PVcase

A General PV Digital Twin Concept: Streamlining the PV Plant Lifecycle Data Exchange

1. Introduction

The PV industry progresses fast on the path of digital transformation. Digital twins are already in use across the lifecycle of a PV asset, starting from design, through monitoring, all the way till decommissioning and dismantling. The two main challenges the application of PV digital twins still need to overcome are the complexity of replicating a physical PV asset in digital terms, and the lack of uniformization across the lifecycle. The current practice involves performing manual assignments, which is not only effort-intensive but potentially inaccurate. Furthermore, it is repeated at each lifecycle stage, using different requirements and information sources, resulting in multiple, independent digital twins that are tailored to the processes that they support. This in turn complicates transitions between subsequent lifecycle stages, as any already-existing PV plant digital identity is incompatible with other lifecycle processes.

This report is based on the TRUST-PV Horizon 2020 funded research project. The project partners are actively working on carrying over the developed concepts into commercially viable digital solutions.

2. A general digital twin for PV plants

One of the main use cases of digital twins is to support PV performance simulation. The information contained in a PV digital twin can be fed to a PV performance model, allowing it 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. The present chapter describes the requirements of a general digital twin concept applicable across the entire PV system lifecycle.

2.1 Definition of digital twin

In its simplest sense, a digital twin is a digital representation of a physical object or system.
For solar PV systems in TRUST-PV, the following definition of a digital twin was agreed.
A digital twin is a parametrized (2D/3D) model of a PV system that contains all the physical information needed to simulate the behaviour and performance of the real PV plant it represents.

2.2 Digital twin of a PV plant

The "physical information", needed to simulate the behavior and performance of a real PV plant (stored in the digital twin), can be broken down into the following key areas, from largest to smallest:

1. the 3D geospatial context of the PV plant, including sources of shading, namely:
2. "Far-shading" from the shape of the horizon, relative to the location of the site, caused by terrain features such as mountains, and
3. "Near-shading" from local objects, such as nearby trees and buildings.
4. the 3D geometric properties of the active PV faces (solar modules),
5. the way in which individual components are connected to produce a functional photovoltaic system (electrical hierarchy), and
6. the electrical properties of individual plant components e.g., PV modules and inverters.

2.3 General digital twin

Respecting the merged requirements across all lifecycle stages results in a digital twin that can enable the collaboration between multiple platforms, serving different lifecycle stages. 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. This enables compatibility with a BIM system
- 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.

3. Creating PV plant digital twins - the role of PV engineering software

PV design software facilitates the process of casting the combination of ideas, concepts, data, best practices, and know-how into PV plant design files. Advanced PV design software such as PVcase Ground Mount not only generates design files but also a structured information model, that can be re-used by various processes requiring a PV digital twin. In most cases, PV design software relies on user input for layout generation. However, the present report also explores the use of already-existing, incomplete design files and documentation for re-modelling existing PV plants.

3.1 New plant in design phase

When a new PV plant is designed, care must be taken to use a design software with an information model compatible with the one required by the outlined general PV digital twin. In this case, the design files can readily be used to create the digital twin and even creating more versions representing different design iterations remains very effective. Utility-scale PV plant design software such as PVcase Ground Mount offer convenient, automatized tools to support the entire process of 3D, topography-based layout and electrical design. Smart functionalities help reaching capacity targets, respecting shading limit angles, implementing specific framing and stringing practices, all the while keeping civil engineering aspects in check. With such tools, detailed and accurate PV plant 3D models can be prepared in a highly efficient way.

3.2 Existing plant 3D layout

For existing PV plants, the main challenge lies in closely matching the real entities with digital ones. Two different approaches have been investigated within the project. One is to perform a comprehensive drone survey for scanning modules, terrain, and shading objects directly in 3D. Then, the post-processed survey data can be further processed using a PV design software to complete the digital twin. The greatest advantage of this method is its independence of the as-built documentation, avoiding error propagation from documentation to the digital twin.

Alternatively, existing documentation can also be used for creating a PV plant 3D model. The minimum input of this process is the PV plant metadata. More accurate results can be obtained if the 2D locations and the geometry of the PV frames is known. In case terrain topography data is available from a site survey (e.g., drone survey), an even more accurate 3D model can be created. Shading objects such as trees, buildings, and fences can be incorporated in multiple different ways. The recommended method is to include them in the 3D data delivered by a drone survey. Alternatively, they can be re-modelled knowing their location and 3D spatial extent. This process can be automated to a large degree using the PVcase Ground Mount software.

