



# Seamless-PV

## D8.5 – Monitoring guidelines, measurements and validation plan for each demo case

T8.4 Monitoring strategies and performance KPI for each IPV use case



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## SEAMLESS-PV PROJECT

### A novel manufacturing process for integrated photovoltaics

Integrated photovoltaics (IPVs) have demonstrated their success and impact in their use as building-integrated photovoltaics. They are also considered promising in several other sectors. Their adaptation to other industries or devices could offer surprising benefits. Unfortunately, the very need for adaptable IPV solutions hinders their expansion as their current manufacturing processes cannot create IPV solutions customised to each sector. The EU-funded SEAMLESS-PV project aims to tackle this by developing revolutionary tools for photovoltaic manufacturing as well as new IPV products that offer improved efficiency, adaptability and integrability while at the same time showcasing their cost-effectiveness in comparison to competitors.

The title of SEAMLESS-PV project is *“Development of advanced manufacturing equipment and processes aimed at the seamless integration of multifunctional PV solutions, enabling the deployment of IPV sectors”*. SEAMLESS-PV is a Horizon Europe Innovation Action started in January 2023 that will continue through December 2026.

More information can be found at:

<https://www.seamlesspv.eu/>

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## EXECUTIVE SUMMARY

This deliverable, *D8.5 – Monitoring Guidelines, Measurements, and Validation Plan for Each Demo Case*, defines a cost-effective and adaptable monitoring framework for various Integrated Photovoltaic (IPV) applications within the SEAMLESS-PV project, ensuring compliance with IEC 61724-1 standards through a Class B monitoring system that balances accuracy, affordability, and scalability across diverse demonstration sites.

The proposed monitoring system is modular and flexible, adapting to BIPV, IIPV, AGRI-PV, and VIPV applications by leveraging Raspberry Pi and Modbus Remote Terminal Unit (RTU) for efficient data acquisition and integration, prioritizing existing infrastructure to minimize costs and offering three deployment scenarios—**Basic Design** utilizing available data, **Modular Design** integrating additional sensors, and **Worst-Case Design** requiring full system installation.

Customized monitoring strategies are defined for each IPV type, ensuring that key performance indicators (KPIs)—such as energy yield, environmental conditions, and system efficiency—are accurately tracked and analysed through the VISUALIA platform, centralizing data collection and visualization.

This monitoring framework ensures scalability, accuracy, and cost-efficiency, with future improvements focused on expanding KPIs, enhancing data validation and error management, and optimizing sensor deployment to refine performance tracking and maximize the reliability of IPV systems across multiple applications.

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## Project partners

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# 1 INTRODUCTION

## 1.1 Description of the deliverable content and purpose

This document provides a detailed framework for selecting and implementing monitoring systems tailored to each demonstration site within the SEAMLESS-PV project. It ensures that Key Performance Indicators (KPIs) can be effectively tracked while balancing cost, accuracy, and adaptability across different Integrated Photovoltaic (IPV) applications.

The approach follows the IEC 61724-1 standard, ensuring a Class B monitoring system, which offers a cost-effective yet precise solution for performance evaluation. This document outlines:

- The general monitoring strategy, emphasizing the use of modular and adaptable sensor configurations.
- The site-specific monitoring requirements for BIPV, IIPV, AGRI-PV, and VIPV applications.
- The selection of sensors, data acquisition methods, and communication protocols to enable reliable data collection.

Given the diverse environments and installation constraints across the demonstration sites, this deliverable adopts a flexible approach, integrating existing monitoring infrastructure wherever possible while deploying additional sensors when necessary.

## 1.2 Reference material

This deliverable incorporates data from the document titled *NBN EN IEC 61724-1:2021* (CENELEC, 2021), which defines the standards for monitoring photovoltaic (PV) system performance. The document provides comprehensive guidance on terminology, equipment, methodologies, and data collection for the effective monitoring and analysis of PV systems.

All equipment selections were made using a comparative analysis based on some partners knowledge and previous experience. Datasheets and quotes for all considered equipment were duly prepared and shared among the project partners.

## 1.3 Relation with other activities in the project

Table 1.1 depicts the main links of this deliverable to other activities (work packages, tasks, deliverables, etc.) within SEAMLESS project. The table should be considered along with the current document for further understanding of the deliverable contents and purpose.

