PVOP

Solution 2. Concept

Smart tracking control for large monofacial and bifacial single-axis tracking PV plants over terrain of arbitrary orientation and slope.

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List of Acronyms

AGR	Avoid Grid Reconstruction
AI	Artificial Intelligence
ARIMA	Auto Regressive Integrated Moving Average
BESS	Battery Energy Storage System
CM	Capacity Market
DT	Digital Twins
EMS	Energy Management System
FR	Frequency Regulation
GARCH	Generalized Autoregressive Conditional Heteroskedasticity
GRU	Gated Recurrent Unit
IoT	Internet of Things
LSTM	Long Short-Term Memory
ML	Machine Learning
MSC	Maximization of Self-Consumption
PS	Peak Shaving
RNN	Recurrent Neuronal Network
SARIMA	Seasonal ARIMA
TOU	Time of Use

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Keywords list

- Simulation
- Control
- Forecasting
- Sun tracking
- Batteries

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1. Executive summary

This document presents the concepts at the root of WP3 solutions, all of them about the Control of PV plants to optimise their performance. This WP3 is divided into two differentiated tasks:

- Task 3.1: Development and demonstration of a simulation tool and control system to maximize the performance of PV plants with sun tracking systems.

- Task 3.2: Development and demonstration of a control system to maximize the performance and energy trading of PV plants with batteries. In turn, this task is divided into two:

  - Chapter A: Battery control system
  - Chapter B: Electricity Market Forecast

The aim of T3.1 is to develop a smart tracking control algorithm and its corresponding simulation tool for large monofacial and bifacial single-axis tracking PV plants over terrain of arbitrary orientation and slope for the performance optimisation, taking into account diffuse irradiance conditions and extreme meteorological events. The concept behind these solutions is that considering terrains of arbitrary orientation and slope mainly requires modifications in the calculation of two different aspects: the backtracking geometry and the ground shading scenes needed to estimate the rear irradiance, G_{REAR}, in the case of bifacial generators. In addition, slopes affect the horizon which, in turn, affects the components of the front irradiance, G_{FRONT}. The 3D approach is likely to entail a significant increase in mathematical complexity, input information and computing time. This leads us to deal with sloping terrain while still relying on a 2D scene.

Once the models are in place, one way to better align the estimate with reality and to refine these models and assumptions is to use digital twins. Digital twins can be used to tune models for complex PV systems without repeated on-site measurement campaigns, provided that PV plants are adequately sensorised (which is an objective of WP2). This leads to a much more precise performance analysis and forecasting throughout the whole operational life of a PV plant.

For the validation, experiments at UPM facilities and at commercial PV plants are foreseen and specific KPIs are proposed.

2. Introduction

This document presents the first deliverable of WP3 (Control of PV plants to optimize their performance), and it explains the main objectives to be reached, the techniques used for that and the KPIs defined for the validation of the different solutions.

This WP3 is divided into two differentiated tasks, and one of them is as well separated into two main lines of work. The deliverable is structured accordingly:

- Task 3.1: Development and demonstration of a simulation tool and control system to maximize the performance of PV plants with sun tracking systems.

- Task 3.2: Development and demonstration of a control system to maximize the performance and energy trading of PV plants with batteries.

    - Chapter A: Battery control system
    - Chapter B: Electricity Market Forecast

This document is focused on Task 3.1 and describes the Solution 2: Smart tracking control for large monofacial and bifacial single-axis tracking PV plants over terrain of arbitrary orientation and slope for the performance optimisation, taking into account diffuse irradiance conditions and extreme meteorological events.

3. Task 3.1: Simulation tool and control system to maximise the performance of PV plants with sun tracking systems

3.1. Introduction

Current PV simulation software includes single-axis tracking and backtracking functionalities, typically assuming that the tracker axes lie within a horizontal plane (Kankiewicz, 2021). This assumption has generally been accurate for real-world systems until recently. However, with the growth of the PV market, single-axis trackers are now being deployed on sloped terrain. A recent solar financing report (kWh Analytics, 2021) indicates that, on average, solar projects underperform their target production (P50) estimates by 6.3%, noting that 'uneven terrain often causes losses for north-south aligned single-axis trackers on east-west slopes' as a significant factor contributing to the observed energy shortfall. Even on nearly flat terrain, actual tracking does not adhere to the ideal calculated values to avoid shading caused by slight terrain roughness.

