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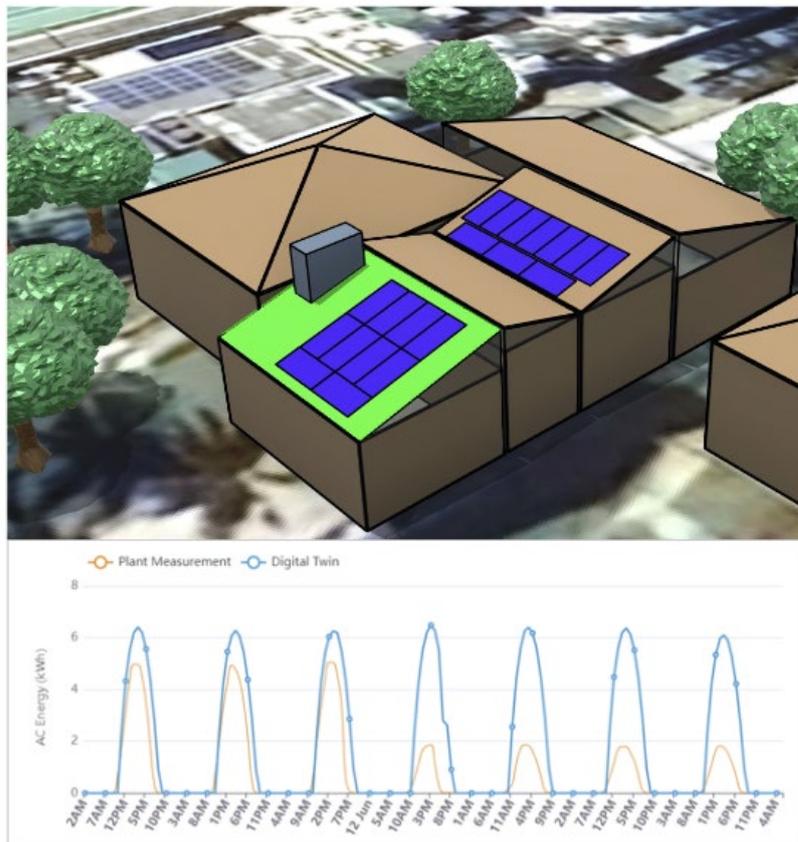**Report dated 23.11.2024**

PV-GOAL

Photovoltaic digital twin for all: Solar digital twin for fault recognition in solar installations

Zusammenfassung

Das Projekt PV-GOAL zielt darauf ab, einen nachhaltigen und effizienten Ausbau der Solarenergie in der Schweiz zu fördern. Dies wird erreicht, indem private, gewerbliche und industrielle Solaranlagen mithilfe fortschrittlicher Digital Twin Überwachungstechnologie automatisch Fehler und Energie Defizite erkennen. Die Fachhochschule Nordwestschweiz (FHNW) steht in Zusammenarbeit mit Solextron AG an der Spitze dieser Initiative, indem sie ausgefeilte Algorithmen und ein einsetzbares Cloud-Überwachungstool entwickelt, das Fehler erkennen kann. Dies ist das erste Mal, dass die Solar Digital Twin Technologie kleinen und mittleren Installateuren zur Verfügung gestellt wird.

Das Projekt hat sein zweites Jahr erfolgreich abgeschlossen und alle geplanten Ziele und Meilensteine erreicht. Die wichtigsten Aktivitäten in diesem Zeitraum umfassten:

- Datenerfassung: Es wurde ein umfassender Datensatz detaillierter Messungen von 80 Solaranlagen in einer Vielzahl von Klimaregionen gesammelt. Dieser Datensatz ist für die Entwicklung und Prüfung der Fehlererkennung Algorithmen von entscheidender Bedeutung.

- Entwicklung der Cloud-Infrastruktur: Es wurde eine Google Cloud Platform (GCP)-Infrastruktur entwickelt, um die Überwachung der Solaranlagen über Wechselrichter-APIs zu ermöglichen. Diese Infrastruktur ermöglicht auch die Manipulation von Daten, um Fehler in den gesammelten Solaranlagen zu untersuchen.

- Fehlerklassifizierung: Die in den Anlagen festgestellten Fehler wurden gesammelt und klassifiziert. Diese Informationen sind für das Training der Digital Twin Modelle zur genauen Erkennung und Vorhersage von Fehlern unerlässlich.

Aus Sicht des Projektmanagements schreitet PV-GOAL wie geplant voran. Das Projekt liegt im Zeitplan und innerhalb des zugewiesenen Budgets und hat die Erwartungen aller Projektpartner erfüllt. Die Erfolge des zweiten Jahres legen eine solide Grundlage für die weitere Entwicklung und den Einsatz der Digital Twin Überwachungstechnologie, die die Zuverlässigkeit und Effizienz von Solaranlagen in der Schweiz deutlich verbessern dürfte. Bis zum Ende des Projekts soll PV-GOAL ein robustes Tool zur automatischen Erkennung von Fehlern und Energie Defiziten bereitstellen und so zu einer breiteren Einführung von Solarenergie und dem Übergang zu einem nachhaltigeren Energiesystem beitragen.

Summary

The PV-GOAL project aims to foster a sustainable and efficient expansion of solar energy in Switzerland. This is achieved by providing residential, commercial, and industrial solar installations with automatic recognition of failures and energy shortfalls through advanced digital twin monitoring technology. The University of Applied Sciences and Arts Northwestern Switzerland (FHNW), in collaboration with Solextron AG, is at the forefront of this initiative by developing sophisticated algorithms and a deployable cloud monitoring tool capable of performing failure recognition. This marks the first time that solar Digital Twin technology is being made available to small and medium installers.

The project has successfully completed its second year, meeting all planned objectives and milestones. The key activities during this period included:

- Data Collection: A comprehensive dataset of detailed measurements from 80 solar installations across a wide range of climate regions was collected. This dataset is crucial for developing and testing the failure recognition algorithms.

- Cloud Infrastructure Development: A Google Cloud Platform (GCP) infrastructure was developed to enable monitoring of the solar plants via inverter APIs. This infrastructure also allows for the manipulation of data to investigate failures in the collected solar installations.

- Fault Classification: The faults encountered in the installations were collected and classified. This information is essential for training the digital twin models to recognize and predict failures accurately.

From a project management perspective, PV-GOAL is progressing as planned. The project is on schedule and within the allocated budget, and it has met the expectations of all project partners. The achievements of the second year lay a solid foundation for the continued development and deployment of the digital twin monitoring technology, which is expected to significantly enhance the reliability and efficiency of solar installations in Switzerland. By the end of the project, PV-GOAL aims to provide a robust tool for automatic failure and energy shortfall recognition, contributing to the broader adoption of solar energy and the transition to a more sustainable energy system.

