (p.p.). and 19p.p. of median and average increase for *ALL Trk*; analogously 6p.p. and 9p.p. increase for *Core Trk*. Therefore, it can be inferred that missing data is an important driver of initial poor tracker availability performance, and especially recurrent and problematic during backtracking, evidenced by the high values in the *ALL Trk* KPI. The causes of more frequent missing data during backtracking are highly site-specific; however, they can be linked to two main situations. One reason is that issues occurring during early operation tend to be flagged by the on-site O&M team and resolved promptly, ensuring full operational conditions during the core tracking phase. In addition, the natural behavior of the system during device wake-up and shutdown tends to be more problematic, leading to more instances in which data is lost.

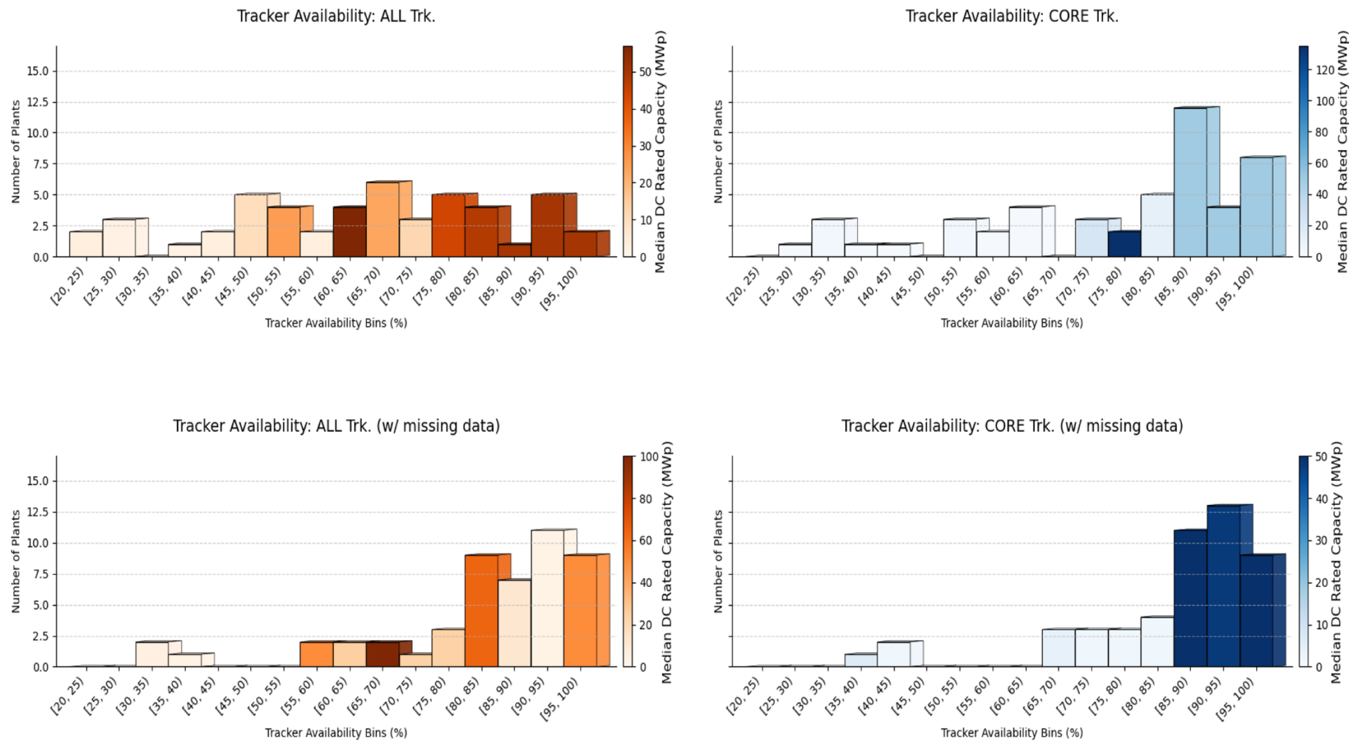

Fig. 10. Tracker availability distribution, in the upper plots considering missing data as unavailable, as in previous figure. In the lower plot considering missing data as devices available The plots consider both ALL and Core Tracker instances. Subplots have same scale in left-hand side y-axis.

