Solution 4. Concept

Near 100% autonomous aerial inspection and fault detection system based on the integration of AI and high temporal and spatial resolution multispectral aerial imaging solutions

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List of Acronyms

AI	Artificial Intelligence
KPI	Key Performance Indicator
PV	Photovoltaic
O&M	Operation and Maintenance
FAD	Fault and Anomalies Diagnosis
PR	Performance Ratio
SVDD	Support Vector Data Description
AGL	Above Ground Level
EVA	Ethylene Vinyl Acetate
EL	Electroluminescence
LL	Logical Layer
ML	Machine Learning
SN	Serial Number
UHR	Ultra-High Resolution
UV	Ultra-Violet

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Keywords list

- Artificial Intelligence
- Machine learning
- Algorithm development
- Data Analytics
- Aerial Imagery
- Fault detection
- AI/ML
- Multi-temporal
- Multi-spectral
- High-Resolution

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PVOP

1. Executive summary

Solar photovoltaic technology has been experiencing exponential growth in recent years and is expected to continue in the coming years. This and other factors mean that its operation is facing new challenges that can only be addressed by digitization and the use of advanced information analysis and management techniques.

The present WP addresses one part of this problem: the automatic diagnosis of faults and anomalies. This automation has great advantages in the operation and maintenance of the PV plants:

- *Considerably reduces the effort of analysing the plant operation, making it more efficient and productive.*
- *Problems are solved more efficiently and quickly, reducing their associated damage.*
- *Plant operators do not waste time on tedious inspections and have prior knowledge of the problem they are facing, reducing unnecessary work and improving workplace safety.*
- *Multiple problems that cannot be located with traditional techniques can be solved, especially those related to predictive maintenance.*

The approach of this project to face this challenge is through the use of AI. This document presents a state of the art on the latest related developments, which serves as a starting point for defining the techniques to be used.

Task 4.2 concept can be found in Chapter B: Near 100% autonomous aerial inspection and fault detection system based on the integration of AI and high temporal and spatial resolution multispectral aerial imaging solutions.

The main objectives of this chapter B are:

- State what current problems in PV plants we address to focus on
- State why T4.2 contribution is crucial for the achievement of PVOP objectives
- Describe the concept of our proposed solution and its six Use Cases
- Indicate validation KPIs and targets to be reached for each Use Case of the solution
- Briefly describe the test campaign that will be carried out

Section Introduction states the current problems in PV farms that PVOP aims to address, their impact they have on the Assets and which general characteristics the solution PVOP proposes presents.

Section Architectural proposal is a comprehensive technical description of the concept proposed by PVOP for this T4.2, with a detailed characterization of each Use Case it is made of.

Section Experiments and KPIs describes the experiments that will be carried out for the validation of the proposed solution, describes the KPIs used for its validation and sets their expected values.

Chapter B:

Near 100% autonomous aerial inspection and fault detection system based on the integration of AI and high temporal and spatial resolution multispectral aerial imaging solutions

2. Introduction

Regarding the **state of the art** of the use of drone-based non-destructive inspections in solar PV sector, one can observe that the technology is well mature when it comes to aerial thermography [1]. The knowledge needed to prepare an automatic flight plan, executing it and collecting the imagery is well developed and used. Also, Artificial Intelligence/Machine Learning (AI/ML) is widely used to identify and classify defects, and automatic customized reports are available by a great number of service providers throughout the world [2].

Based on Aeroprotechnik experience, in the vast majority of cases, the thermography of solar PV plants is conducted at most once per year, with high effort in terms of equipment and human resources (all the images have to be reviewed by a L2 thermographer as per IEC 62446-3). The low granularity of the inspections opens the door to great losses of performance and energy yield, due to unnoticed defects on the PV generators, that can stay in place as long as one year until detected, reported and fixed. The lack of automation in nowadays majority of inspections, on the other hand, increases costs, human effort, and delays results availability.

Moreover, not every defect in PV modules generates a hotspot and therefore can be spotted by thermography: very early-stage millimetric cell cracks, for example, are rarely detected by IR imagery and therefore they can stay “under the radars” till the moment in which the fault evolves to something bigger. On the other hand, the PV generators themselves are not the only reason for performance losses: one can note that the default of a tracking system (for the large PV plants that have this design) is rarely detected before some weeks (or even months) of constant underperforming of the subset of strings affected, and even when noticed it is difficult to geo-locate the faulty equipment.

Vegetation management is another factor that Asset Owners of a PV asset must take into important consideration: the shadow on the PV modules caused by the growing vegetation leads to losses of energy yield and even to their early degradation if shadow is prolonged over time [3]. The vegetation trim often requires extensive use of manpower, it is costly and therefore carried out with lower-than-optimal intervals between cuts.

A crucial aspect on a solar farm is the Asset integrity: in the event of a fire, the farm can be completely destroyed, and therefore this incident must be avoided at all costs. **Error! Reference source not found.** shows an example of fire in a farm in Fresno, California, whose trigger was a faulty connector.

Figure 1. Solar farm after fire. Source: https://kmph.com/

There is evidence [4] that the majority of fire events in solar farms are triggered by short-circuits in faulty electrical equipment, for example switchers, boards, isolators and cable connectors. We observe that while the bigger electrical equipment is usually easily accessible (inverters for example), the connectors spread throughout the PV plant can only be inspected by foot, with extensive usage of manpower, high costs and low efficiency.

Depending on some factors such as the conditions of contract in place with the PV modules manufacturers or the age of the farm, there can be in place measures that assure that defective modules are replaced under warranty. In some cases, for the claim to be successful, the Serial Number (SN) of the defective module needs to be added in the process and it might not have been inventoried by the Asset Owner. The manual collection of the SN on the field is time-consuming, expensive and its reliability is low due especially to the high margin of error in the geo-location of the SN.

2.1. Going beyond the state of the Art

In PVOP, and in this T4.2 in particular, we propose to overcome some of the limitations in the actual technology stated in the previous sections by using aerial imagery and AI/ML to go **beyond the state of the art**, in order to contribute to the achievement of one of the main objectives of the project (SO1): *Increase the performance of PV asset portfolios by 4.7% and reduce their management and O&M costs by 32%.*

The key point of PVOP proposed solution are:

- **Use of high temporal resolution imagery**

Thanks to extensive use of automation and reduction (or elimination) of human supervision on-site, the frequency of inspections will be significantly increased. Issues with PV modules or other parts of the farms will be earlier detected and corrective measures will be deployed straight after. Furthermore, PVOP proposed solution relies on the cross-relation between multiple inspections on the same farm area.

- **Use of high spatial resolution imagery**

It is expected to dramatically increase the imagery resolution, both in terms of sensor quality/capability and in terms of proximity from the sensor to the inspected equipment. It will be then possible to detect even the smallest anomalies (e.g., millimetric micro-cracks), leading to early corrective measures adoption and follow-up.

- **Use of multispectral imagery:**

The proposed solution is expected to use imagery available from multiple portions of electromagnetic spectrum: UV (<380 nm), IR (7500-13000 nm), visible (entire spectrum: 380-700 nm, or divided in channels: RGB), NIR (900-1100 nm).

- **Extensive use of AI/ML and LL for data processing**

AI/ML and LL (logical layers) are seen as an extremely powerful tool to improve results accuracy, reliability, scalability and standardization.

3. PVOP Architectural proposal

An architecture, whose conceptual modules are represented below in **Error! Reference source not found.**2, has been proposed aiming to provide the "Autonomous Aerial Inspections and Fault Detections" system with the required modules to implement a near 100% automation but as well the required flexibility and modular concept to accommodate several scalable PV-related Use Cases.