Content

Abbreviations

AC	Alternate Current
CAMS	Copernicus Atmosphere Monitoring Service.
DC	Direct Current.
DHI	Diffuse Horizontal Irradiance.
DNI	Direct Normal Irradiance.
EPIA	European Photovoltaic Industry Association.
GCP	Google Cloud Platform.
GHI	Global Horizontal Irradiance.
IAM	Incidence Angle Modifier.
LID	Light-Induced Degradation.
MAE	Mean Absolute Error.
ML	Machine Learning.
MPP	Maximum Power Point.
MPPT	Maximum Power Point Tracker.
NIST	National Institute of Standards and Technology.
NOCT	Normal Operating Cell Temperature.
NREL	National Renewable Energy Laboratory.

1. Introduction

1.1. Background information and current situation

Switzerland`s solar energy production is expected to significantly grow from today`s 3.8 GWh up to about 19 TWh in the next 30 years [1]. In fact, according to the Swissolar managing director, David Stickelberger, "For the decarbonization of the energy system and for the replacement of nuclear power, a massive expansion of solar energy, to around 50 GW, with an annual electricity production of 45 TWh, is required, e.g. within just 30 years, we have to add 15 times the capacity installed today."
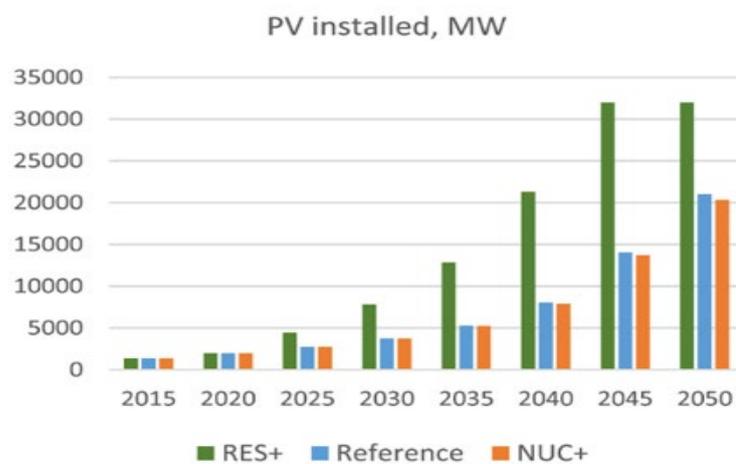
Figure 1 – Forecasted PV capacity in Switzerland.

Considering the PV installed capacity per capita, Switzerland occupies the 9th place in the world rank (Figure 2). The expansion of PV in Switzerland is accelerated not only by the global declining costs of PV systems but also by the rising energy prices from grid operators, which encourages people to increase their energy independence. Residential (<10 kW) and commercial (<250 kW) rooftop installations make the bulk of Swiss solar capacity. As outlined in SolarPower Europe's report, "Switzerland's solar PV market is almost exclusively based on rooftop projects. These installations are standard, as ground-mounted systems outside building zones are usually not approved, and within building zones, land is too expensive". This trend is expected to be maintained in the near future, as projected by SolarPower Europe.

Legend
Watt/capita in 2022
(Watt/capita) in 2021

Australia — 1ST — 1,191 (1,048) Watt/capita

Netherlands — 2ND — 1,029 (801) Watt/capita

Germany — 3RD — 815 (727) Watt/capita

Denmark — 4TH — 713 (424) Watt/capita

Japan — 5TH — 677 (621) Watt/capita

Belgium — 6TH — 667 (585) Watt/capita

Estonia — 7TH — 601 (404) Watt/capita

Spain — 8TH — 572 (400) Watt/capita

Switzerland — 9TH — 535 (422) Watt/capita
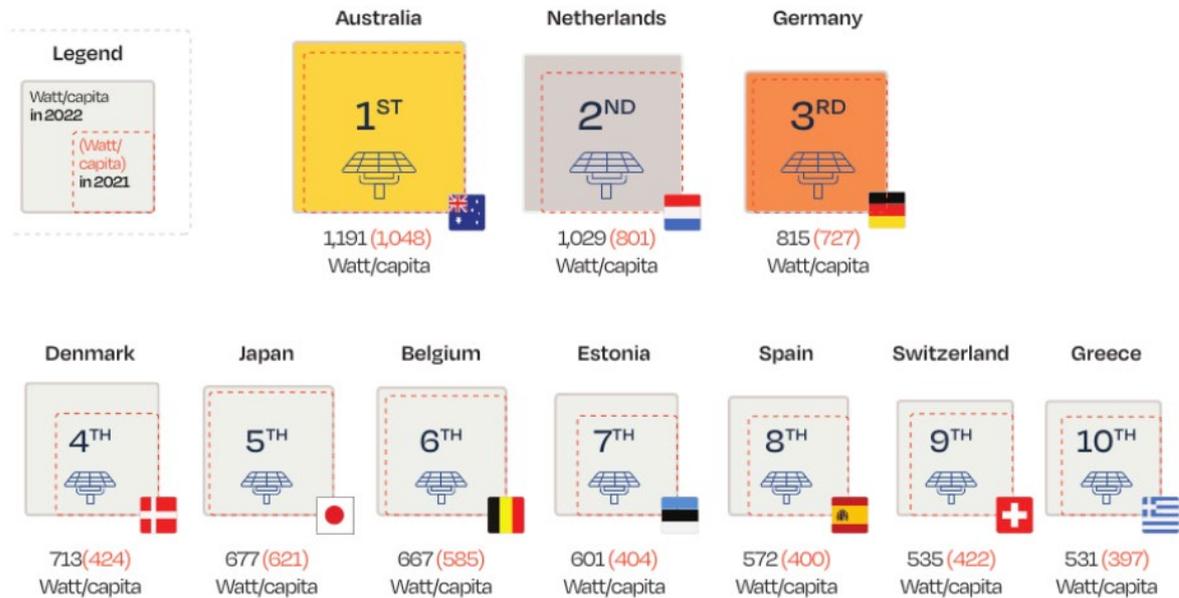
Greece — 10TH — 531 (397) Watt/capita

Figure 2 - Ranking of world's top 10 countries in PV installed capacity per capita in 2022.

Unfortunately, this distributed sector is characterized generally by a lack of highly qualified resources as well as technology access compared to the utility segment, particularly because the volume of investment for each installation project is significantly lower and the financial implications of performance shortfalls very weak for the installer. This trend is becoming even more critical following the recent strong increase in the solar market, as many new inexperienced installers enters the market.