3.3 Existing plant electrical design

For an existing PV plant, accurate and well-maintained documentation is a valuable information source for PV plant digital twin creation. Despite some promising recent efforts to develop automatized parameter identification algorithms, relying on documentation is the only currently cost-effective option for digitizing the electrical topology of an existing PV system. This step requires human interaction for reading and interpreting the electrical diagrams, as the format of these diagrams is not standardized, and greatly varies between examples. Once read and understood, PV design tools such as PVcase Ground Mount offer automated processes for incorporating the intended electrical design into a model file with the option of creating 3D cable paths essential for accurate cable length inputs for PV performance simulations.

For the specifications of the installed electrical components, the component data sheets (occasionally factory .PAN and .OND files) as part of the plant documentation are practically the only information source.

4. Demonstration in a real scenario

A test PV plant (South of Spain, BayWa r.e.) is taken as a case study to illustrate the workflow to create a digital twin for PV performance simulations. The 50 MWp plant was commissioned in 2020 and consists of 131,404 PV modules mounted on HSATs with North-South axis, connected to string inverters. The majority of the modules are monofacial.

4.1 As-built documentation and its processing

The as-built documentation of a PV power plant consists of many different documents, most of which might be useful when instantiating the digital twin. The simplest and least error-prone identified procedures are described in this section, assuming the use of the PVcase Ground Mount software. Having access to the as-built CAD design files greatly simplifies the digital twin creation process. The first step is to identify the most important layers and objects: terrain topography, frame polygons, DC and AC cable paths, inverters, substations, and shading objects.

First, the identified topography layer is assigned as terrain surface. This data will be used to adapt each deployed frame to the local ground topography. Next the identified frame polygons need to be converted to PVcase Ground Mount frame objects. This requires the upfront set-up of the frame geometry attributes of each frame type: module dimensions, module spacing, number of module rows and columns, orientation angle, and tilt angle (fixed-tilt only). Having entered this information, the software finds all identical frames and converts all of them into PVcase Ground Mount objects in a single operation (Figure 2). The converted frames are three-dimensional, and they are automatically adapted to follow the terrain topography. Using this procedure, the 3D geometry reconstruction process requires minimal human effort.