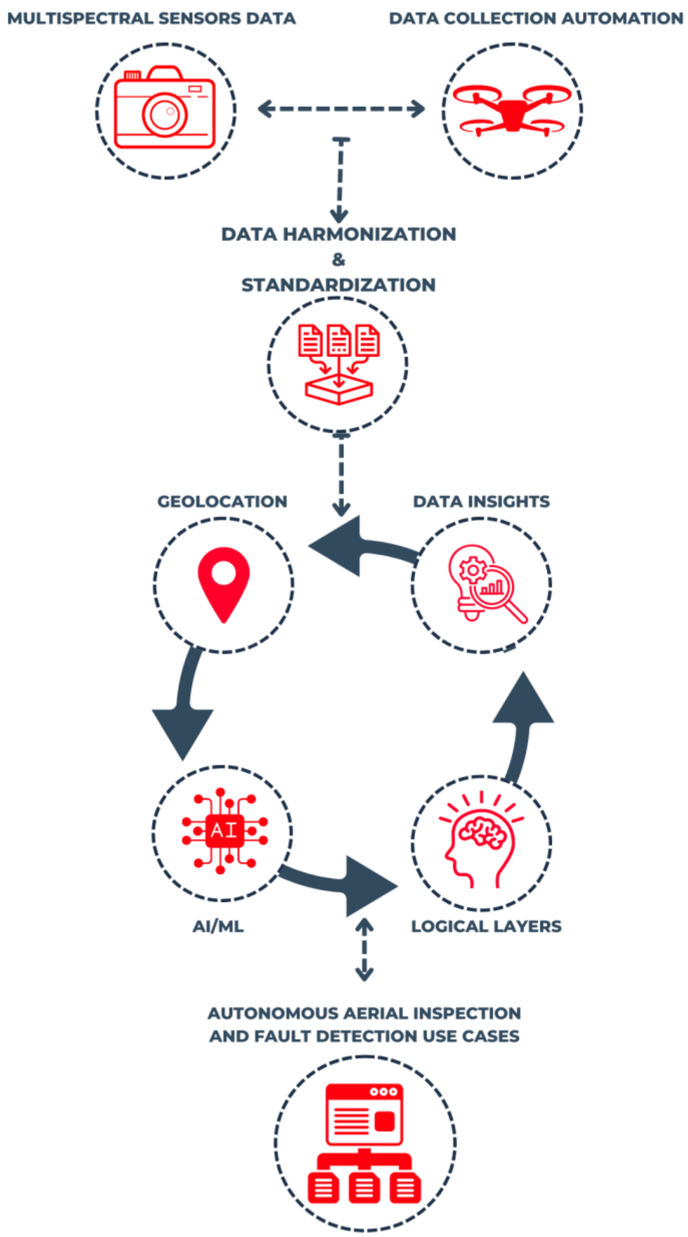

Figure 2. PVOP T4.2 Architectural proposal

The several architectural conceptual modules are described below:

- **Multispectral sensor Data**

  Multispectral Data collected through several sensors working in different regions of the electro-magnetic spectrum as such (Blue, Green, Red, Red Edge, Near Infrared, others), IR, RGB, EL, UV, others to be studied.

- **Data Collection Automation**

  This module implements a set of algorithms specifically designed to automate the data collection for the multiple use cases, it will implement routines as such as Flight Height Level Control, Sensor triggering, dynamic flight adaptation, high proximity flight and collision avoidance techniques.

- **Data Harmonization and Standardization**

  This module makes sure that all data is initially harmonized both in terms of pre-processing imagery settings and tunings as well as adjust imagery Raw data to a Standardized format. Such actions will ensure data consistency, fidelity and reliability allowing the solution to accommodate huge amounts of data in a scalable way and implement the baseline for High Temporal and Spatial Resolution data techniques.

- **Geo-location**

  Geo-location is a very important component of any automated solution: it will provide the system with capabilities to identify faults down to the PV module and cell level in an efficient and error-free way.

- **AI/ML**

  Artificial Intelligence algorithms will be created and trained in order to identify faults in an automated and scalable way based on object detection patterns. Such algorithms will be trained with real datasets in a retrofitted loop allowing their accuracy and reliability to improve over time. Data augmentation techniques will be used in order to improve accuracy and efficiency (in terms of human time) during data tagging phase.

  The general overview of this conceptual module is represented in the following diagram:

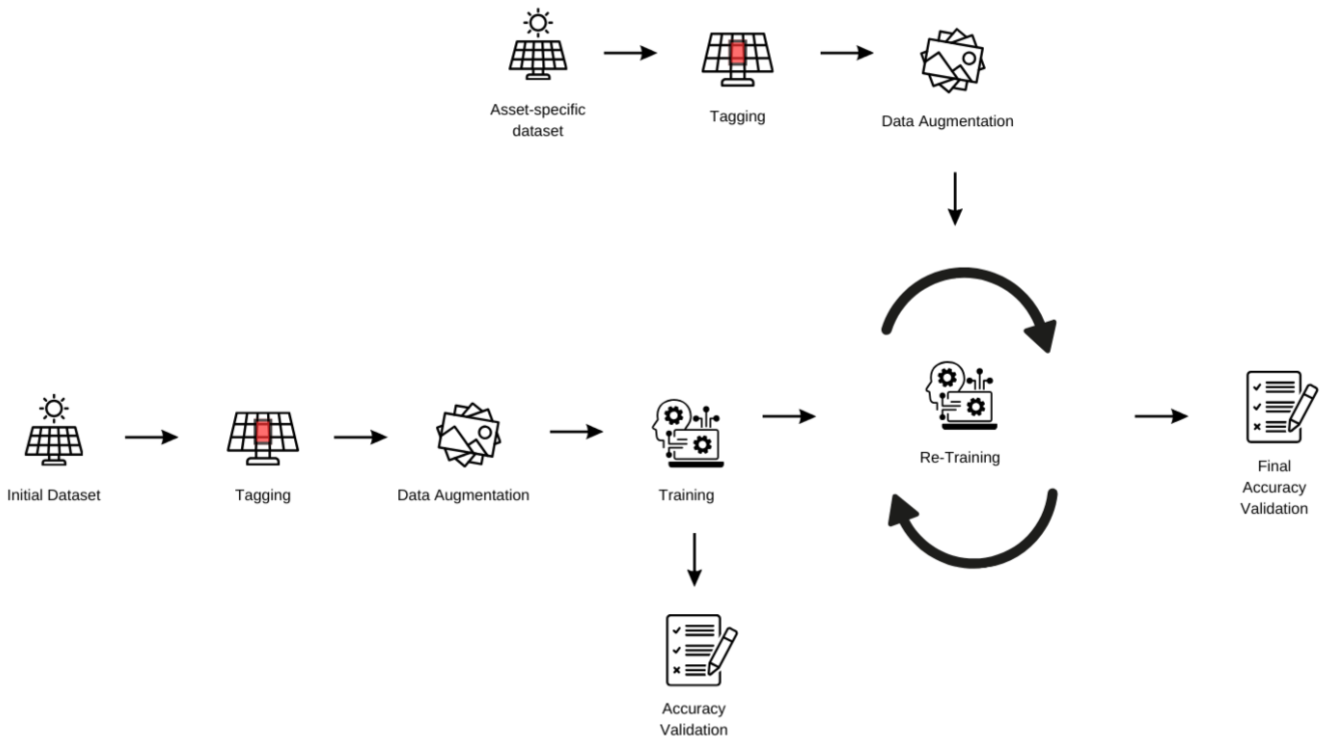

Figure 3. PVOP T4.2 AI/ML diagram

- **Logical Layers**

  Provides the system with logic and threshold trigger rules in order to complement and improve native AI/ML algorithms. Such layer is of extreme importance in the effective integration & adaptation of AI/ML algorithms for every specific proposed use case. It implements complex rules, calculations, fuzzy systems, fault classification and quantification functionalities.

- **Data insights**

  Ultimately, this module transforms the full system analysis into Actionable Insights leading to PV Asset Performance enhancement, OPEX optimization and Asset de-risking.

4. Use Cases

The solution is constituted by 6 modules (use cases) that can be used in combination between themselves or as stand-alone modules. The adoption of the most complete solution (all the use cases) will be encouraged by the fact that some of the use cases share hardware components.

Error! Reference source not found. shows the Uses Cases PVOP solution for T4.2 is made of:

Autonomous Aerial Inspection for fault detection system – Use Cases	
Use case No.	**Brief description**
1	Automated Aerial Electro-Luminescence (EL) testing and failure detection
2	Ultra-High-Resolution imagery applied to detect different problems at PV modules and to inventory PV module serial numbers
3	UV Fluorescence to detect defects in PV modules such as cracked cells in a fast and cost-efficient way
4	Real-time identification of misaligned trackers
5	Real-time identification of hanging DC cables as potential fire Risk Automatic Detection
6	Vegetation Management

Table 1. Autonomous Aerial Inspection for fault detection systems - Use Cases

4.1. Automated Aerial Electro-Luminescence (EL) testing and failure detection

Electro-luminescence (EL) testing is a non-destructive method used to identify defects and issues in PV modules, like cell cracks and micro-cracks [5]. EL is based on the silicon cells property of emitting photons (light) when electrically biased. Imagery is usually captured at night (due to the low intensity of the emission, that would be completely overcome by the Sun during the day) by a camera with properly filtered lens.