PV simulation software carries out its computations with nominal parameters for system components, as given by their manufacturers. However, real equipment may have a performance which differs from nominal values due to manufacturing, handling, installation, operation, and aging factors. Typical practice is to make a campaign of on-site key measurements at the beginning of the life of a PV plant to tune model parameters, but this requires quite a significant effort, so that it is rarely repeated unless significant performance degradation is observed. As time goes on, there is a widening gap between expected and actual performance.

This drives the need to enhance PV software capabilities to **overcome the horizontal constraint** and to **improve performance forecasts as a PV plant evolves**.

Background on tracking software

Today's software for simulating tracking PV plants relies on two **simplifying assumptions**. Firstly, it assumes that the axis length is infinite (practically much longer than the tracker width) and that the axis height above the ground remains constant along its entire length. This leads to 2D modelling, reducing the geometric description to a projection onto a plane perpendicular to the tracker axes, i.e., the cross-axis plane. Secondly, it assumes an infinite number of axes (practically more than ten) arranged periodically so that they all lie in the same plane, parallel to the ground, and are evenly spaced. This approach neglects all edge effects and restricts the calculations to a single representative tracker row. This method is compatible with considering shading: mutual shading between adjacent tracker rows for backtracking algorithms and ground shading for estimating the rear global irradiance, GREAR. Together, these conditions—2D modelling and limiting calculations to one tracker row—significantly reduce the simulation load, both in terms of the number of input parameters needed to define the PV array configuration and the computation time. The simplifying assumptions and models of the tracking simulation software **apply equally to the tracker control**.

PV software is continually evolving, but it usually does not disclose internal model details or submit its procedures to peer-reviewed scientific journals. This opacity makes it challenging to determine the exact state-of-the-art. Nonetheless, it appears that most software currently used by the PV industry to simulate the energy yield of large PV plants employs such a 2D approach. Furthermore, software may have additional constraints. At present, much of the industry standard software is still limited by the horizontal constraint. PVsyst announced plans to overcome this limitation by using 3D modelling, but at least they decided to use a 2D model as well. DNV's Solar Farmer software claims to simulate complex terrain using both 2D and 3D modelling (Leung et al., 2022). We use SISIFO, open software developed by IES-UPM, available freely at https://www.sisifo.info, with its internal models thoroughly published (Lorenzo et al., 2011) (de la Parra et al., 2017) (Moretón et al., 2017) (Ledesma et al., 2020). For the purposes of this report, it is sufficient to know that, despite differences in detail, all these software are fundamentally compatible, leading to similar results when provided with the same input data and loss scenarios. Transitioning from 2D to 3D scenes likely involves a significant increase in mathematical complexity and simulation overhead. This motivates extending the capabilities of SISIFO to overcome the horizontal constraint while still relying on 2D modelling and a single representative tracker row. Interestingly, the authors of Solar Farmer also consider this approach viable. Indeed, (Leung et al., 2022) state that "… we observed that using a simple geometric shading approach for trackers provides sufficient accuracy for tracker shade, while 3D approach can be used for shade obstacle …".

Digital twins

Once the simplifying assumptions and models are in place, one way to better align the estimate with reality and to refine these models and assumptions is to use digital twins.

Digital twins (DT) are virtual replicas of physical entities or systems, integrating technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), and data analytics to simulate, analyse, and control their real-world counterparts. The primary components of digital twins include the physical entity, digital model, and connectivity infrastructure. The physical entity is the actual object or system being replicated. The digital model is a virtual representation constructed using data and algorithms, mainly through advanced analytic tools or machine learning, able to estimate outputs from given inputs. Real-time and historical data are collected from sensors and other sources to populate and update this digital model. Connectivity is required to enable continuous data exchange between the physical entity and its digital model. A human interface usually lets users interact with the digital twin, enabling them to monitor, analyse, and optimise the performance of the physical system.