This gap increases for Operation and Maintenance (O&M) service. Solar plants starting above ~50MW capacity have access to highly qualified engineering teams, which use modern modeling and data techniques for monitoring the performance of such large installations. Because of the small and medium characteristic of the solar Swiss market, such O&M practices and available technologies are practically nonexistent. *In fact, as highlighted in the PV-PMC conference at SUPSI on 08.11.2023: there are no intelligent monitoring solutions available today for installations of "non-rich-people"*. In simple words, today, a PV owner in Switzerland is very likely unable to say if his installation is performing as expected.

Switzerland has long passed the period when growth stimulation for solar energy was necessary, and because of its high social acceptance and profitability, the aforementioned forecasted capacity expansion is likely to happen. Before such high solar energy capacity levels are achieved, it is of major importance that technologies are available to small and medium PV owners for tracking potential energy losses. *This will avoid significant energy and financial losses accumulated until 2050*.

Some countries that rapidly expanded solar capacity such as Brazil and India are already experiencing massive losses of non-properly monitored solar plants. In the Indian case, solar plants affected by soiling are operating at about 50% of its ideal performance [2]. Because there are no digital tools available to actually confirm that, findings of such studies are most likely reproduced over the entire country. A Swiss study reported that installations analyzed in 2013-14 exhibit a wide range of performance from below 50% to above 85% [3]. It is however challenging to infer conclusions for today's scenario, because the uncertainties of the analysis were very broad, possibly because the installation capacity at the time was relatively small and the solar installations new, and further on, all those plants could very well be underperforming now. The capacity installed in 2022 was already much higher than in 2013, and there is no data today about the quality or maintenance of installations.

Although a detailed estimation of potential losses of Swiss solar systems in 2050 is challenging to perform due to several factors such as age, region and quality of installations, one could make an educated guess with rough assumptions based on the aforementioned studies that all non-monitored/performing half-life installations would feature an average performance shortfall of between 30 and 40%. Based on PSI figures of 19 TWh, and assuming an average tariff of 0.25 CHF/kWh and installed energy yield of 90% of expected generation, one could draw two scenarios:

Scenario	Yearly energy losses (TWh)	Yearly financial losses (BCHF)
All PV plants operating at 70% of expected yield	3.8	0.95
All PV plants operating at 60% of expected yield	5.7	1.43

As one can see, the energy and financial losses of non-performing solar systems in a scaled scenario are massive, affecting both Switzerland`s energy strategy and economy. The availability of a technology that assists PV owners to properly monitor and maintain their installations must be part of a PV strategy.

In PV-GOAL, we aim to tackle this challenge by developing a solar Digital Twin technology able to recognize failure in PV installations for the residential, commercial and industrial segments. The project mission is to make available for any installer, no matter how small, access to the best digital technology for O&M, which will directly benefit PV owners.

The failures or shortfalls should be recognized in two critical moments of the PV installation lifetime: **during commissioning phase and during the lifetime operation**. This will guarantee that actions can be taken on time, thus minimizing potential energy losses. The technology will also benefit the emerging PV business trends of PV contracting and energy trading by guaranteeing both long-term profitability.

Residential | Commercial & industrial | Large scale

- Lack of manpower and know-how for O&M
- Few or no development resources
- Access to basic O&M technologies

- Access to highly qualified workforce for O&M
- Access to high development budgets
- Access to advanced technology and processes for O&M

PV-GOAL Project

Failure recognition with Digital Twin

Figure 3 - Mission of PV-GOAL project: to make advanced O&M technology available for small and medium solar installers in Switzerland.

[1] Switzerland's solar power production could reach 19 TWh by 2050 – pv magazine International (pv-magazine.com)

[2] Challenges | Free Full-Text | Soiling Losses: A Barrier for India's Energy Security Dependency from Photovoltaic Power (mdpi.com)

[3] T. Nordmann, «Wie gut funktionieren die Schweizer KEV PV-Anlagen?», 15. Nationale Photovoltaik-Tagung, 2017.

1.2. Goals of the project

Solar digital twins are virtual representations of the physical PV systems that can simulate in real time their behavior and performance under different scenarios. Unlike Machine learning methods, which require historical data to predict solar energy production and are intrinsically biased by the present state of health of the solar installation, digital twins provide absolute electric equivalent circuit reference for the energy production of the solar plant, and as such are able to recognize failures on it. Furthermore, simple data driven analytics cannot distinguish between functional characteristics of PV installations, such as clipping and degradation without a good digital twin, which results in high prediction deviations in the order of 25-30%.

The main barrier to scale solar digital twins is the need to model the individual PV installation at electrical equivalent circuit level, which requires deep understanding of PV modeling as well as knowledge of the small PV installation itself. The cost of engaging dedicated and qualified resources to perform such engineering level modeling is too prohibitive for the smaller scales associated with the rooftop sector.

Solextron has solved this challenge, by creating an optimization design tool, which can automatically generate solar digital twins during the design phase. A key source of uncertainty about the predicted energy is the lack of radiation measured on the site. Whereas the technology (which is currently in first deployment phase with partners) was able to bring the deviations between produced and predicted energy generation from the +-25-30% down to +-5%, the model is still not able to recognize failures.

The goal of this project is to develop the first solar digital twin for small and medium sized installations able to:

1) Recognize potential sources of shortfalls or installations errors during commissioning phase, thereby improving quality of commissioned solar installations
2) Recognize failures during operation of the solar plant, thus guaranteeing long term high performance.

1.3. Project evolution

This report describes the results achieved during the first year of the project. The schedule plan is shown below, and gives an overview of the results presented in this report. The focus of the first phase of the project was to collect data from solar installations featuring issues, in order to provide information necessary for the failure recognition. Further, algorithms for the recognition of faults have been developed.

		2023	2024				2025				2026			
		Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WP1	Selection and analysis of fault data from PV plants													
T1.1	Data collection and analyses of real installations					M1								
WP2	Development of digital twin platform for failure recognition													
T2.1	Develop parametrization algorithms for PV panels and system level build-up											M2		
T2.2	Classification of failures and sources of shortfalls													
T2.3	Cloud infrastructure and UI/UX development													
WP3	Technology verification													M3
T3.1	Failure or energy shortfall recognition for datasets													
T3.2	Failure recognition during commissioning													
WP4	Technology assessment and disseminations													
T4.1	Analysis of impact of failures and energy shortfalls in PV installations													
T4.3	Dissemination													

The milestones of the project are listed in the table below.