EL test is usually performed:

- At origin (factory), for manufacturing quality control and pre-shipment validation
- At modules reception, for verification of absence of damage after transportation

- After modules installation, for verification of damage absence after mounting

Normally, PV modules factories are equipped with labs in order to perform EL tests on modules, while tests executed on the field are carried out in closed shelters (mobile labs). Regarding the testing on the field the present-used field setup (mobile lab) is ineffective and time-consuming because it is necessary to unmount and remount the PV module each time, and the mobile lab deployment can be expensive and inefficient.

IEC/TS 60904-13 sets the methods and best practices for capturing electroluminescence images of PV modules, in a field or laboratory setup. Quantitative (processing of images to obtain quantitative metrics about them) and qualitative (provide guidance to qualitatively interpret the images for features that are observed) methods are addressed. In its Annex D the defects that are possible to identify using EL are presented; among them, we'd like to point the ones difficult to spot with other techniques in crystalline silicon modules, such as:

- Cell cracks (with or without isolation of regions of the cell)
- Missing, broken, or delaminated grid finger lines
- Wafer/cell contamination
- Solder flux interaction with grid finger metallization — silicon interface

As an example of a EL picture, **Error! Reference source not found.**4 shows the post-processed EL image of a PV module taken in the field by Aeroprotechnik in a solar farm located in France, with a DSLR camera mounted on a tripod. A cell crack in the upper part of the module is easily visible: this issue would be hardly detected with other types of non-destructive tests.

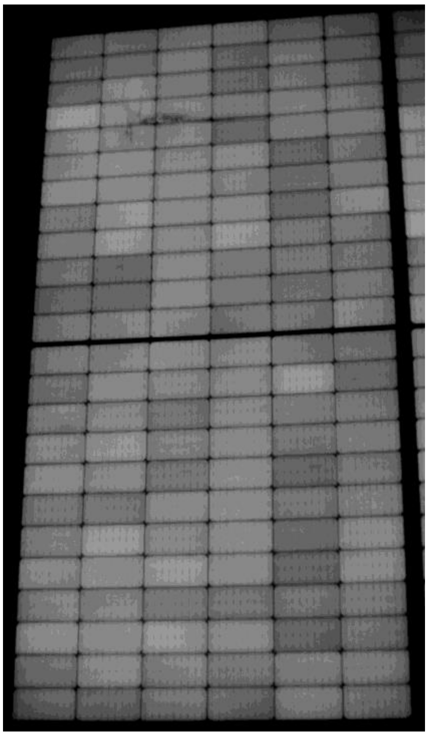

Figure 4. Post-processed EL image of PV module

PVOP proposal for this Use Case is an aerial-based platform capable to autonomously perform EL Tests on a selected and biased section of a PV farm, transfer the images to a processing area, process them with AI/ML/LL in order to identify and geo-locate issues and automatically provide results to designated receivers.

The proposed architecture of this module is shown in **Error! Reference source not found.**5:

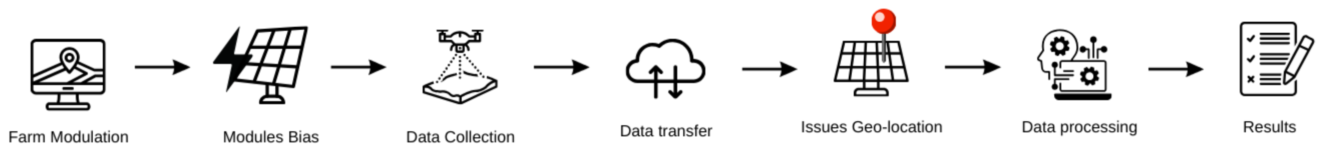

Figure 5. Automatic EL Test - Architecture

The equipment expected be used for this module are presented in Table 2:

Automatic EL Test - Equipment	
Equipment type	**Purpose**

DC power source	Biases multiple strings in absence of the possibility of direct biasing from the inverters
Drone	Carries the selected payload
Sensor	Data collection

Table 2. Automated EL Test - Equipment

4.1.1. Field Setup

The biasing of the modules is the most challenging difficulty to overcome in order to reach a certain degree of scalability (in terms of PV modules/strings inspected per night).

PVOP proposes two solutions in order to save time and costs:

- Bias of the modules directly from the inverters

  The possibility to have the PV modules biased directly from the inverters will be investigated and contacts will be made with a number of manufacturers in order to study the possibility that the equipment works as AC-DC converter. In this case, with a careful synchronization between the drone location and the biasing sequence, the drone will always be flying in biased sections of the farm.

- A sufficient powered programmable DC source is used to bias multiple strings at the same time.

  The DC source can be placed close to the center of the area of inspection, fed with AC power available on-site and connected to all the strings of the inspection area via a switcher. With a careful synchronization between the drone flights and the switcher (integration between programmable DC source and drone will be addressed), the source will always be injecting power in the string (or strings) the drone is flying over.

4.1.2. Data Collection

The farm is mapped once in its lifetime based on the As-Builts available from the Asset Owner and with the IDs already set. Whenever the As-Builts are not available (older farms, ownership change without transfer of documentation) or not up-to-date (expansions, tables/trackers removed), farms can be mapped with other methodologies, as satellite images, imagery and/or point clouds collected on the field.

Taking into consideration that EL flights will be executed at night, some challenges related to data acquisition need to be addressed: the drone proximity sensors, for example, will not operate as expected in these conditions. To mitigate this issue, and reach the required level of automation and safety, the flight plans will be generated with alternative obstacle avoidance methodologies.

The preparation of the flight plans is also the first pillar for the subsequent data flow process: a correct data collection planning will endorse the imagery acquisition in the exactly expected location, and all collected imagery will be integrated with the necessary metadata needed later on for their processing.

Since no commercial drone camera with the required specification is currently available on the marked, this module will require the preparation of a customized payload. At the end of the missions, the customized payload will connect to a local network and synchronize the data, after the synchronization process, the payload will be prepared for a new data collection.

4.1.3. Data processing

As the data is being received by the data processing engine, the analysis process will start immediately. Data processing is divided into several steps, each of them being responsible for a part of the process that will, in the end, associate all identified anomalies to the specific PV modules as per solar assets As-Built information. The required metadata needed for the subsequent steps is extracted from the imagery and cross-related with the drone flight plans, the areas of interest are identified, isolated and geo-located, and autonomous defect detection module, using AI/ML/LL algorithms is triggered. IEC/TS 60904-13 will be taken as reference regarding the type of anomalies (and their criticality) that will be searched.

4.2. Ultra-High-Resolution imagery applied to detect different problems at PV modules and to inventory PV module serial numbers

As second Use Case of the global solution, T4.2 intends to develop a use case that will drastically increase the resolution of the RGB imagery collected on the field. The proposed use case consists in an autonomous airborne platform equipped with Ultra-High-resolution camera (>= 50 MPx) that will fly at a very close distance (< 1 m expected) from the PV modules, transfer the images to the processing environment, process them with AI/ML/LL in order to identify and geo-locate issues (or read Serial Number labels) and automatically provide results to designated receivers.

Among the defects that the proposed module will be able to autonomously detect and geo-locate, we can include:

- Split glasses (that sometime have not a thermal pattern and therefore are difficult to detect by thermal inspection)
- Delamination (especially for thin film modules)
- Gas pockets (especially early-stage ones)
- Sub-millimeter level cracks

Figure 6 shows a broken glass (better visible in the enlargement) in a solar farm in France, collected by Aeroprotechnik with a drone flying at 7 m AGL.