Table 1.1 – Relation between current deliverable and other activities in the project

| Project activity | Relation with current deliverable                                                                                                                                   |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Task 8.3         | “Design of demonstration installations and use cases”. The monitoring will be dedicated to collecting the data of the demonstration site and lined to the inverters |
| Task 8.6         | Installation, commissioning and implementation assessment of IPV solutions. The monitoring system will feed the data for the assessment of the IPV solutions        |

## 1.4 List of acronyms

Table 1.2 – List of acronyms

| Acronyms    | Meaning                                   |
|-------------|-------------------------------------------|
| <b>AC</b>   | Alternating Current                       |
| <b>AGRI</b> | Agriculture Photovoltaics                 |
| <b>BIPV</b> | Building Integrated Photovoltaics         |
| <b>DC</b>   | Direct Current                            |
| <b>GHI</b>  | Global Horizontal Irradiance              |
| <b>IEC</b>  | International Electrotechnical Commission |
| <b>IIPV</b> | Infrastructure Integrated Photovoltaics   |
| <b>KPI</b>  | Key Performance Indicator                 |
| <b>POA</b>  | Plane of Array                            |
| <b>PV</b>   | Photovoltaic                              |
| <b>RTU</b>  | Remote Terminal Unit                      |
| <b>SW</b>   | Software                                  |
| <b>VIPV</b> | Vehicle Integrated Photovoltaics          |

## 2 GENERAL DESCRIPTION OF THE MONITORING PLAN

The monitoring activity objective is to evaluate the real performance of the PV products developed in WP6. OPT will lead the monitoring process, with support from RTOs. Each IPV demo owner will provide access, facilities and all the necessary support to locally carry out this task. Monitoring strategies will be based on project performance KPIs defined for each application.

The task will comprise:

- (1) *Monitoring equipment design* where both a common set of monitoring guidelines and a specific measurement plan will be defined for all IPV demo cases.
- (2) *Configuration of the monitoring equipment and data acquisition platform development* where the equipment's defined in the previous sub task will be ordered, setup and configured at OPT facilities, with support from CEA, including the hardware setup and the setup of the various pieces of equipment.
- (3) *Development of the common data acquisition platform*, where the Software (SW) to perform the data acquisition for all demos will be developed using the OPT low-code platform (VISUALIA). The goal is to have a common platform, allowing to visualize the KPIs for all demos, accessible to all partners. Once developed, the monitoring equipment's will be tested at OPT facilities for robustness regarding any issues such as communication issues or equipment reboot.
- (4) *Installation for each pilot*. OPT, RTOs and LY for EVs will install the equipment at each IPV site. This will require OPT personnel to travel to each of the 8 demonstrators. Each demo owner and reference RTOs will support closely to this task to provide the necessary access and assistance.
- (5) *Results analysis*. The IPV systems multifunctional performance (PV, acoustic, etc.) will be monitored after the effective implementation of the solutions in each demonstrator for at least 1 year. This task will lead to a set of lessons and guidelines allowing us to evaluate in detail the most important KPIs for the deployments of these technologies.

OPT will lead the monitoring activity and has the budget for purchases related to monitoring equipment. CEA will support OPT. RTOs, AKUO (glass-glass use case) and LY (VIPV) will support the onsite installation of monitoring equipment, the monitoring data follow-up and perform the data analysis in those demonstration activities in which they participate, specifically:

- TECNALIA will support the PVNB monitoring and the lightweight AGRI use case.
- SUPSI will support PIZ's demo.
- CSEM will support 3S's demo.
- CEA will lead FACT's demo and CASA SPA's demo.
- LY will take the lead with the monitoring of VIPV use cases.
- AKUO will support the glass-glass AGRI use case.

## 2.1 Quantities classification

According to IEC 61724-1: 2021, there's three types of monitoring:

1. **Class A** (High Precision Monitoring Systems):
  - Typically used for large utility-scale PV installations or critical applications requiring high accuracy.
  - Suitable for scenarios where performance comparison against guarantees, precise fault detection, or detailed performance analysis is essential.
  - Class A systems include high-quality sensors for irradiance, temperature, and electrical measurements, with frequent calibration and minimal uncertainty.
2. **Class B** (Medium Precision Monitoring Systems):
  - Commonly used in commercial or mid-sized installations.
  - Designed to balance cost and performance with slightly lower accuracy requirements compared to Class A systems.
  - Suitable for non-critical commercial applications, where high precision is important but not as critical as in large-scale power plants.
3. **Class C** (Basic Monitoring Systems):
  - Used for small-scale or residential PV systems where cost constraints are significant, and precision is less of a concern.
  - Typically used for simple performance monitoring without the need for detailed data analysis or frequent recalibration.