Milestone	Description	Timeline
M1 – Dataset collected	All dataset collections completed and documented.	Q4-2024
M2 – Algorithm completed	Algorithms for digital twin parametrization and failure classification completed.	Q1-2026
M3 – Verification performed	Tests for long and short dataset performed.	Q3-2026

2.   Procedures and methodology

The following procedures have been followed for the realization of the respective goals:

2.1.   Selection of data

The collection of data for the analysis of the solar digital twin was made through the partnership of Solextron with solar installers. In total, 89 installations with size ranging from 3 kWp up to 1.2 MWp have been connected to the monitoring platform of Solextron, and the individual Digital Twins created for each plant.

In order to calibrate the loss parameters of the Digital Twin, we have selected installations in different climate zones, and with different sizes, which would allow us to better investigate the combinations of irradiance and temperature in the modeling, as well as the impact of cloud coverage. In terms of climatic regions, we have collected data from five zones in Brazil (equatorial, tropical, semi-arid, highland tropical and subtropical), and one zone in Aargau, Switzerland (Oceanic Climate). Figure 4 displays the pinned geolocations of the selected installations.
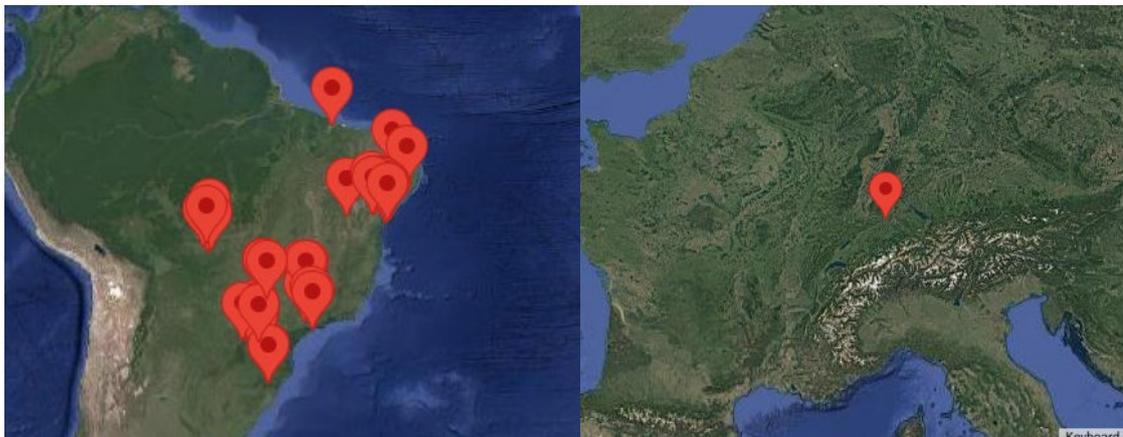

Figure 4 - Pinned geolocations of the selected installations used for investigation of the digital twins, (left) in Brazil and (right) in Switzerland.

Data has been ingested through API connection of four inverter and datalogger manufacturers. To this aim, Solextron has developed specific APIs with schedulers to collect both historical and recent data.

2.2. Digital Twin concept

Digitalization of solar systems can be achieved through the integration of smart monitoring systems, weather databases and PV modeling for performing diagnostic analysis, enabling automated maintenance procedures. Operators can then identify and address issues promptly, reducing downtime and improving the overall efficiency of the systems. A diagram of a Digital Twin integrated into a solar installation is shown in figure 5.
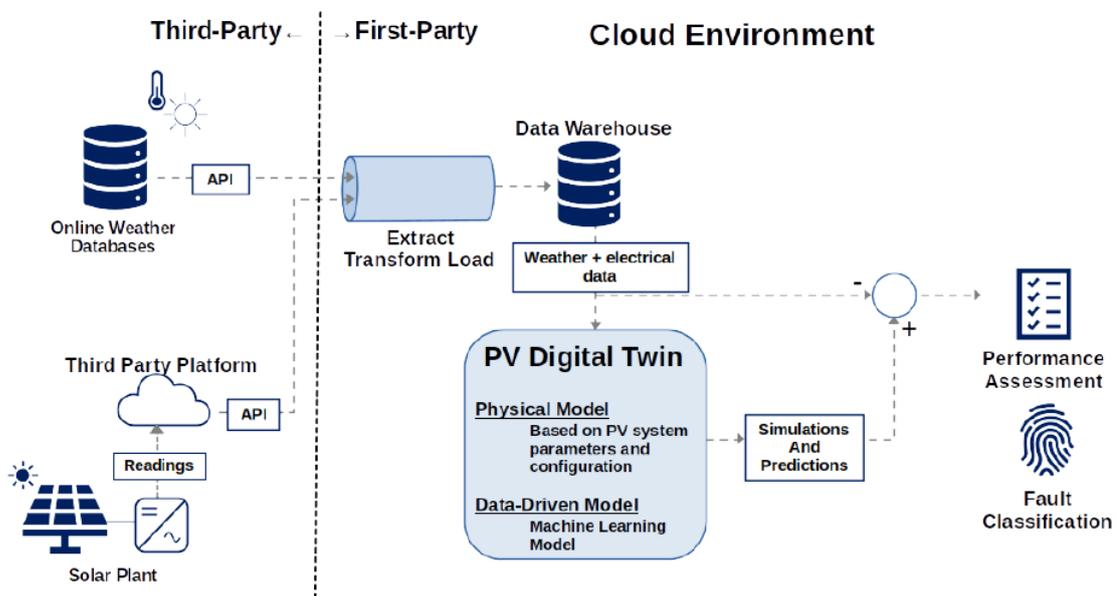

Figure 5 - Concept of monitoring of solar installations using Digital Twins.

The figure above divides the solution between third-party infrastructure on the left and first party infrastructure on the right. Third-party refers to data pulled from external providers, in our case, APIs from inverter manufacturers and weather services. Essentially, third-party data must be ingested in the first-party infrastructure passing through an Extract-Transform-Load (ETL) pipeline. This pipeline guarantees that the data can be stored in a standardized manner to be used posteriorly. The third-party data comprises weather databases and electrical readings from the solar plants on the field. Once the data is available, it can be used to power PV physical models hosted on the cloud or to train Machine Learning (ML) models that can be used for simulating the expected output of the solar plant and make predictions about the generated energy. In our case, we focus only on Physical models. By comparing the predictions to the real measurements, performance assessment can be carried-out automatically. Furthermore, by analyzing the dependence of the difference between predictions and measurements with respect to weather input and electrical parameters, fingerprints of certain malfunctions can be identified, enabling for fault classification.

The Digital Twin (Physical modeling) includes both electrical and geometrical configuration of the solar installation. In order to rapidly build the Digital Twins, the Solextron design tool has been used to create the model (Figure 6) following the steps described below:

1 - The exact coordinates of the PV system must be known in order to be able to design the virtual replica as accurately as possible.