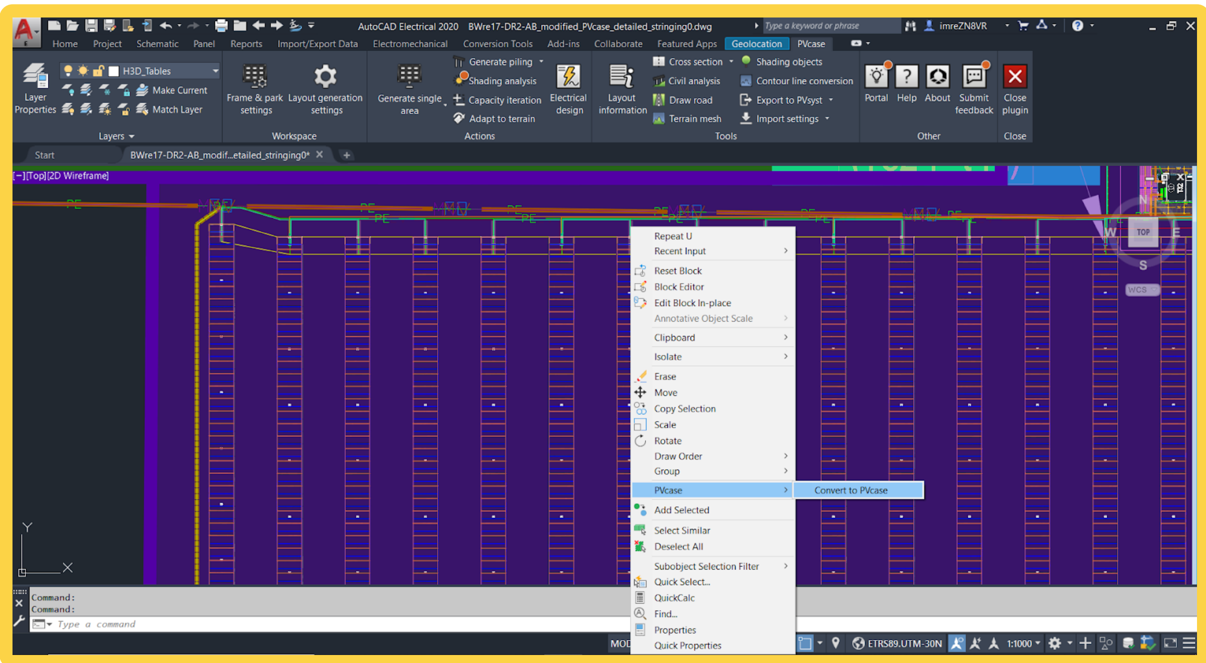

Figure 1: Converting frame polylines to PVcase Ground Mount frame objects in a test PV plant.

The next step is to replicate the electrical design of the power plant. Unfortunately, automation cannot fully replace human input: the operator performing the digital twin instantiation needs to read the PV plant single-line-diagrams (SLDs) or directly the CAD file, and define the stringing pattern, assign strings to inverters, and inverters to substations, using the electrical design toolbox of PVcase Ground Mount. It is important to perform this task with high precision, to ensure that the digital twin can be used for analyzing location-dependent performance. The final step of the electrical design is re-creating cabling. This task requires locating the original cable trench lines and defining them as PVcase Ground Mount trench line objects. Once the software recognizes these objects as trench lines, the automatic DC and AC cable generation algorithms can be used yielding cable paths very similar to the original design. In the final step, cables can be converted to 3D cables using an automated process that adds vertical cable sections wherever a height difference is present (e.g., transition from frame to underground), resulting in more accurate cable length values for yield simulations.

In the final step, shading objects need to be re-created for transformer stations and trees (not present in a test PV plant). The location and dimensions of transformer stations are clearly marked in the design files, except for object height, which can only be guessed. After entering the station dimensions to PVcase Ground Mount, these can be manually placed to the right locations.

The finalized digital twin can be visually inspected (Figure 3) and exported in various file formats.

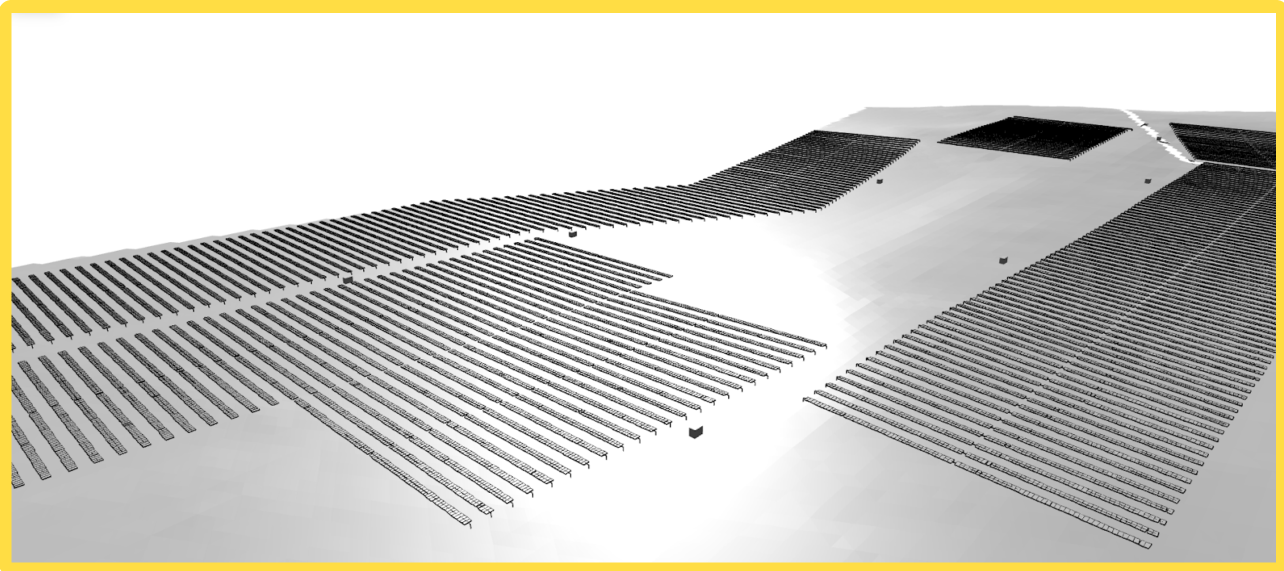

Figure 2: Visual representation of the complete digital twin generated based on as-built documentation, part of a test PV plant.