This section shows how influential is missing data in the calculated KPI, changing results by many percentual points. However, it is important to note that the median, or average, of the distribution is still far from 99% tracker availability, which would be a figure analogous to the practice for inverter availability guarantees. In addition, only five plants performed above the threshold for ALL Trk conditions, representing only 10% of the analyzed power plants. This information supports the discussion proposed in this paper, highlighting not only the data quality challenges for trackers but also, based on the analyzed data, an opportunity for operational optimization of PV power plants. Single-axis trackers are not operationally reaching their full potential.

4 Conclusion

In our knowledge, this is one of the first studies to analyze such a vast number of PV power plants with sole focus on single-axis tracker operations. Assessing over 2 GWp of data has provided insights not only single-axis tracker availability (or uptime), but also on data quality and related limitations.

The findings highlight the importance of single-axis trackers in modern utility-scale PV power plants. Despite significant advancements in the industry over the past few years, there remains a substantial information gap regarding the large-scale operation of trackers. This gap encompasses not only their actual availability but also data curation and quality control. Tracker systems may have been historically ignored by researchers and industry, due to the high volume of data, and smaller energy contribution than devices that directly generate electricity (e.g. inverters, strings modules).However, in an increasingly competitive industry, accurate information on equipment availability is crucial for feeding simulation models and meeting contractual guarantees.

This work aims to generate awareness of the relevance of such equipment in modern utility-scale PV power plants. Even though the industry has advanced significantly in recent years, there is still a significant information gap in large-scale operation of trackers, not only referring to their actual availability but also data curation and quality control. This is a very important topic. As the industry becomes more competitive, and a key contributor to the energy mix in many countries, its players require accurate information on equipment availability to feed into simulation models and contractual guarantees. A broader communication of issues and lessons learned between stakeholders may optimize energy generation and collaborate to a more competitive and transparent industry.

Glossary

Nomenclature
Definition
Single-Axis Tracker
A device that follows the sun's path to maximize solar energy capture by adjusting its angle.
PV (Photovoltaic)
Technology that converts sunlight directly into electricity using semiconducting materials.

LCOE (Levelized Cost of Energy)
A measure of the average net present cost of electricity generation for a generating plant over its lifetime.
KPI (Key Performance Indicator)
A measurable value that demonstrates how effectively a company is achieving key business objectives.
PR (Performance Ratio)
A metric used to evaluate the efficiency of a PV plant by comparing the actual energy output to the theoretical energy output.
SCADA (Supervisory Control and Data Acquisition)
A system used to monitor and control industrial processes, including PV power plants.
GCR (Ground Coverage Ratio)
The ratio of the area covered by PV modules to the total available land area.
Backtracking
A strategy used by solar trackers to avoid self-shading by adjusting their position based on topographic conditions.
Availability or Uptime
The proportion of time that a system or component is operational and functional.
DC Capacity
The total power output of a PV system measured in direct current (DC).
O&M (Operation & Maintenance)
Activities required to operate and maintain PV power plants to ensure optimal performance.
IEA (International Energy Agency)
An organization that works to ensure reliable, affordable and clean energy for its member countries.
PVLIB
An open-source library for simulating the performance of PV systems.
Step Angle
The fixed angular increment by which a solar tracker adjusts its position during each control action.
Modelled Angle
The theoretical angle calculated for a solar tracker based on solar position equations and other inputs.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

Data associated with this article cannot be disclosed due to confidentiality and legal reasons.

Author contribution statement

Conceptualization: Giuliano L. Martins, Elena Koumpli; Methodology: Giuliano L. Martins, Lucas Z. Sergio, Gofran Chowdhury, Elena Koumpli; Validation & Formal analysis: Maitheli Nikam, Lucas Z. Sergio and Giuliano L. Martins; Writing – Original Draft Preparation: Giuliano L. Martins; Writing – Review & Editing: Lucas Z. Sergio, Gofran Chowdhury and Maitheli Nikam; Supervision: Gofran Chowdhury, Elena Koumpli and Jan Muller.

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