2 - A 3D model of the building on which the system is located is created. The height and orientation of the building, the shape of the roof and the pitch of the roof must be specified. Possible obstacles such as chimneys, ventilation systems or general bulges on the roof must also be constructed. If the object is surrounded by higher neighboring buildings or tall trees, these must also be reproduced so that the shading behavior is correctly simulated.

3 - The components of the system are selected. Since only the energy yield is of interest in the analysis, it is sufficient to specify the panel model and inverter. In order to be able to deliver correct results, it is important to ensure that the correct versions or variants of the components are selected.

4 - The system is dimensioned. The number of panels and the number of inverters must be specified. This gives the installed output of the PV system.

5 - Finally, the panels are placed in the correct position on the roof, analogous to the real system. The position is important so that the shading from obstacles falls correctly on the panels. For flat roofs, the installation angle and orientation of the panels must also be specified.
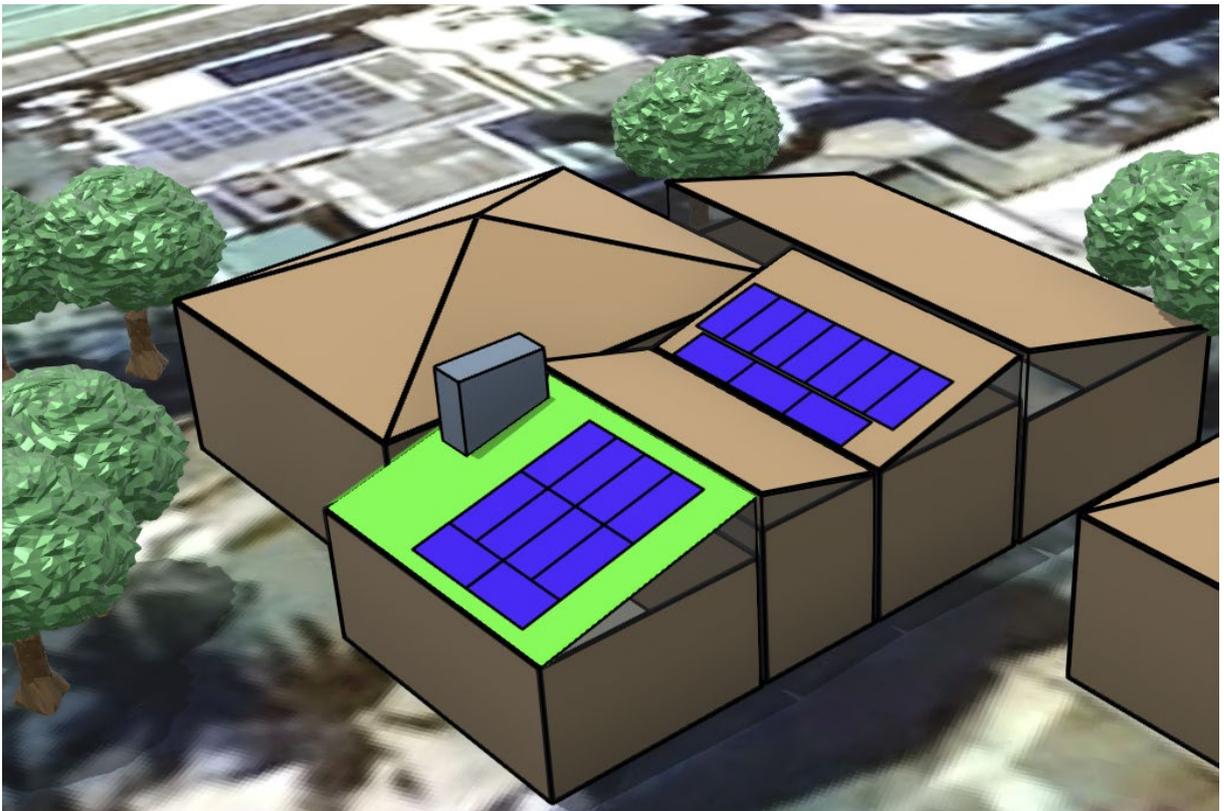

Figure 6 - Example of 3D model of the Digital Twin used in this project.

The Digital Twin was implemented in the Solextron GCP platform, which allowed rapid and practical analysis of data.

2.3. Weather data

The primary factor influencing energy production in solar plants is the incident solar irradiance. Following the IEC 61724-1 standards, this work makes a distinction between solar radiation and solar irradiance. The former refers to the energy incident on a surface and given in units of $Wh/m2$, while the latter is defined as the rate at which solar energy is transported to a surface per unit of area as is given in units of $W/m2$. In this report, irradiance will be of greater interest than solar irradiation. When modeling the irradiance on a PV array, the primary concern is the solar irradiance incident on the array's (usually tilted) plane, known as the Irradiance on the Plane of Array (GPOA). While ground-based weather stations typically measure GPOA directly, their adoption is limited due to the added costs and complexities they bring to PV plants. For the far more common case where a weather station is not available at the plant's location, an alternative approach for modeling incident irradiance involves using estimates derived from satellite measurements. In this work, we employ CAMS weather data, which is a European satellite service. The Copernicus Atmosphere Monitoring Service (CAMS) is a European Union initiative that provides accurate and up-to-date information about the composition of the Earth's atmosphere. It's part of the broader Copernicus program, which is a European Earth observation program developed in collaboration with the European Space Agency (ESA) and the European Centre for Medium-Range Weather Forecasts (ECMWF) [30]. CAMS gathers data from various sources, including satellites, ground-based measurements, and numerical models. It processes this data using advanced computer models to generate accurate and reliable information about the state of the atmosphere. Among the services provided by CAMS is CAMS's Radiation Service (for simplicity, henceforth referred to as CAMS), which uses the Heliosat-4 model [31] to derive accurate estimations of solar irradiation based on satellite images of Earth's atmosphere. CAMS Geographical coverage is the field-of-view of the Meteosat satellite, roughly speaking Europe, Africa, Atlantic Ocean, Middle East and part of South America (-66° to 66° in both latitudes and longitudes).

2.4. Model calibration of loss parameters

In order to be able to diagnose a solar installation, it is first important to verify the physical model as well as the input loss parameters of the design match the analyzed installations. This has been performed by assessing the energy match between the produced energy and the Digital Twin forecasted. The main components of losses analyzed are listed below:

Soiling
Over time, soling builds up on top of the PV panels, partially blocking the incident light. Soiling losses can typically are < 5%, but in some locations can be significantly higher

Shading
Shading from small or big objects can significantly impact the production of solar arrays. Anything from trees, buildings or even bird droppings can cause shading, leading to losses.

Snow
Snow coverage over the PV panels can cause losses ranging from 10% to 30%, depending on the tilt of the array.