4.2 Digital twin from drone survey data

Digital twin instantiation using drone-survey data follows a process similar to documentation-based reconstruction. This process similarity is enabled by a convenient CAD output format, delivered by Above Surveying. The CAD file contains the ground topography, frame objects, and shading objects (as mesh objects). The only notable difference relative to instantiation using as-built documentation is that drone survey data contains only visible objects. Therefore, the location of cable tranches needs to be guessed. On the other hand, drone survey provides a 3D representation of all objects, enabling a more accurate 3D reconstruction. The location and 3D extent of shading objects can accurately be captured, and these objects can be matched with pre-defined shapes as shown by Figure 4.

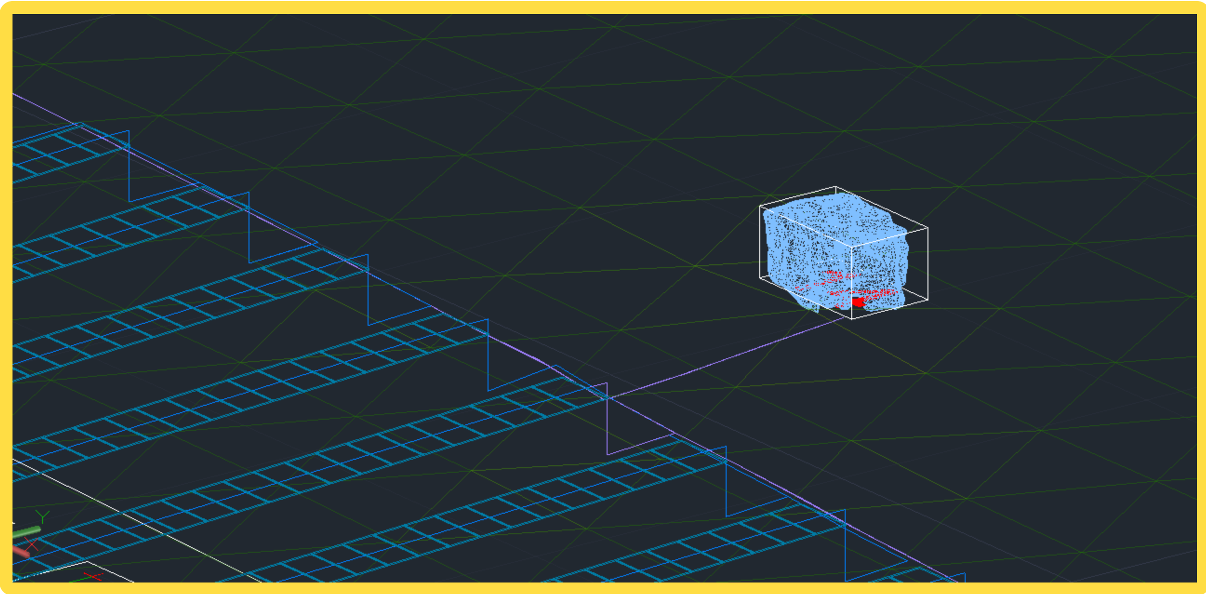

Figure 3: Part of a test PV plant reconstructed using drone survey data. The mesh object represents a transformer station.

The digital PV plant reconstruction accuracy is also improved by limiting the dependence on existing documentation.

The main limitation of the described digital twin creation processes is that electrical connectivity can only be digitized by manually interpreting PV plant single-line-diagrams (SLDs) or processing the respective layers of the CAD file. This limitation needs to be addressed by future research.

4.4 Yield simulation using the digital twin

The created digital twin can readily serve as input to physics-based PV system performance simulation software, such as IMEC's energy yield simulation framework, or PVcase Yield.
To verify whether the 3D model built based on the drone survey can be used instead of the as-built model, two initial simulations of a single inverter were performed in part of a test PV plant – one considering the drone-based 3D model and the other one the as-built model. If the drone-survey-based model is correct and has the required level of geometric detail, there should not be major differences between the results of the two simulations.

Figure 5 compares DC power, respectively, between the two simulations on an example day. Apart from minor fluctuations, the output time series of the two simulations agree well with each other. Hence, it can be concluded that the simulation based on the drone-based geometric data can be expected to have an accuracy comparable to that of the simulation based on the as-built 3D data.