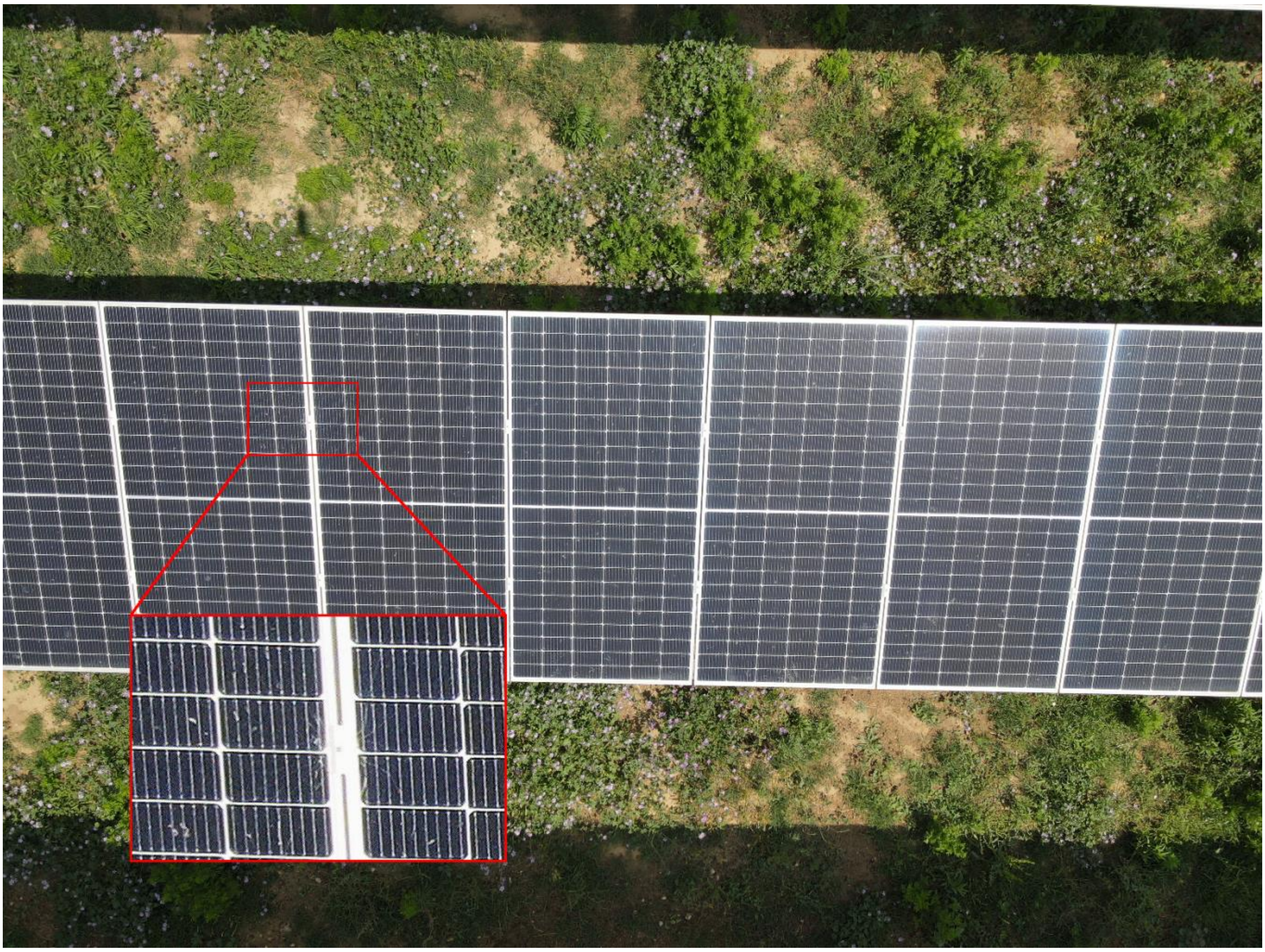

Figure 6. Broken glass in solar plant

The equipment and technology embedded in this module will also empower the possibility of performing an automatic reading of the PV modules Serial Number, an activity meant to be performed only once for the entire life of the asset but, as stated in the previous sections, particularly useful for claims. It is advisable that SN reading is performed as soon as possible after panels installation in order to avoid that dirtiness, prolonged sunlight or other ambient factors worsen the readability of the labels.

Figure 7 shows the full-picture (with label detail) of a PV module collected by Aeroprotechnik in Portugal, with an airborne 20 MPx camera, manually operated at a distance of approximately 1.5 m to the module. It is possible to observe that despite the number is readable, the image resolution and definition is not high enough to clearly view the barcode (whose reliability is much better than a printed number).

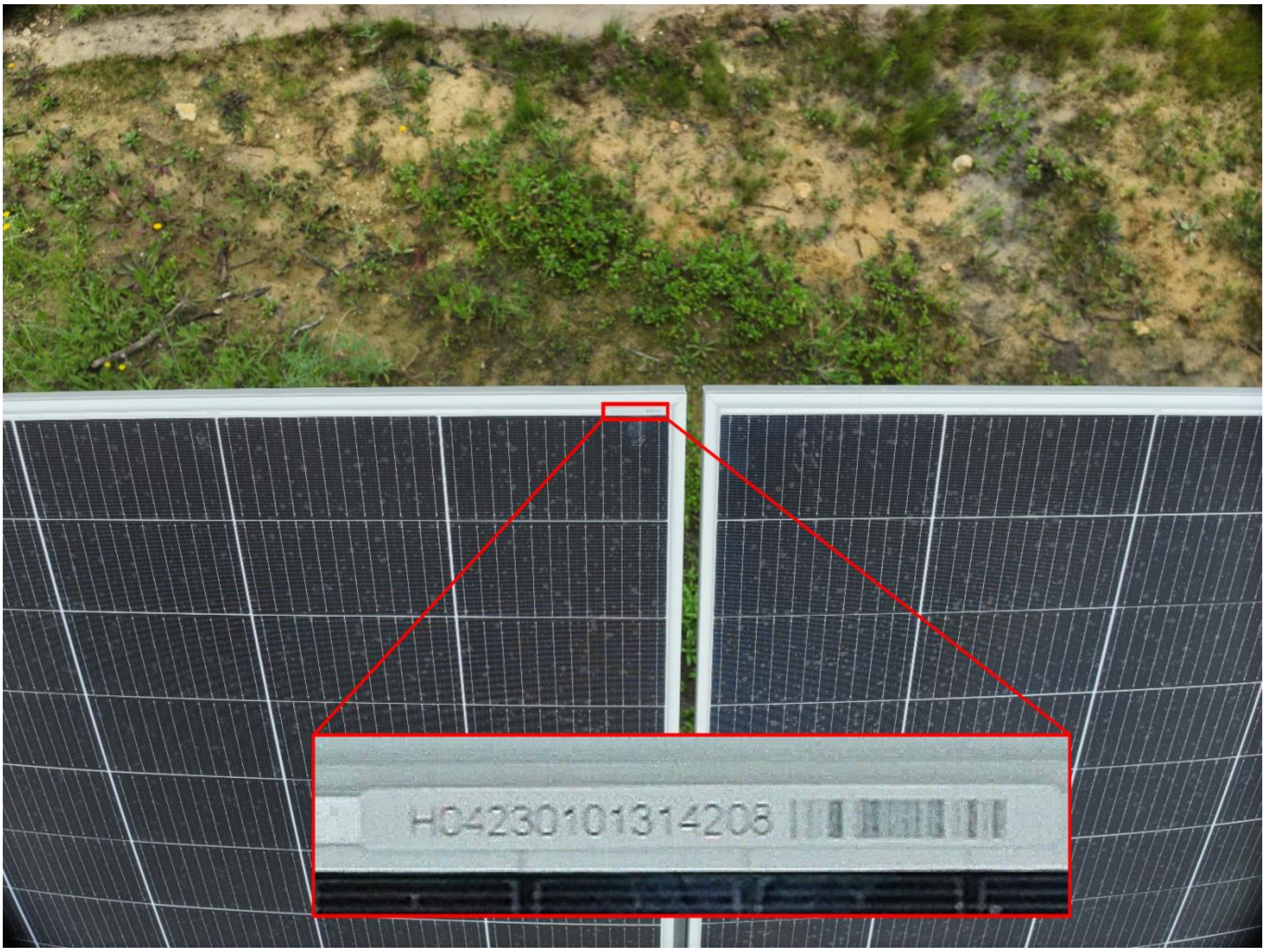

Figure 7. Serial Number of PV module

For both scenarios (defect detection or SN inventory), the proximity from the drone to the PV modules necessary to reach the desired resolution (< 1 m) requires an accurate **collision avoidance system** in order to maintain operations safe and avoid damages to the Asset. The details of this system will be discussed in Section 13.2.2.

Ambient conditions (light conditions, Sun position, weather) and characteristic of the farm (PV modules material reflectivity, colour, type of soil) have a big influence on the quality and usability of the imagery, so they must be taken into important consideration and settings of the camera should be set accordingly.