Mismatch
Since an array is formed by associations of PV panels in series and parallel, if a single panel operates at conditions different from the others, it will affect the performance of the whole string.

DC and AC Wiring
Models losses in cables and wires in the PV panels and array.

3. Results and discussion

3.1. Digital Twin calibration

The challenge of determining faults in solar installations is based on the uncertainties inherent from the differences between a real solar system and a virtual one. The main uncertainties of the Digital Twin are related to:

Modeling
The Digital Twin modeling can display uncertainties either in the 3D or in the electrical models. For instance, uncertainties on the definition of azimuth or tilt angle of the panels, as well as height and form of objects generating shadows can affect the model. Regarding the electrical model, panels and inverter parameters already have uncertainties as per datasheet (e.g., ~5% for panel parameters), and there are further uncertainties regarding determination of losses. In our case, because the dataset was collected over a wide range of climate regions, we could minimize uncertainties of loss parameters by making sure that the DIgital Twin would provide a good match for all regions.

Weather data
The weather data is also a source of uncertainty. Weather satellites divide the earth into grids or quadrants, and the installation coordinates are used to select the quadrant in which the PV system is located. The Digital Twin obtains the temperature and radiation data from the weather satellites, which are averages for the temperature and radiation values are calculated for the relevant quadrant. If there are a lot of clouds in the specific region of the installation, the values can be inaccurate. A similar problem can occur with the temperature values. Here, too, average values are calculated for each quadrant. If the system is located on a roof with a low albedo, for example, much higher temperatures can arise under these circumstances than the data would suggest. These uncertainties in the weather data are part of the Digital Twin and cannot be avoided.

In order to calibrate the Digital Twin model, we tested different loss parameters in order to minimize the Mean Square Error between the produced (orange) and forecasted (blue) energies over an year, thereby obtaining a large statistical dataset as shown in Figure 7. We estimate that the total uncertainty will be between 5-10%, depending on the region.
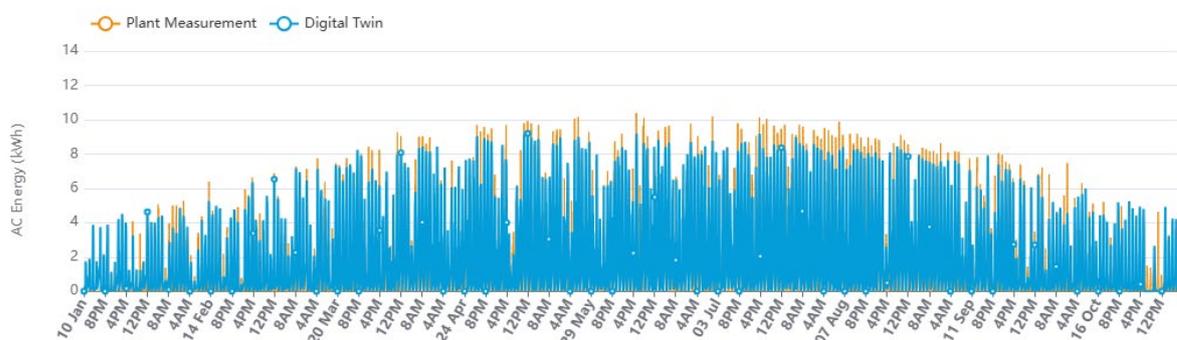

Figure 7 - Yearly dataset of solar installation in Switzerland, where blue is the Digital Twin forecast and orange the produced energy.

3.2. Collection of data with faults

After discussion with large solar installers, which commission up to 8`000 installations per year, we have selected the four most sources of issues in solar installations, whose case studies are displayed below.

3.2.1. Soiling

Soiling is an unavoidable source of energy loss in solar installations, and it is highly dependent on the region landscape as well as roof geometry. For example, installations in rural areas displayed consistently strong soiling losses after just one year, likely because of dust contamination. Based on this hypothesis, one could also expect accentuated losses in regions next to mountains or railway lines. The fingerprint for spilling losses is simple loss of energy produced compared to the digital twin. In order to guarantee that the investigated losses were due to spilling, we have collected data of installations that recovered energy production after cleaning maintenance. In the following example, an 1.2 MWp solar installation in a rural area, installed in 07/07/2022 has clearly exhibited energy loss due to soiling as shown in Figure 8 (top). In the 2023 comparison between the Digital Twin (blue) and the produced energy (orange), there was a consistent loss of 17% of energy produced, confirming that even for early installations, systems in rural area will strongly suffer from soiling losses, and should undergo strong monitoring using Digital Twins.

3.2.2. Clipping

Figure 9 shows a solar installation displaying clipping behavior. As aforementioned, clipping refers to a phenomenon where the power output from a solar photovoltaic (PV) system is limited by the capacity of the inverter. This occurs when the solar panels generate more electricity than the inverter can convert from direct current (DC) to alternating current (AC). The excess energy that cannot be processed by the inverter is essentially "clipped" and lost, which is why this effect is called clipping.

Clipping typically happens during periods of peak sunlight, when the solar panels are operating at their maximum capacity. For instance, on exceptionally sunny days, the DC power generated by the panels might exceed the inverter's maximum AC output capacity, leading to a flat-topped power curve where the output is capped at the inverter's limit. While this means some potential energy is lost, it's important to note that clipping does not damage the solar panels or the inverter. However, excessive clipping could indicate that the inverter is undersized for the solar array, which might lead to a less consistent power supply during peak production times.