We decided to define the **monitoring system as Class B** for several reasons:

1. **Cost-Effectiveness:** With a budget of 4000€ per site, we cannot afford the high-quality sensors required for a Class A system. Class B allows us to balance cost and performance, using mid-high-quality sensors for all key quantities.
2. **Sufficient Precision:** Class B offers the accuracy needed for performance monitoring at our demo sites without the excessive costs of Class A, making it suitable for commercial applications.
3. **Number of quantities to monitor:** Class B enables us to monitor all necessary parameters using cost-effective sensors. This ensures we can cover a wide range of measurements without exceeding the budget, something that would be impossible with Class A systems.
4. **Installed Power:** IEC 61724-1 monitoring class A is designed for installations in the megawatt range (power plants and the like), while class B is suitable for our demonstration sites, whose installed power is in the order of a few dozen kilowatts.

### 2.1.1 General Requirements

Table 2.1 illustrates all the parameters required for a Class B system. The symbol “R” indicates a parameter that may be determined based on remote meteorological data or satellite data rather than by on-site measurement.

Table 2.1 - Parameter Required for a Class B system

| Parameter                          | Symbol    | Units            | Monitoring Purpose                                             | Minimum number of sensors |
|------------------------------------|-----------|------------------|----------------------------------------------------------------|---------------------------|
| In-plane irradiance (POA)          | $G_i$     | W/m <sup>2</sup> | Solar resource                                                 | 1                         |
| Global horizontal irradiance (GHI) | $GHI$     | W/m <sup>2</sup> | Solar resource, connection to historical and satellite data    | 1 or R                    |
| PV module temperature              | $T_{mod}$ | °C               | Determining temperature related losses                         | 1                         |
| Ambient air temperature            | $T_{amb}$ | °C               | Estimation of PV temperatures, connection to prediction models | 1 or R                    |
| Wind speed                         |           | m/s              |                                                                | 1 or R                    |
| Rainfall                           |           | cm               | Estimation of soiling losses                                   | 1 or R                    |
| Output voltage (AC)                | $V_{out}$ | V                | Energy output, diagnostics and fault localization              | 1                         |
| Output current (AC)                | $I_{out}$ | A                |                                                                | 1                         |
| Output power (AC)                  | $P_{out}$ | kW               |                                                                | 1                         |
| Output energy                      | $E_{out}$ | kWh              |                                                                | 1                         |
| Output power factor                | $\lambda$ | /                | Utility request compliance                                     | 1                         |

### 2.1.2 Data acquisition timing and reporting

Regarding sampling and recording interval requirements, the maximum interval is 1 min between each sample and 15 min between each recording. The aim is to have enough samples to obtain a usable average for the recording.

The objective is to **sample every 20sec** and **recording every 5min** to have 15 samples for averaging, depending on the sensors chosen for the different quantities to be measured.

Each recording will include a timestamp.

## 2.1.3 Quantities Requirements

### 2.1.3.1 Irradiance

For a class B system, we can monitor the irradiance with a pyranometer or a PV reference device with same requirements:

- Calibration uncertainty  $\leq$  3% at 1000 W/m<sup>2</sup>
- Range up to 1 500 W/m<sup>2</sup>
- Resolution  $\leq$  1 W/m<sup>2</sup>

### 2.1.3.2 Environmental factors

#### a. PV Module Temperature

- Resolution  $\leq$  0.1°C
- Measurement Uncertainty  $\pm$  1°C

#### b. Ambient air Temperature

- Resolution  $\leq$  0.1°C
- Measurement Uncertainty  $\pm$  1°C

Collectors should preferably be placed at least 1 m from the nearest photovoltaic module and in locations where they will not be affected by heat sources or heat sinks.

#### c. Wind speed

- Resolution  $\leq$  0.1°C
- Measurement Uncertainty  $\leq$  0.5m/s and  $\leq$  10% for wind speed upper than 5m/s

### 2.1.3.3 Electrical measurement

Table 2.2 – Electrical measurement requirement

| Parameter           | Measurement requirements |
|---------------------|--------------------------|
| Output voltage (AC) | $\pm$ 3.0 %              |
| Output current (AC) | $\pm$ 3.0 %              |
| Output power (AC)   | $\pm$ 4.5 %              |
| Output energy       | Class 0.5S – IEC-6253-22 |
| Output power factor | Class 1 – IEC61557-12    |

## 2.1.4 Acquisition systems

### 2.1.4.1 Basic design – All Data are available on demo site (without SEAMLESS-PV equipment required)

This is the simplest configuration for the monitoring system, where all necessary data is already available in the demo site database because the equipment is already on site from the partner. In this case, the 'SEAMLESS-PV' system only needs to access the database to retrieve the relevant data for visualization in Visualia. No additional sensors or equipment installation is required, as the entire system relies on the existing infrastructure.