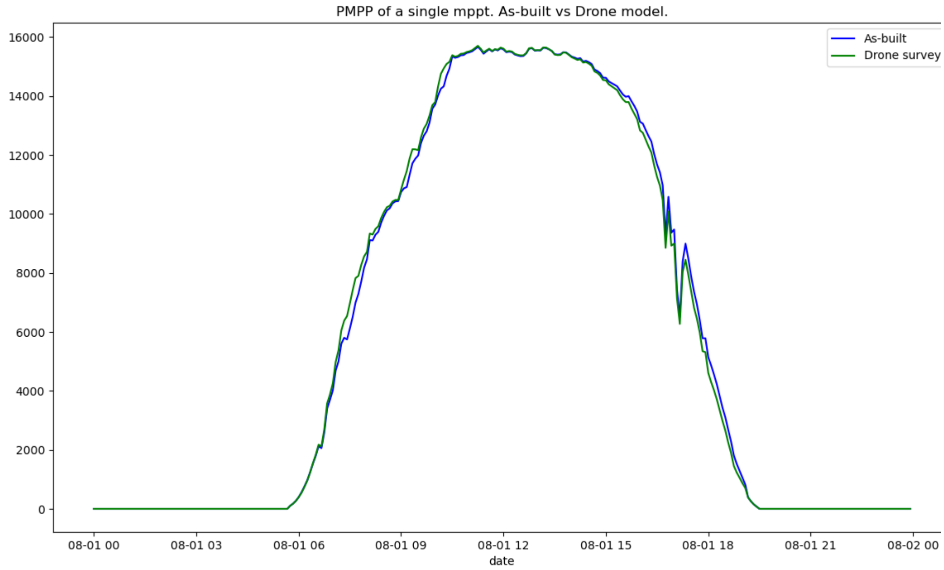

Figure 4: MPPT inlet power (PMPP) on an example day estimated based on the as-built model (blue) and the drone survey (green).

Executive summary

This report summarizes the results obtained during the execution of TRUST-PV Task 2.1. First, the definition of the PV plant digital twin was established in line with existing digital twin definitions but ensuring its relevance and compatibility to all relevant PV plant lifecycle processes. The adopted definition enables the digital twin to act as a single source of static asset information throughout the PV plant lifecycle.

The developed new requirements encourage the improved digital representation of the 3D geometrical, geospatial, and functional connectivity of PV plants as well as a high degree of similarity between the physical and digital assets. The developed methods enable accurate, topography-based 3D modelling and the reconstruction of far shading through processing high resolution Digital Elevation Models into location-dependent skyline profiles. The greatest unresolved challenge remains the digitalization of the electrical design of existing plants, and the identification of their component characteristics as both aspects are invisible to optical sensing techniques. The current work relies on as-built PV plant documentation for digitalizing these aspects.

The developed new digital twin concept paves the way for advanced, physics-based yield simulation techniques capable of processing the complex, 3D illumination scene and the corresponding detailed electrical connectivity. The output of such a yield simulation process can directly be mapped to the PV plant 3D model, enabling the location- and context-dependent analysis of simulated performance and its direct comparison to monitoring data. Therefore, the same digital twin structure can be used throughout the entire PV plant lifecycle: design, optimization, monitoring, operation and maintenance, decision support system, and building information modelling.

The presented demonstration case proves that the developed concepts are practically feasible and applicable on an extended scale. The accuracy benefits of basing digital twin creation on sensing the real, physical asset have also been demonstrated.

Future developments should focus on developing an automated, scalable method for discovering the electrical connectivity and component characteristics of real PV plants. Validating the accuracy of the automated digital twin-based yield simulation framework, and its integration into advanced digital services such as a Decision Support System are also parts of our future work. Furthermore, benchmarking the different PV digital twins' accuracy and efficiency at the monitoring and inspection stages could help to evaluate the value of the described concepts.

Finally, WP7 of the TRUST-PV project will attempt to put in practice the developed concepts in order to evaluate the technical/economical feasibility.

Industrial implementation of the developed concept

PVcase Ground Mount and Yield can be employed for fast and efficient digital twin construction. An engineer can use the Ground Mount tool to design a digital twin and then directly export it to PVcase Yield. Both these tools can also convert drone survey data into digital twins of existing plants.
The developed digital twin concept not only enables accurate simulations, but it also serves as a communication tool between various digital processes such as PV system design, yield simulation, O&M platform, and construction monitoring (Figure 6).