In the case of study, the installed power is 11 kWp while the inverter has a power of 7.7 kW, yielding a high DC/AC ratio of 1.43. From the figure one can see that in months with string irradiance, the output of the PV panels becomes too high for the inverter. Normally, the course of the day should resemble a parabola, showing however a "cut off" at 7.7 kW. Strikingly, the Digital Twin closely resembles the shape of the clipped energy production, demonstrating the fidelity of the model. Clipping is in fact a very typical type of fault caused by poor design engineering.
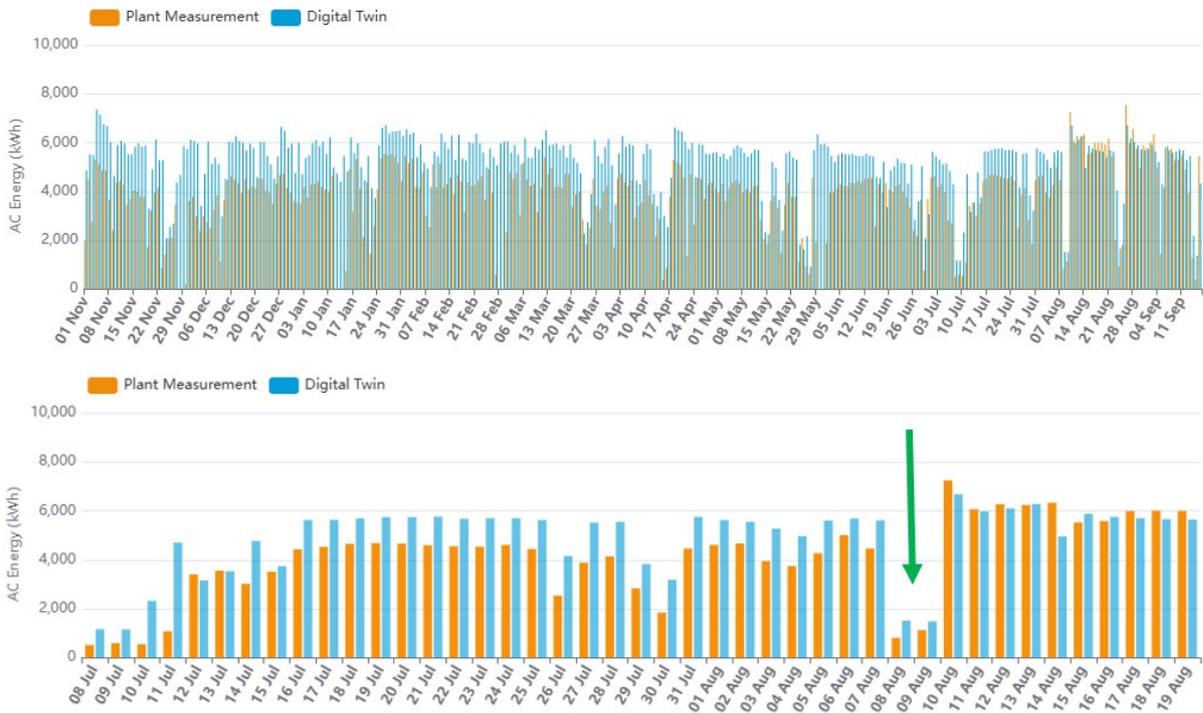
Figure 8 - (Top) Gmap view of the 1.2MWp solar installation featuring spilling, and in the middle and bottom, the time series of the produced and forecasted energy of the installation, where blue is the DIgital Twin forecast and orange the produced energy.

The effect is further confirmed by the cleaning executed on 09/10/2024, which restored energy production in the installation up to about 100%. Nevertheless, the accumulated financial losses were significant for the owner.

Figure 9 - (top) solar installation featuring clipping with a 1.43 DC/AC ratio, and (bottom) time series data of DC current and voltage as well as GHI.

3.2.3.   Derating

Typically, derating refers to saturation of energy converted in the solar inverter due to temperature operation above specification limits. At high temperatures, the power conductors responsible for converting the electrical signals overheat, and in order to avoid catastrophic failure, the MPPT track will automatically "derate" the inverter to provide less energy from the DC-DC boost converter to the DC-AC.

In the case of study, the solar installation has an installed capacity of 12.9 kWp and an inverter capacity of 10 kW, i.e., with a DC/AC ratio of 1.29. As shown in figure 10, the curve of energy production collected in the inverter flattens at 9 kW. Because the limit of energy is below the inverter 10kW power, the effect cannot be attributed to clipping but to derating. It is important however to mention that not ambient temperature but other failures such as fan failures, internal errors, protection mechanisms, etc. could also cause the derating. It should be noted that the flattening of the curve also sometimes occurs between 7 kW and 8 kW, which further indicates that the inverter is undergoing a high temperature increase. Derating is observed often in ground mounted and roof top building installations, particularly when the inverter and hanged on walls that are exposed heavily to sun irradiation.

Figure 10 - (top) solar installation featuring derating with a 1.29 DC/AC ratio, and (bottom) time series data of DC current and voltage as well as GHI.

3.2.4. String disconnection

Together with soiling, string disconnections is on the top of the list of issues that happen in solar installations, and it reaches up to 62% North American large scale installations. String disconnections in solar installations can occur due to a variety of reasons, often related to poor installation, or wrongly connected cabling. Here are some of the common causes:

1. Ground Faults: A ground fault is an unintentional electrical connection between a current-carrying conductor and the ground. In solar PV systems, ground faults can happen due to installation errors, such as pinched wires or wires damaged during installation. They can also occur over time due to thermal expansion and contraction, or wind motion causing wires to rub against module frames or racking, wearing down the insulation.

2. Cable Management Issues: Poor cable management, such as the use of standard plastic wire ties that fail prematurely due to heat or UV exposure, can lead to electrical faults and power loss, necessitating string disconnections for repair.

3. Connection Failures: The connection point between a string and the input point of an inverter, where there is a fuse or switch, may fail in the event of a voltage spike, causing a string disconnection.

4. Connector Failures: The connectors linking cables between panels, e.g., MC4 connectors, might be either wrongly assembled, or simply degraded overtime. This will lead to string disconnections.