The proposed architecture of this module is shown in **Error! Reference source not found.**8:

Figure 8. Ultra-High Resolution Imagery - Architecture

The equipment expected be used for this module are presented in **Error! Reference source not found.**3:

Ultra-High Resolution Imagery - Equipment	
Equipment type	**Purpose**
Drone	Carries the selected payload
Sensor	Data collection

Table 3. Ultra-High Resolution Imagery - Equipment

4.2.1. Data Collection

The farm is mapped once in its lifetime based on the As-Builts available from the Asset Owner and with the IDs already set. Whenever the As-Builts are not available (older farms, ownership change without transfer of documentation) or not up-to-date (expansions, tables/trackers removed), farms can be mapped with other methodologies, such as satellite images, orthophotos and/or point clouds collected on the field.

To achieve the required detail level for ultra-high-resolution imagery, data collection must be executed closer than 1m from the area of interest. This level of proximity implies the developing of new techniques for collision avoidance and improved precision flights. Each image will be captured at the precise locations calculated taking in consideration the distance to the area of interest and camera characteristics, and will be embedded with all required metadata for the posterior data-processing stage. Taking in consideration the hardware currently available in the market, several payloads present the required quality for this type of data collection, the major obstacles to overcome will be the proximity requirement. The possibility to acquire data without stopping the drone for each photo will be evaluated, with the objective to maximize batteries duration and decrease collection time. At the end of the missions, all acquired data will be automatically synchronized and data processing will be triggered.

4.2.2. Collision avoidance system design

In order to comply with the precision level required for this type of autonomous flights, new approaches must be addressed: PVOP proposal takes advantage of the asset area digitalization, already realized with a centimeter-level precision, and cross-relates it with the asset As-Built to identify all data collection points. After optimal data collection points have been identified, a predictive flight plan will be generated and validated over the centimeter-level digitalization. All flight plans will be optimized in terms of quality and checked for their safety: the drone flights will be virtually simulated and automatically adjusted if a potential collision point is detected.

4.2.3. Data processing

The sub-section 13.2.3.1. and 13.2.3.2. will describe the data processing flow for the two possible uses of this Use Case: anomalies detection in the PV modules and SN Inventory.

4.2.3.1. Data processing (anomalies detection)

Regarding data processing for anomalies detection, analysis process starts immediately as the data is being received by the data processing engine. Data processing is divided into several steps, each of them being responsible for a part of the process that will, in the end, associate all identified anomalies to the specific PV modules as per solar assets As-Built information. The required metadata needed for the subsequent steps is extracted from the imagery and cross-related with the drone flight plans, the areas of interest are identified, isolated and geo-located, and autonomous defect detection module, using AI/ML/LL algorithms, is triggered.

4.2.3.2. Data processing (SN Inventory)

Regarding data processing for SN Inventory, the process is significantly similar to the previous one: the required metadata is extracted from the captured data and cross-related with the drone flight plans, the areas of interest (location in the PV module where the serial number is attached) are identified, isolated and geo-located. From this point, several processing layers will be sequentially deployed in order to read the serial number: among them, barcode reading and OCR.

4.3. UV Fluorescence to detect defects in PV modules such as cracked cells in a fast and cost-efficient way

UV Fluorescence has been proposed in recent years [6] as a fast, cheap and reliable non-destructive test for the in-situ detection of cracks and other issues in the PV module cells. Differently from Electroluminescence, PV modules do not need to be biased, so the scalability is much higher when compared to the traditional EL Test.

When PV modules are irradiated with UV light (310 to 400 nm), they present a fluorescence signal that can be recorded by a camera and subsequently analysed for anomalies detection.

Error! Reference source not found.9 [7] shows the physical process responsible for the phenomenon.

- In its original state, the encapsulant material (Ethylene-vinyl acetate, EVA) does not contain fluorophores and therefore does not exhibit fluorescence.
- Fluorophores formation starts when the module is deployed on the field, and it is triggered by aging, exposure to Sunlight, degradation of the UV-active curing agents and permeation of water vapor into the rear encapsulant material via the polymeric backsheet.

- On the other hand, fluorophores are extinguished by chemical photo-bleaching in the presence of irradiation and oxygen permeating in the PV module through the backsheet.

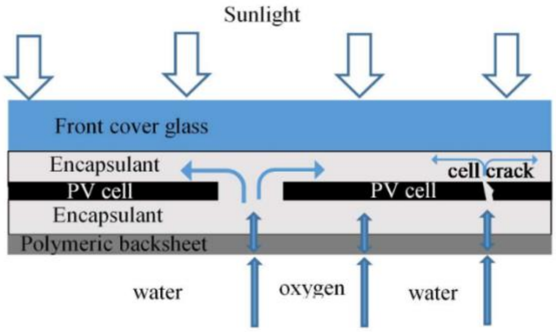

Figure 9. Formation and extinction of UV Fluorescence

An example of fluorescence pattern resulting from both the formation and the extinction of the Fluorophores is represented in **Error! Reference source not found.**10 (imagery collected by Brightspot Automation with a hand-held camera in a solar farm in the US, post-processed by Aeroprotechnik [8]):

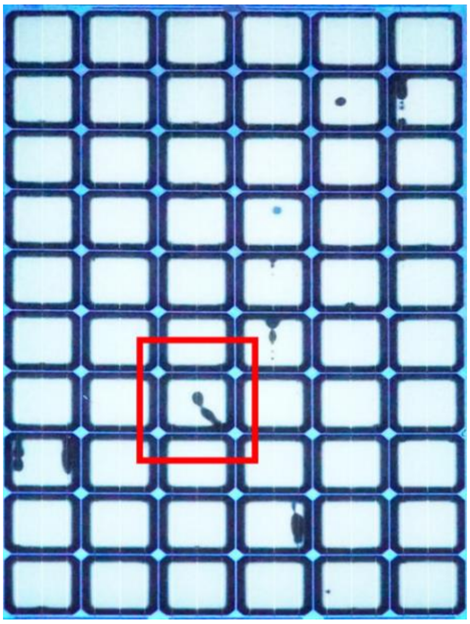

Figure 10. UVF imagery of PV module

One of the cracked cell of this PV module can be observed highlighted in the red square: as shown in the right part of10, the crack (as a discontinuity of the cell), makes room for the oxygen from the backsheet to penetrate in the front part of the PV module and therefore extinguish the UV fluorescence.

Since it does not require power to be injected in the modules, UVF has been considered a scalable alternative to EL, however, two main challenges need to be considered:

- The UV-F pattern of the PV modules heavily depends on their material, brand, technology, and even on different production batches of the same PV module from the same producer [9]. Furthermore, in recently spreading into the market glass/glass PV modules, due to the absence of the backsheet, the signal can be very weak.
- There is no IEC standard set with methods and best practices for this non-destructive inspection technique.

PVOP proposal for this Use Case is an aerial-based platform capable to autonomously perform UV-F Tests on a PV farm, transfer the images to a processing area, process them with AI/ML/LL in order to identify and geo-locate anomalies and automatically report to designated receivers.

The proposed architecture of this module is shown in **Error! Reference source not found.**11:

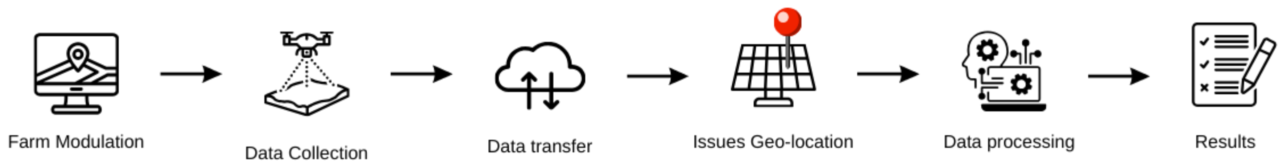

Figure 11. UV Fluorescence - Architecture

The equipment expected be used for this module are presented in **Error! Reference source not found.**4:

UV Fluorescence - Equipment	
Equipment type	**Purpose**
Drone	Carries the source and the sensor
UV Source	Provides UV light to the modules
Sensor	Data collection

Table 4. UV Fluorescence - Equipment

4.3.1. Data Collection

The farm is mapped once in its lifetime based on the As-Builts available from the Asset Owner and with the IDs already set. Whenever the As-Builts are not available (older farms, ownership change without transfer of documentation) or not up-to-date (expansions, tables/trackers removed), farms can be mapped with other methodologies, such as satellite images, orthophotos and/or point clouds collected on the field.