Digital twins can be used to tune models for complex PV systems without repeated on-site measurement campaigns, provided that PV plants are adequately sensorised (which is an objective of WP2). This leads to a much more precise performance analysis and forecasting throughout the whole operational life of a PV plant.

3.2. PVOP simulation tool and control system proposal for solar trackers

3.2.1. Aim

To develop a **smart tracking control** algorithm **and its corresponding simulation tool** for large monofacial and bifacial single-axis tracking PV plants over **terrain of arbitrary orientation and slope** for the performance optimisation, taking into account diffuse irradiance conditions and extreme meteorological events.

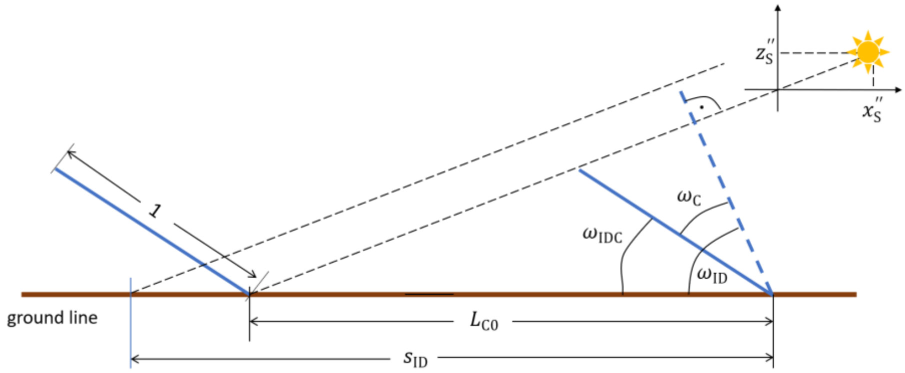
3.2.2. Conceptual aspects of PV simulation on uneven terrains

Considering terrains of arbitrary orientation and slope mainly requires modifications in the calculation of two different aspects:

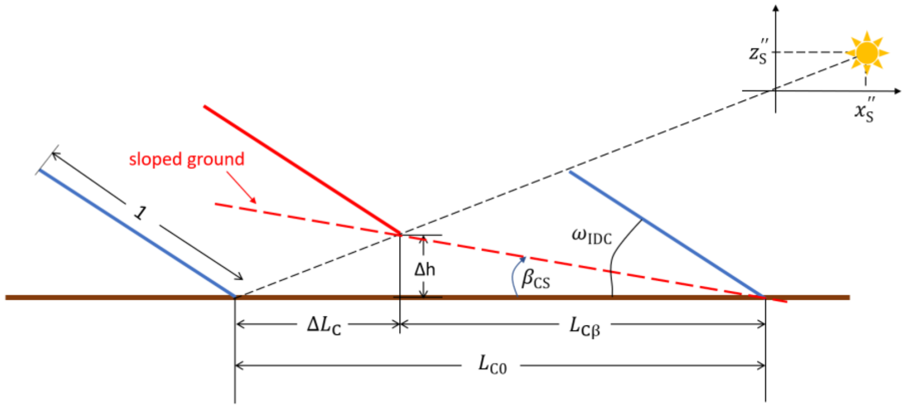
- the backtracking geometry and
- the ground shading scenes needed to estimate the rear irradiance, G_{REAR}, in the case of bifacial generators.

In addition, slopes affect the horizon which, in turn, affects the components of the front irradiance, G_{FRONT}. Slope-aware backtracking has been explored by (Schneider, 2012), (Nascimento et al., 2015), and (Anderson & Mikofski, 2020), so backtracking formulations that consider both horizontal and vertical row offsets are available. Current available PV energy yield simulation software has relied on 2D to define the shading scenes required for G_{REAR} calculations and seems to be moving towards 3D scenes to deal with complex terrains. The 3D approach is likely to entail a significant increase in mathematical complexity, input information and computing time. This leads us to deal with sloping terrain while still relying on a 2D scene. This is being implemented in SISIFO, an open software developed by the IES-UPM available at www.sisifo.info.