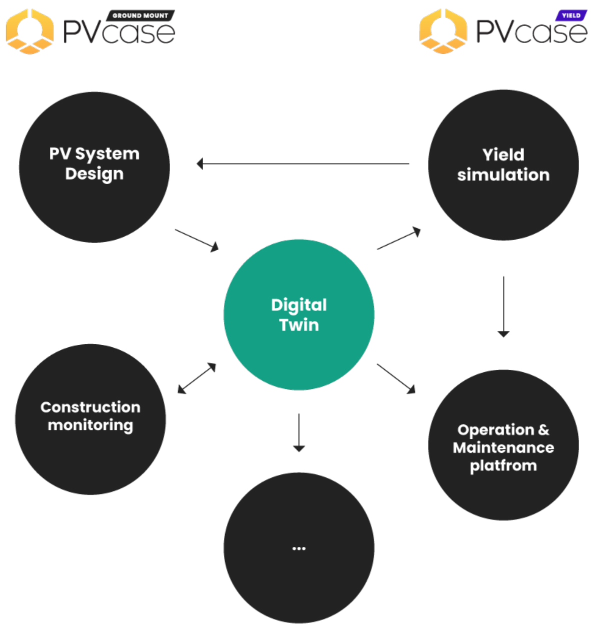

Figure 5: Digital twin blends PVcase software and other services together.

The ultimate benefit of the developed concept is acting as a single source of truth about physical asset information from a PV plant's early-phase design to an eventual decommissioning, making information federation and data-informed decision making ever more accessible, as illustrated by Figure 7.

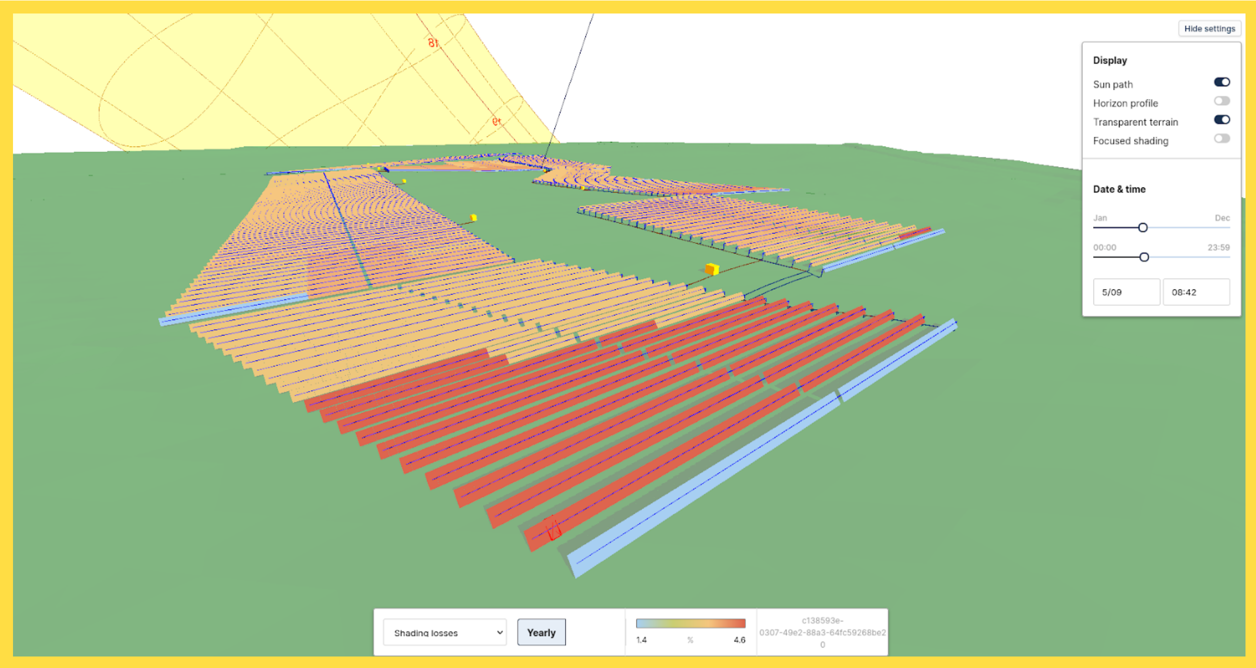

Figure 6: The 3D layout of a test PV plant visualized with string-by-string near-shading losses.

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