Taking into consideration that UV Fluorescence data acquisition will be executed at night, some challenges need to be addressed: the drone proximity sensors, for example, will not operate as expected in these conditions. To mitigate this issue, and reach the required level of automation and safety, all the flight plans will be generated with alternative obstacle avoidance methodologies. The preparation of the flight plans is also the first pillar for the subsequent data flow process: a correct data collection planning will make possible the imagery acquisition in the exact expected locations, and all collected data will be integrated with the necessary metadata needed later on for the data processing.

Since no commercial equipment with the required specification is currently available on the market, this module will require the preparation of a customized payload that will include the camera and the UV light emitter. At the end of the missions the data synchronization will automatically begin, and once the synchronization process is completed the payload will be prepared for a new data collection.

4.3.2. Data processing

As the data is being received by the data processing engine, the analysis process will start immediately. Data processing is divided into several steps, each of them being responsible for a part of the process that will, in the end, associate all identified anomalies to the specific PV modules as per solar assets As-Built information. The required metadata needed for the subsequent steps is extracted from the imagery and cross-related with the drone flight plans, the areas of interest are identified, isolated and geo-located, and autonomous defect detection module, using AI/ML/LL algorithms and data augmentation technics if required, is triggered.

4.4. Real-time identification of misaligned trackers

A misaligned tracker can cause an energy loss up to 44% [10] per year, so their early detection and subsequent maintenance is key in order to improve Asset’s energy yield. Stopped trackers are usually caused either by faults in the tracking system or by problems in the communication between the NCUs (Network Control Units) and each tracker’s TCU (Tracker Control Unit).

Based on the consortium experience, misaligned trackers can stand for months before being noticed and fixed. Especially in larger plants, where there is no possibility to easily see every part of the field from the O&M base, it is possible to notice the drop in power production and deduce that some trackers might be not properly orientated, but it is very difficult to:

- Determine that the power drop is due principally to misaligned trackers (the drop itself is not constant over time, since the difference between the orientation angle of the non-functional tracker and the other ones depends on the moment of the day)
- Once being sure that there is one or more misaligned trackers, geo-locate them.

Figure 12 shows a stopped tracker captured by Aeroprotechnik from a drone flying at 80 m AGL in a solar farm in Spain. Picture was collected at 3.20 pm. It is interesting to note that at the time of inspection the non-functional tracker orientation is completely opposite compared to the others. If the same photography had been taken in the morning, the identification of the non-functional tracker would have been a much more difficult challenge, since its orientation angle would have been very close to the functional ones.

Figure 12. Misaligned tracker in a solar farm

PVOP technical concept for this module is an AI/ML-powered airborne system capable to autonomously identify, geo-locate and report misaligned trackers of a solar farm by comparison of multi-temporal imagery. Numerous inspections during the same day on the same farm area are expected, so one can eliminate the possibility that, if unlucky enough, the orientation angle of the non-functional trackers at the moment of the inspection is undistinguishable from the normally working ones.

The proposed architecture of this module is shown in **Error! Reference source not found.**13:

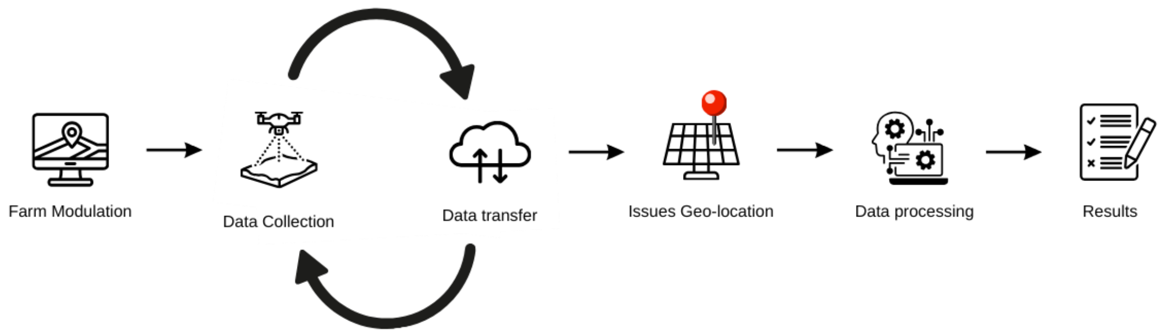

Figure 13. Misaligned trackers - Architecture

The equipment expected be used for this module are presented in **Error! Reference source not found.**5:

Misaligned trackers - Equipment	
Equipment type	**Purpose**
Drone	Carries payload
Sensor	Data collection

Table 5. Misaligned trackers - Equipment

4.4.1. Data Collection

The farm is mapped once in its lifetime based on the As-Builts available from the Asset Owner and with the IDs already set. Whenever the As-Builts are not available (older farms, ownership change without transfer of documentation) or not up-to-date (expansions, tables/trackers removed), farms can be mapped with other methodologies, as satellite images, orthophotos and/or point clouds collected on the field.

To increase the accuracy of the misaligned tracker detection and at the same time decrease the collection time, the altitude of this type of data collection should be higher than all the others. Taking into consideration the behaviour of the trackers and their orientation, autonomous flights must be repeated at different times of the day and the exact same data must be acquired at predefined moments. Each image will be taken at precise locations, calculated taking in consideration the distance from the area of interest and camera characteristics, and embedded with all required metadata for the posterior data-processing stage. Taking in consideration the hardware currently available in the market, several payloads present the required specifications for this type of data collection. At the end of all the missions, all acquired data will be automatically synchronized in order to trigger the data processing.

4.4.2. Data processing

At a specific time of the day, the data processing engine will start to process the collected data in different moments of the day. The data processing is divided into several steps, each of one being responsible for a part of the process The required metadata needed for the subsequent steps is extracted from the imagery and cross-related with the drone flight plans, the areas of interest are identified, isolated and geo-located. All the multitemporal datasets will be cross-related to each other and, if available, with the expected orientation angle for that day/hour of the year. This analysis will allow to identify all trackers presenting a misalignment behaviour.

4.5. Real-time identification of hanging DC cables as potential fire Risk Automatic Detection

As discussed in the previous section, hanging DC cables/connectors are one of the principal causes of fires in PV plants: a defective connector can reach temperatures up to 72 ºC, as shown by **Error! Reference source not found.**14 (thermography collected by Aeroprotechnik in a PV farm whose location can't be disclosed).

Error! Reference source not found.15 shows a hanging DC connector captured in a PV farm in France by an Aeroprotechnik technician inspecting the farm by foot in order to assess damages after a fire. We don't have information about the cause of this fire, but a hanging defective connector, with sufficient dry vegetation around, can serve as a fire trigger, with potential destructive outcomes.

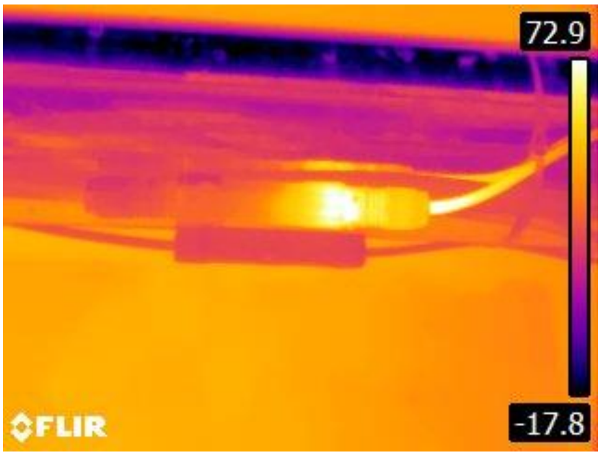

Figure 14. Overheated DC connector

Figure 15. Hanging DC cable

PVOP technical concept for this module is an airborne system capable to autonomously identify, geo-locate and report hanging DC cables and connectors of a solar farm by AI/ML/LL-powered analysis of imagery coming from low-altitude flights behind the tables/trackers.

The proximity from the drone to the ground (< 1 m) necessary to visually reach the potential hanging cables requires:

- An accurate **collision avoidance system** in order to maintain operations safe and avoid damages to the Asset. The details of this system will be discussed in Section 13.5.2.
- A meticulous organization between the drone inspection and other activities carried out in the affected part of the farm (maintenance, grass cutting, vehicles moving around, people walking, animals grazing) in order to avoid injuries to people and equipment damage.