Figure 1-a shows the principle of the backtracking calculation under horizontal constraint for PV arrays consisting of many relatively long rows of PV trackers equally spaced across the ground plane. Figure 1-b depicts that in the case where the terrain has a cross-axis slope angle, β_{CS}. The point now is to note that this situation is equivalent to the previous one, that is, both lead to the same rotation angle ω_{IDC}, given the horizontal distance between the rows, $L_{\mathrm{C\beta}}$, by adjusting the distance considered for horizontal terrain tracking, $L_{\mathrm{C0},}$ to satisfy the condition $L_{\mathrm{C0}} = L_{\mathrm{C\beta}} + \Delta L_{\mathrm{C}}$



(a)



(b)

Figure 1. Geometry of backtracking for **(a)** horizontal and **(b)** sloping terrain. Both are equivalent, i.e. lead to the same rotation angle if $\Delta L_C = L_{C0}\tan(\omega_{ID})\tan(\beta_{CS})$.

3.2.2.1. More in detail

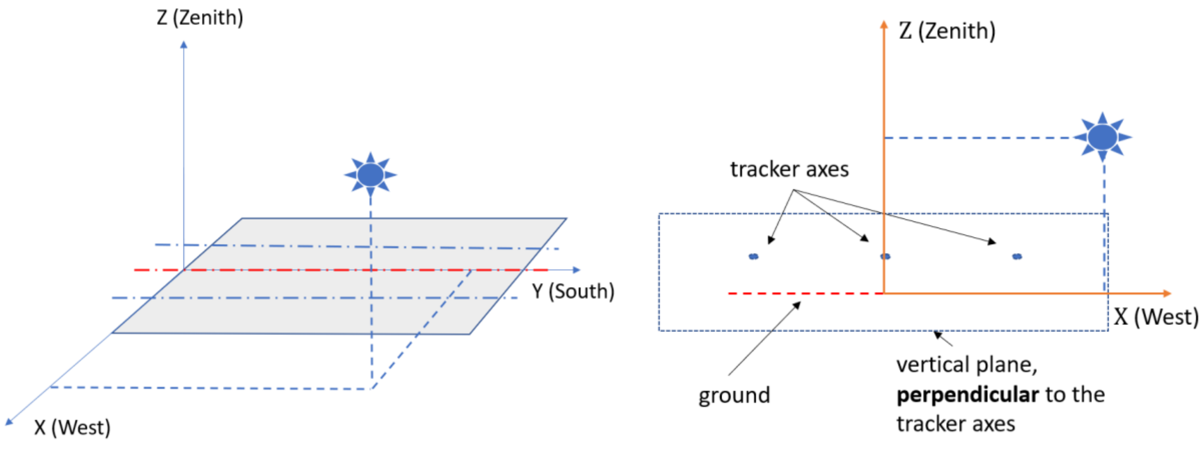
It is worth taking a moment to introduce the relevant reference frames and coordinate systems involved in the calculations of a tracked PV system. Figure 2 (left) shows the position of both the sun and the tracker in a site reference frame, using a right-handed three-dimensional Cartesian coordinate system with the X-axis pointing West, the Y-axis pointing South and the Z-axis pointing upwards. The tracker axes are shown as dotted and dashed lines. The coincidence with the Y axis, in red, is the representative row for which calculations are made. Figure 2 (right) shows the projection of both positions onto a cross-axis plane (a tracker reference frame) with a Cartesian coordinate system where the X axis contains the tracker axis points. Note the latter is a 2D scene. The depicted cases are:

(a) The traditional case of horizontal ground and north-south oriented axes, implemented in all the current PV software that we know of. The position of the sun in the global reference frame, i.e., the solar coordinate vector (x_S, y_S, z_S) is easily derived from the latitude and time. It should be noted that the position of the sun in the 2D scene, i.e. the vector (x_S, z_S) determines both the angle of rotation of the trackers and the shading scene cast on the ground by the tracker rows.