The case study shown in figure 11 shows an example of a solar installation with string disconnection. While the Digital Twin remains constant, the actual energy production drops abruptly. In other words, the connection of an entire string to the inverter is broken or interrupted. This would be confirmed by a closer look at figure 11. This system has two 7-strings and one 4-string. The energy drops by almost 2/3. This could mean that one of the two 7-strings and the 4-string have failed. If only 7 instead of 18 panels are supplying power, this would account for around 2/3 of the energy production, thereby supporting the hypothesis. The abrupt loss of power is a typical fingerprint observed in solar installations featuring string disconnection
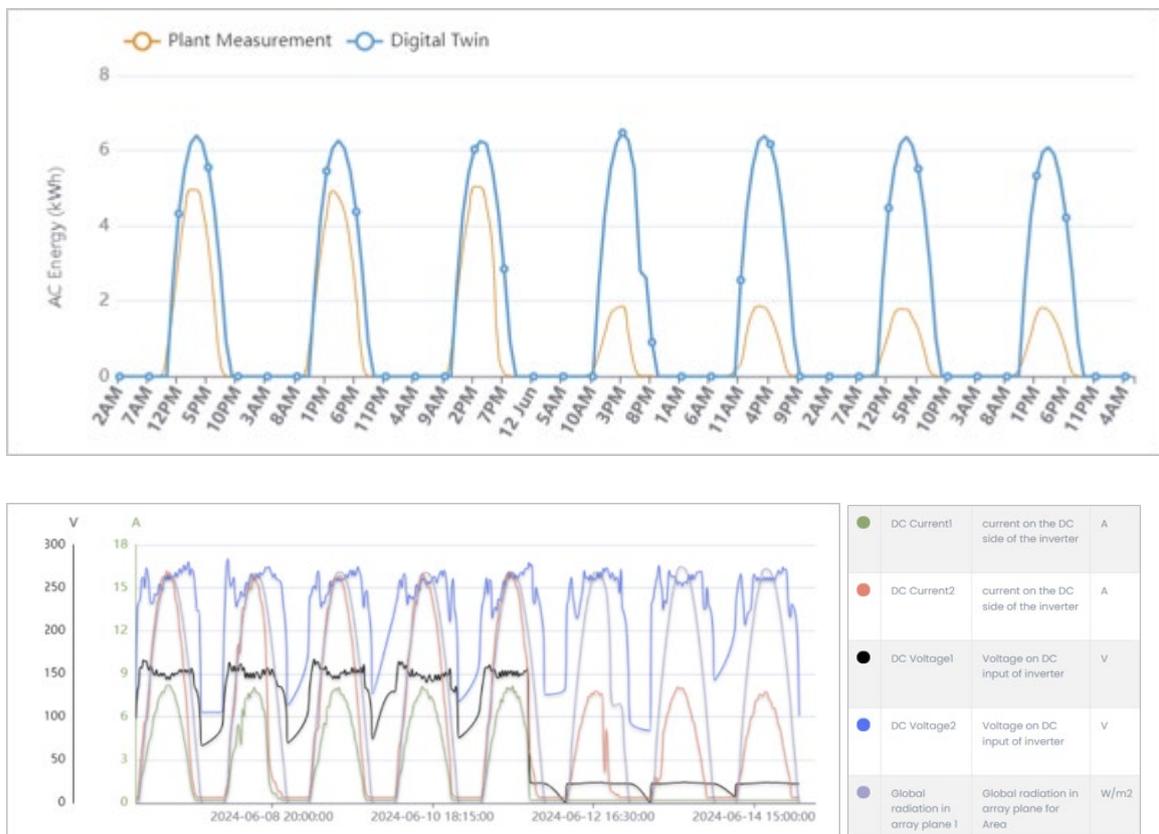

Figure 11 - (top) solar installation featuring string disconnection in one of the strings, and (bottom) time series data of DC current and voltage as well as GHI.

3.2.5. Combined faults

In our investigations, we have also encountered installations featuring combined faults, as in the case study of a 7.7 kWp installation, which was suffering from soiling, and during a period experienced a string disconnection. After reconnection, the installation remained dirty, even because without the Digital Twin, the owner is not capable of determining the energy losses.
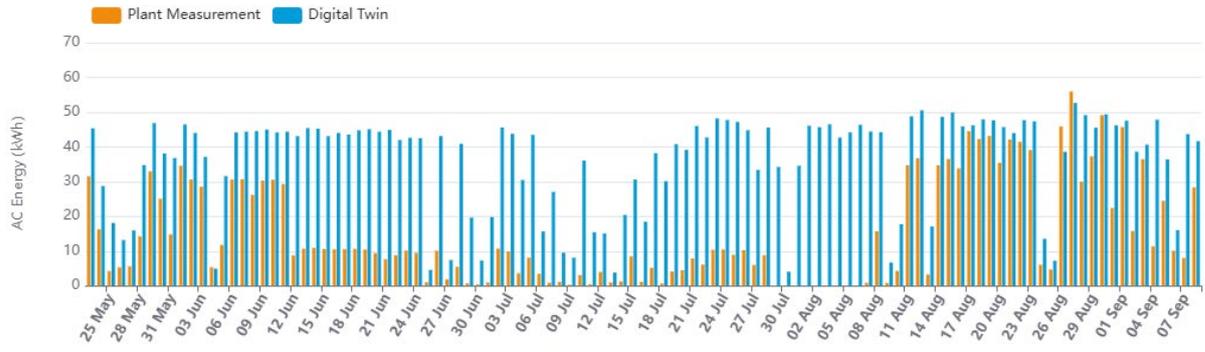
Figure 12 - Solar installation featuring string disconnection in one of the strings as well as soiling.

4. Conclusions

The PV-GOAL project aims to foster a sustainable and efficient expansion of solar energy in Switzerland. This is achieved by providing residential, commercial, and industrial solar installations with automatic recognition of failures and energy shortfalls through advanced digital twin monitoring technology. The University of Applied Sciences and Arts Northwestern Switzerland (FHNW), in collaboration with Solextron AG, is at the forefront of this initiative by developing sophisticated algorithms and a deployable cloud monitoring tool capable of performing failure recognition. This marks the first time that solar Digital Twin technology is being made available to small and medium installers.

The project has successfully completed its second year, meeting all planned objectives and milestones. The key activities during this period included:

- Data Collection: A comprehensive dataset of detailed measurements from 80 solar installations across a wide range of climate regions was collected. This dataset is crucial for developing and testing the failure recognition algorithms.

- Cloud Infrastructure Development: A Google Cloud Platform (GCP) infrastructure was developed to enable monitoring of the solar plants via inverter APIs. This infrastructure also allows for the manipulation of data to investigate failures in the collected solar installations.

- Fault Classification: The faults encountered in the installations were collected and classified. This information is essential for training the digital twin models to recognize and predict failures accurately.

From a project management perspective, PV-GOAL is progressing as planned. The project is on schedule and within the allocated budget, and it has met the expectations of all project partners. The achievements of the second year lay a solid foundation for the continued development and deployment of the digital twin monitoring technology, which is expected to significantly enhance the reliability and efficiency of solar installations in Switzerland. By the end of the project, PV-GOAL aims to provide a robust tool for automatic failure and energy shortfall recognition, contributing to the broader adoption of solar energy and the transition to a more sustainable energy system.

5. Outlook and next steps

Building upon the successful completion of the first year, the next steps for the PV-GOAL project will focus on the development and refinement of the algorithms that will be used for failure recognition in solar installations. The extensive dataset collected from the 80 solar installations, which spans a wide range of climate regions, will serve as the foundation for this development. The data will be meticulously analyzed to identify patterns and correlations that indicate potential failures or energy shortfalls. By leveraging machine learning and data analytics techniques, the project team aims to create robust algorithms capable of accurately detecting and predicting issues in solar systems.

In parallel, the project will continue to enhance the GCP cloud infrastructure to support the deployment of these algorithms. This will involve integrating the failure recognition algorithms with the cloud monitoring tool, allowing for real-time analysis and detection. The classified faults from the first year will be used to train the digital twin models, improving their accuracy and reliability. Additionally, the project will begin testing the digital twin technology in a controlled environment before deploying it to a select number of pilot installations. This phased approach will ensure that any issues are identified and addressed early, leading to a more reliable and effective solution.

6. Publications

At this stage, no publications have been made.

7. References

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