The proposed architecture of this module is shown in **Error! Reference source not found.**16:

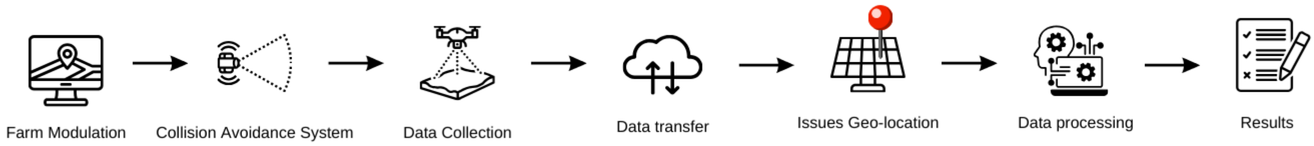

Figure 16. Hanging DC cables - Architecture

The equipment expected be used for this module are presented in **Error! Reference source not found.**6:

Real-time identification of hanging DC cables	
Equipment type	**Purpose**
Drone	Carries payload
Sensor	Data collection

Table 6. Hanging DC cables - Equipment

4.5.1. Data Collection

The farm is mapped once in its lifetime based on the As-Builts available from the Asset Owner and with the IDs already set. Whenever the As-Builts are not available (older farms, ownership change without transfer of documentation) or not up-to-date (expansions, tables/trackers removed), farm can be mapped with other methodologies, such as satellite images, orthophotos and/or point clouds collected on the field.

Data collection for this Use Case requires a very low altitude flight looking at the back of the modules, where the cabling is situated. This level of proximity implies the developing of new techniques for collision avoidance and improved precision flights. Each image will be captured at the precise locations calculated taking in consideration the distance to the area of interest and camera characteristics, and will be embedded with all required metadata for the posterior data-processing stage. Taking in consideration the hardware currently available in the market, several payloads present the required quality for this type of data collection, the major obstacles to overcome will be the proximity requirement. The possibility to acquire data without stopping the drone for each photo will be evaluated, with the objective to maximize batteries duration and decrease collection time. At the end of the missions, all acquired data will be automatically synchronized and data processing will be triggered.

4.5.2. Collision avoidance design

In order to comply with the precision level required for hanging DC cables data collection, new approaches must be addressed: PVOP proposal takes advantage of the asset area digitalization, already realized with a centimeter-level precision, and cross-relates it with the asset As-Built to identify all data collection points. After optimal data collection points have been defined, a predictive flight plan will be generated and validated over the centimeter-level digitalization. All flight plans will be optimized in terms of quality and checked for their safety: the drone flights will be virtually simulated and automatically adjusted if a potential collision point is detected.

4.5.3. Data processing

As the data is being received by the data processing engine, the analysis process will start immediately. Data processing is divided into several steps, each of them being responsible for a part of the process that will, in the end, associate all identified anomalies to the specific strings as pear solar assets As-Built documentation. The required metadata is extracted from the imagery and cross-related with the drone flight plan, then automatic AI/ML/LL defect detection algorithms (developed and trained on both RGB and thermal pictures) will analyse the entire images in order to identify hanging cables as points of potential fire risk.

4.6. Vegetation Management

Vegetation management is an extremely important part of an asset's management. It is frequently included in O&M contracts, with specific KPIs and penalties to be paid if those are not met.

PVOP technical concept for this module is an airborne system capable to autonomously identify, geo-locate and report areas of the farm that need priority intervention in terms of vegetation management, based on available multi-spectral data processed with AI/ML and LL tools.

Error! Reference source not found.17 shows the visual picture (left) and IR (right) captured by Aeroprotechnik during the thermal inspection of a PV farm in France with a problem of abnormally growing vegetation in one particular section (probably due to the different type of soil in this part). It is important to notice that the hotspots created by the shrubs not only reduce the energy yield of the farm, but can lead to early degradation of the PV modules if shadow is prolonged over time.

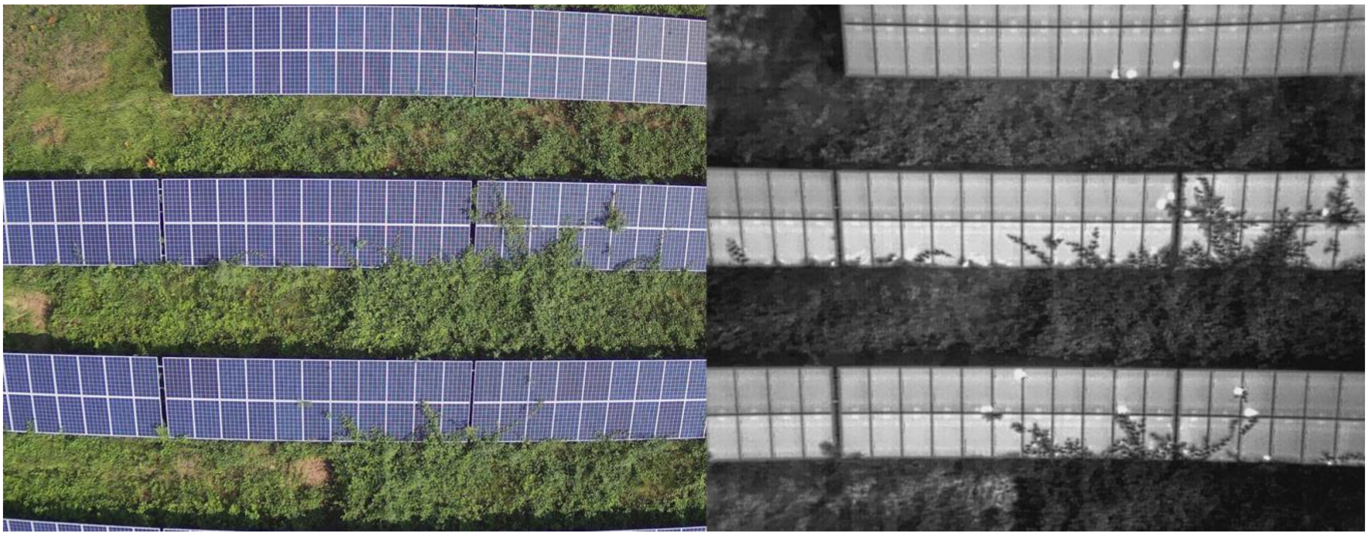

Figure 17. Abnormally growing vegetation in solar plant

The proposed architecture of this use case is shown in **Error! Reference source not found.**18:

Figure 18. Vegetation Management - Architecture

The equipment expected be used for this use case are presented in **Error! Reference source not found.**7:

Vegetation Management	
Equipment type	**Purpose**
Drone	Carries payload
Sensor	Data collection

Table 7. Vegetation Management - Equipment

4.6.1. Data Collection

The farm is mapped with a Geographic Information System (GIS) software based on the As-Builts available from the Asset Owner and with the PV modules/trackers IDs already set. Whenever the As-Builts are not available (older farms, ownership change without transfer of documentation) or not up-to-date (expansions, tables/trackers removed), farms can be mapped with other methodologies, as satellite images, orthophotos and/or point clouds collected on the field.

Taking in consideration the drone altitude required to perform the data collection (safe altitude with normally no obstacles), we believe there is no need to use precise flight plans with the collision avoidance layer incorporated. Each image will be captured at the precise locations calculated taking in consideration the distance to the area of interest and camera characteristics, and will be embedded with all required metadata for the posterior data-processing stage. Regarding the hardware currently available in the market, several payloads present the required technical specs for this type of data collection (multispectral). At the end of the missions, all acquired data will be automatically synchronized and data processing will be triggered.

4.6.2. Data processing

As the data is being received by the data processing engine, the analysis process will start immediately. Data processing is divided into several steps, each of them being responsible for a part of the process that will, in the end, identify areas where priority actions should be taken, in order to control the vegetation growth and proliferation, with multiple criticality levels classification.

The required metadata is extracted from the imagery and cross-related with the drone flight plan and the assets As-Built documentation. Multiple spectral layers are combined, recreating a visual image over which several AI/ML/LL algorithms developed and trained will identify the type of vegetation and its grow ratio, resulting the action plan for the required asset areas.