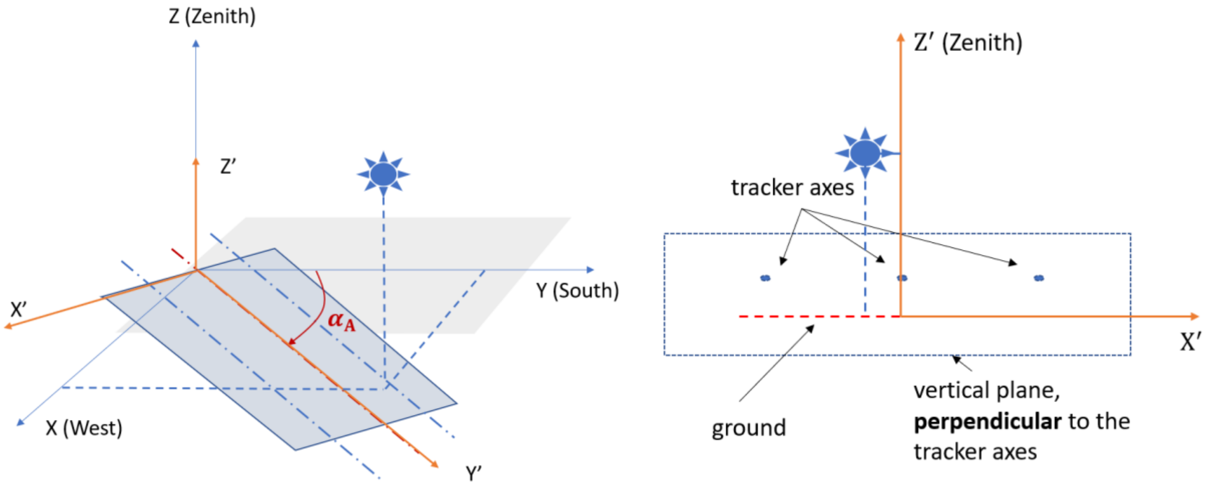
(b) The case of axes with given azimuth, α_A, on flat terrain. The relevant change from the previous case is the position of the sun in the cross-axis plane. The new sun position can be obtained from the former by applying a basic rotation matrix, rotating the sun position vector counter-clockwise by an angle α_A about the Z-axis.

(c) The case of both ground and axes with given azimuth and tilt. That is, here $\alpha_A = \alpha_G$ and $\beta_A = \beta_G$, where α and β are azimuth and tilt respectively, and the subscripts 'A' and 'G' denote axis and ground respectively. The new sun position is obtained by rotating the sun position vector counter-clockwise by an angle β_A about the X' axis. Note that although the ground plane is not horizontal, the intersection of the ground with the cross-axis plane is. Therefore, the axes line, the line that connects the axes crosswise, is also horizontal in the 2D-scene. This is why we say that in this case the horizontal constraint is still respected. SISIFO incorporates this feature from previous versions.

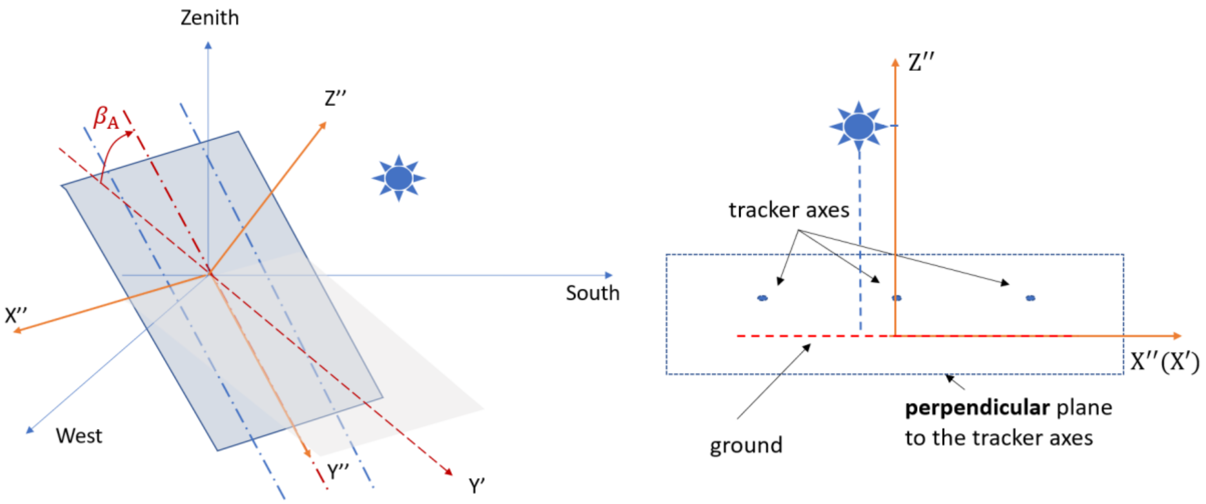
(d) The case for **sloping terrain** where the horizontal and the axes line have, irrespective of α and β, a non-zero cross-axis slope angle, β_{CS}. The axes are not parallel to the steepest line of the terrain and, therefore, $\alpha_A \neq \alpha_G$ and $\beta_A \neq \beta_G$. Again, this implies a change in the position of the sun in the cross-axis plane, and the new position can be obtained by rotating the sun vector counter-clockwise by an angle β_{CS} about the Y'' axis.



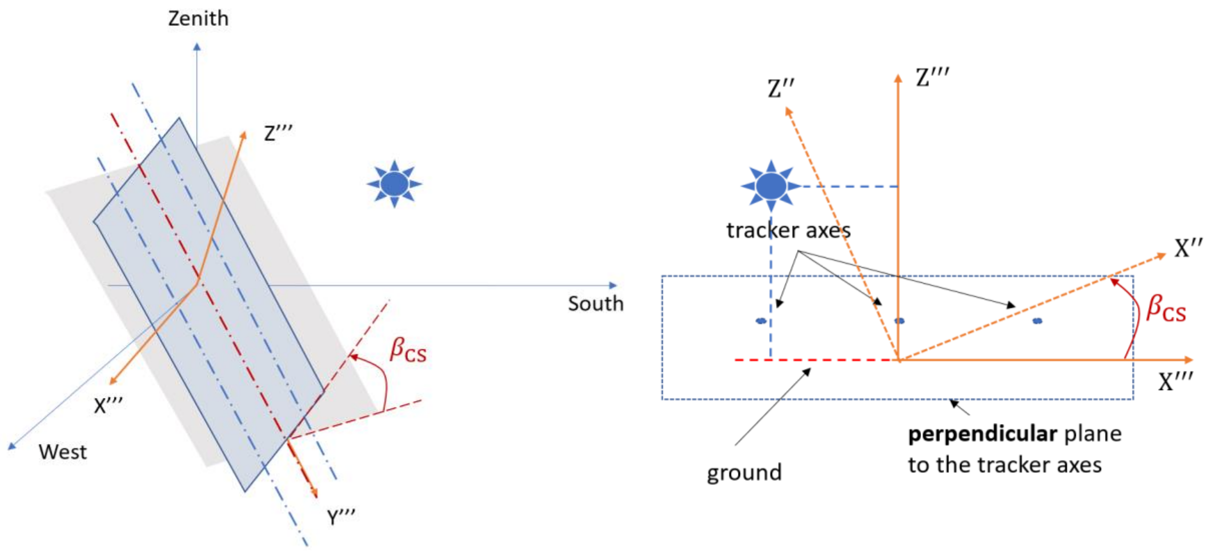
(a)


Z (Zenith)
Z'
X'
Y (South)
α_A
X (West)
Y'
Z' (Zenith)
tracker axes
X'
ground
vertical plane, **perpendicular** to the tracker axes

(b)