5. Experiments and KPIs

It is extremely important for technical solution validation that experiments are carried out throughout all the developing phases, starting from each module individually, going up to each entire Use Case and ultimately to the solution as a whole. The validation phases are represented below in **Error! Reference source not found.**19. Use Cases modules can be tested at the same time (in parallel) and they are integrated into each Use Case when their behaviour meets expectations. Finally, the whole solution is submitted to an extensive test campaign with the objective to check the interaction between Use Cases, their synergies and results.

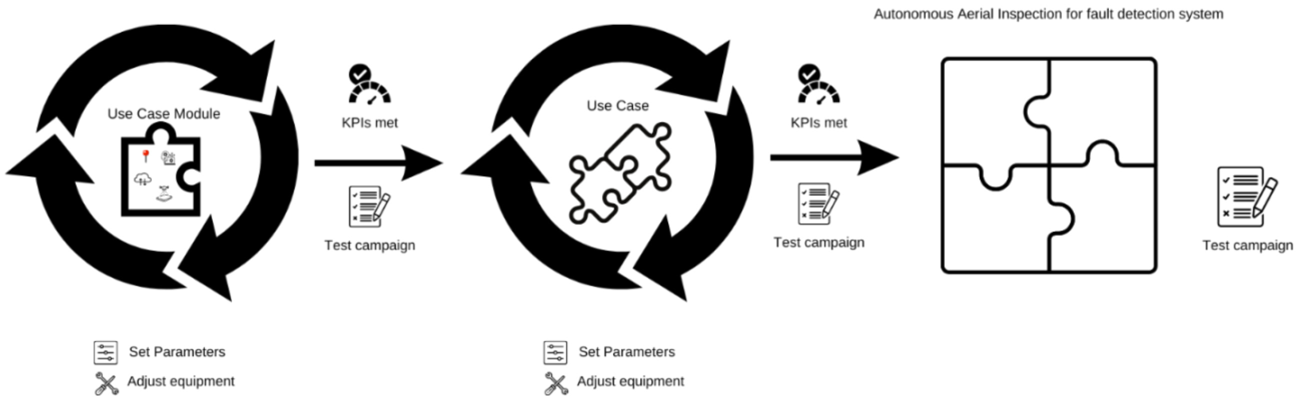

Figure 19. Experiment and validation phases

5.1. Experiment locations/Validation environment

Experiments and Validation phase will be conducted in two Phases:

- **Phase 1**: Validation in a controlled environment
- **Phase 2**: Validation in Real-condition environment

The selected locations for experiments and validation are:

- Aeroprotechnik office in Viseu, Portugal (**Phase 1**)
- Aeroprotechnik field test facility (not a solar farm, but equipped with some PV modules) (**Phase 1**)
- Open fields far away from houses, natural or artificial obstacles, airports, heliports (**Phase 1**)
- PV farms (in Portugal) belonging to a long-term customer Company that Aeroprotechnik has a strong relation with, having already used its installations for test purposes and whose contact for PVOP testing purposes has

already been made. The selected Company has farms with PV modules of different technologies, brands and power levels, so tests will be conducted in several environments. (**Phase 2**)

Error! Reference source not found.8 shows the locations selected for testing each module of the global solution:

Selected locations for Testing				
Module	**AERO office**	**AERO field test facility**	**Open fields**	**Real PV farms**
Sensors parameters	✓	✓	✓	✓
Data collection Automation	✓	✓	✓	✓
Data Harmonization and Standardization	✓			
Geo-location	✓	✓		✓
Algorithms, AI/ML/LL	✓			
Solution as a whole				✓

Table 8. Selected locations for testing

5.2. KPIs

Global solution provided by T 4.2 will contribute to the SO1 of PVOP project: "*Increase the performance of PV asset portfolios by 4.7% and reduce their management and O&M costs by 32%.*"

Proposed KPIs for each Use Case are detailed in the following sub-chapters.

5.2.1. KPIs - Automated Aerial Electro-Luminescence (EL) testing and failure detection

Proposed KPIs – EL Test			
KPI Category	**Description**	**Target Values**	
		Phase 1	**Phase 2**

System Availability	Availability of the system for the inspection given favorable environment conditions and excluding force majeure cause.	> 90% of the time	> 99% of the time
Performance	Percentage of existent defects correctly identified, geo-located and classified. (Benchmark: manual revision)	> 85%	> 97%
	Percentage of non-existent defects pointed out as such: False Positives (Benchmark: manual revision)	< 15%	< 5%
	Percentage of existent defects not pointed out as such: False Negatives (Benchmark: manual revision)	< 15%	< 3%

Table 9. Proposed KPIs - EL Test

5.2.2. KPIs - Ultra-High-Resolution imagery applied to detect different problems at PV modules and to inventory PV module serial numbers

Proposed KPIs – UHR Imagery			
KPI Category	**Description**	**Target Values**	
		Phase 1	**Phase 2**
System Availability	Availability of the system for the inspection given favorable environment conditions and excluding force majeure cause.	> 90% of the time	> 99% of the time
Performance (Defect detection)	Percentage of existent defects correctly identified, geo-located and classified. (Benchmark: manual revision)	> 85%	> 97%
	Percentage of non-existent defects pointed out as such: False Positives (Benchmark: manual revision)	< 15%	< 5%
	Percentage of existent defects not pointed out as such: False Negatives (Benchmark: manual revision)	< 15%	< 3%

Performance (SN Inventory)	Percentage of labels correctly identified and geo-located Note: the proposed target value assumes clean modules and labels in good readability conditions.	> 80%	> 95%
Safety	Percentage of collisions avoided by the Collision Avoidance System	100%	100%

Table 10. Proposed KPIs – UHR Imagery

5.2.3. KPIs - UV Fluorescence to detect defects in PV modules such as cracked cells in a fast and cost-efficient way

Proposed KPIs – UV Fluorescence			
KPI Category	**Description**	**Target Values**	
		Phase 1	**Phase 2**
System Availability	Availability of the system for the inspection given favorable environment conditions and excluding force majeure cause.	> 90% of the time	> 99% of the time
Performance	Percentage of existent defects correctly identified, geo-located and classified. (Benchmark: manual revision)	> 85%	> 97%
	Percentage of non-existent defects pointed out as such: False Positives	< 15%	< 5%
	Percentage of existent defects not pointed out as such: False Negatives (Benchmark: manual revision)	< 15%	< 3%

Table 11. Proposed KPIs – UV Fluorescence

5.2.4. KPIs – Real-time identification of misaligned trackers

Proposed KPIs – Misaligned trackers		
KPI Category	**Description**	**Target Values**

		Phase 1	Phase 2
System Availability	Availability of the system for the inspection given favorable environment conditions and excluding force majeure cause.	> 90% of the time	> 99% of the time
Performance	Percentage of existent misaligned trackers correctly identified and geo-located. (Benchmark: manual revision)	> 85%	> 97%
	Percentage of correctly aligned trackers reported as misaligned: False Positives	< 15%	< 5%
	Percentage of misaligned trackers not pointed out as such: False Negatives (Benchmark: manual revision)	< 15%	< 3%

Table 12. Proposed KPIs – Misaligned trackers

5.2.5. KPIs – Real-time identification of hanging DC cables as potential fire Risk Automatic Detection

Proposed KPIs – Hanging DC cables			
KPI Category	**Description**	**Target Values**	
		Phase 1	**Phase 2**
System Availability	Availability of the system for the inspection given favorable environment conditions and excluding force majeure cause.	> 90% of the time	> 99% of the time
Performance	Percentage of existent hanging DC cables correctly identified and geo-located. (Benchmark: manual revision)	> 85%	> 97%
	Percentage of non-existent hanging DC cables reported as such: False Positives	< 15%	< 5%
	Percentage of existent hanging DC cables not pointed out as such: False Negatives (Benchmark: manual revision)	< 15%	< 3%

Safety	Percentage of collisions avoided by the Collision Avoidance System	100%	100%

Table 13. Proposed KPIs – Hanging DC cables

5.2.6. KPIs - Vegetation Management

Proposed KPIs – Vegetation Management			
KPI Category	**Description**	**Target Values**	
		Phase 1	**Phase 2**
System Availability	Availability of the system for the inspection given favorable environment conditions and excluding force majeure cause.	> 90% of the time	> 99% of the time
Performance	Equivalence between the priority zones pointed by this Use Case and a manual identification of priority zones of intervention	> 85% of the zones must coincide	> 97% of the zones must coincide

Table 14. Proposed KPIs – Vegetation Management

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