Zenith
β_A
Z''
X''
South
West
Y''
Y'
Z''
tracker axes
X''(X')
ground
perpendicular plane to the tracker axes

(c)



(d)

Figure 2. Sun and tracker positions in site (left) and tracker (right) reference frames. Depicted cases are: **(a)** Horizontal ground and north-south oriented axes; **(b)** Axes with given azimuth, α_A, on flat terrain. **(c)** Ground and axes with given azimuth, $\alpha_A = \alpha_G$, and tilt, $\beta_A = \beta_G$; **(d)** Ground and axes with different azimuth, $\alpha_A \neq \alpha_G$, and tilt, $\beta_A \neq \beta_G$, leading to a non-zero cross-axis slope angle, β_{CS}, between horizontal and the axes line.

It should be stressed that the tracker axes must be parallel to the ground in order to preserve the 2D scenes. It is worth noting that this is the current state of the art for industrial single-axis tracker products. Furthermore, case (d) gives the principle for solving the mathematical problem of cross-axis sloping terrain, as it allows the system to be treated as if it were a simple north-south horizontal axis system, and this is the model that will be implemented in the SISIFO simulation tool. However, it will also be interesting to approach the problem in the framework of case (c), as this is the framework that most actual trackers may use for horizontal terrain, and it would allow them to be easily upgraded.

This algorithm will be transferred to some control hardware for validation with real trackers. In order not to be dependent on the tracker manufacturer's control algorithm in real installations, a processing and control hardware will be designed to replace the one currently supplied by the manufacturer. This will be done in a non-invasive way, so that it will be possible to revert to the original manufacturer's control if necessary, or to compare results. To this end, this alternative control hardware will take control of the existing tracker motor and gearbox system when tested on real plants.

3.2.2.2. Irradiance components

Typically, software authors tend to model as many details as possible, regardless of their weight in the results. We are no exception. SISIFO will take into account the seven irradiance components listed in Table 1, despite four of them: $G_{\mathrm{FRONT}}^{\mathrm{RG}}$, $G_{\mathrm{REAR}}^{\mathrm{B}}$, $G_{\mathrm{REAR}}^{\mathrm{DS}}$ and $G_{\mathrm{REAR}}^{\mathrm{RG}}$ are almost irrelevant to the annual radiation in most practical cases. The table includes comments on how β_{CS} affects each component.

G_{FRONT}	G_{REAR}
Beam, $G_{\mathrm{FRONT}}^{\mathrm{B}}$ β_{CS} affects the skyline.	**Beam, $G_{\mathrm{REAR}}^{\mathrm{B}}$** This component is zero for trackers.
Diffuse from the sky, $G_{\mathrm{FRONT}}^{\mathrm{DS}}$ β_{CS} entails a vertical offset between the rows. This in turn affects the amount of sky covered by the adjacent frontal row.	**Diffuse from the sky, $G_{\mathrm{REAR}}^{\mathrm{DS}}$** β_{CS} entails a vertical offset between the rows. This in turns affects the amount of sky covered by the adjacent rear row.
	Reflected by the rear row, $G_{\mathrm{REAR}}^{\mathrm{RR}}$ β_{CS} entails a vertical offset between rows. This in turn affects the view factor from the adjacent rear row.
Reflected by the ground, $G_{\mathrm{FRONT}}^{\mathrm{RG}}$ β_{CS} affects the view factor from the shaded and unshaded areas of the ground.	**Reflected by the ground, $G_{\mathrm{REAR}}^{\mathrm{RG}}$** β_{CS} affects the view factor from the shaded and unshaded areas of the ground.

Table 1. Influence of β_{CS} on the different irradiance components.

3.2.3. Tracking control under conditions of diffuse irradiance and extreme meteorological events

Under conditions of high diffuse irradiance, or in the presence of certain extreme weather events, the most optimal position of the tracker may not be the astronomical position calculated by the previous model. These cases will also be taken into account in the simulation tool.

For instance, when diffuse irradiance is high, a horizontal angle in the tracker may produce a better yield. Also, heavy snow or hail may lead to a steeper tracker angle, and strong winds may lead to a protection angle to avoid damage in the components.

3.3. Experiments and KPIs

3.3.1. At the IES-UPM outdoor facilities

A scale model of a single axis tracker PV generator will be designed and built. This will be used to test the control of the tracker on sloping terrain and under conditions of diffuse irradiance. Using a scale model makes sense because with a proper design and construction all relevant effects scale and consequently the results are extrapolable to real generators.

The scale model we are planning to build could be made of 156-millimetre PERC bifacial cells to simulate scaled trackers. A total of 14 cells can simulate a typical tracker carrying a string of 28 modules. Better still, we will investigate the feasibility of laser cutting commercial PV modules to obtain the scaled down strings of modules, as this would better match the properties of the scale trackers to the real properties of commercial PV modules. A scale model made of five rows, each with several scaled trackers in a line would be sufficient to do representative experiments.

The scale model will have a flexible floor that allows to set up several arbitrary terrain slopes of up to 35 degrees, to vary the spacing between rows of trackers (ground cover ratio), and to use different substrates (with different albedos). This would be sufficient to set different tracking angles in each row and to simulate different terrain configurations.

These scaled PV generators would also allow testing and verification of the associated digital twin.

3.3.2. At a commercial PV plant

In order to test the control of solar trackers on real tilted terrain systems and to feed the associated digital twins, a non-invasive alternative will be chosen on real PV plant trackers. To this end, an alternative hardware device to the current tracker controller will be designed, based on the experience gained with the previous scale systems, which will generate the necessary signals to set the tilt angles using the real tracker motor. The current tracker control provided by the manufacturer will be disconnected from the actual tracker motor and switched to control the actual tracker motor resulting from the proposed new model. This allows the change to be undone, if necessary, without affecting the current infrastructure.

A continuous data feed is required between each real plant and its digital twin. It is envisaged that this data can be collected from the SCADA deployed in the actual PV plant. This data can be supplemented with data from some additional sensors deployed in WP2. If, for some reason, these cannot be integrated into the SCADA, the necessary communication system to obtain them will be analysed and designed.

3.3.3. Targets for KPI

- Deviation of the Real angle vs the Optimum Angle on Arbitrarily Oriented Sloping Terrain, which should be < 2°
- Validation of the model based on 2D view factors for the estimation of the irradiance on the back side of a PV system on a sloping site by comparison with the real scaled system. Error (Estimated - Actual) / Estimated < 10% after excluding the effects of inhomogeneity due to shading of the structure itself.

- Correlation of real system and digital twin > 94% (for each of the three twins and for 1-2 key variables in each) under normal operating conditions and without failures.

3.4. Conclusions

The concept of the simulation and control solutions is based on some relevant assumptions that standard PV software relies on to simplify the energy yield simulation, and pinpoints the horizontal constraint, which does not necessarily require the ground to be horizontal, only that its cross-axis slope angle be zero. The mathematical basis for modifications to overcome the horizontal constraint while preserving these assumptions will be established. Therefore, the sensitivity of the annual energy yield to the slope of the terrain could be analysed in the light of simulation exercises performed with SISIFO for commercial PV plants.

Evaluating the use of scale models to test tracker control on sloping terrain is a promising approach. This method involves simulating different configurations and measuring parameters such as front and rear irradiance on both edge and interior scaled trackers. The experimental setup should allow for adjustable ground slope and albedo to accurately assess the effects of sloping and uneven terrain, including potential shading effects. This would enable the application of proposed tracker controls and the validation of associated digital twin models, providing valuable insights into tracker performance in varying real-world conditions.

In short, the goal is to get a good representation of reality under normal operating conditions and without failures. Some KPIs are established to quantify the goodness of this representation. Once this is achieved, the deviation of the digital twin output from the sensed data will act as a trigger to initiate the specific fault classification mechanisms that are likely to trigger more advanced and specific fault-finding processing. These fault classification mechanisms will be addressed in WP4.

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