Following picture describes this best-case (basic) data acquisition system design.

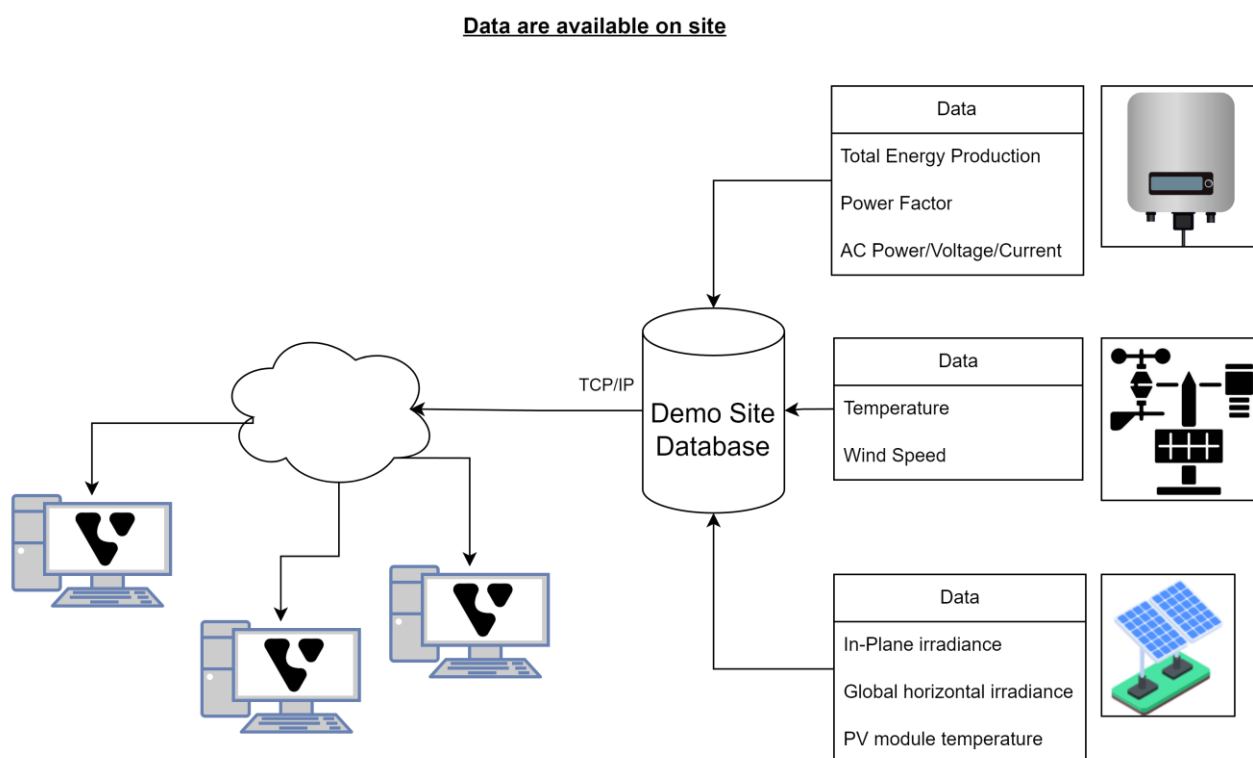


Figure 2.1: Basic (best-case) acquisition system design

### 2.1.4.2 Worst-case design – No data are available on site

In the worst-case scenario, where no data is available on site, additional sensors (for the SEAMLESS-PV project) must be installed to gather all the necessary information. The following components would be required:

1. **Sensors:** See Table 2.1 for the complete list of measurements (sensors) required. If electrical measurements cannot be obtained from the inverter via communication protocols like Modbus, additional sensors for voltage and current would be necessary.

## 2. Data Acquisition

- **Raspberry Pi 4:** This device will collect the data from the sensors and store it on its SD card (either as individual files or directly into Visualia), before transmitting it to the database.
  - **Microcontrollers** (Optional): Depending on the complexity of the system, microcontrollers may be required to process data before sending it to the Raspberry Pi.
  - **Database Server:** A server will be required to store and manage the data collected, making it accessible for the Visualia platform.
3. **Power Source:** A suitable power source is needed to power the sensors and data acquisition equipment, depending on the type of sensors used (e.g., solar power, external batteries).
  4. **Internet Connection:** An internet connection will be necessary for transmitting data from the Raspberry Pi to the database and making the data accessible to Visualia.

Following picture describes this worst-case data acquisition system design.

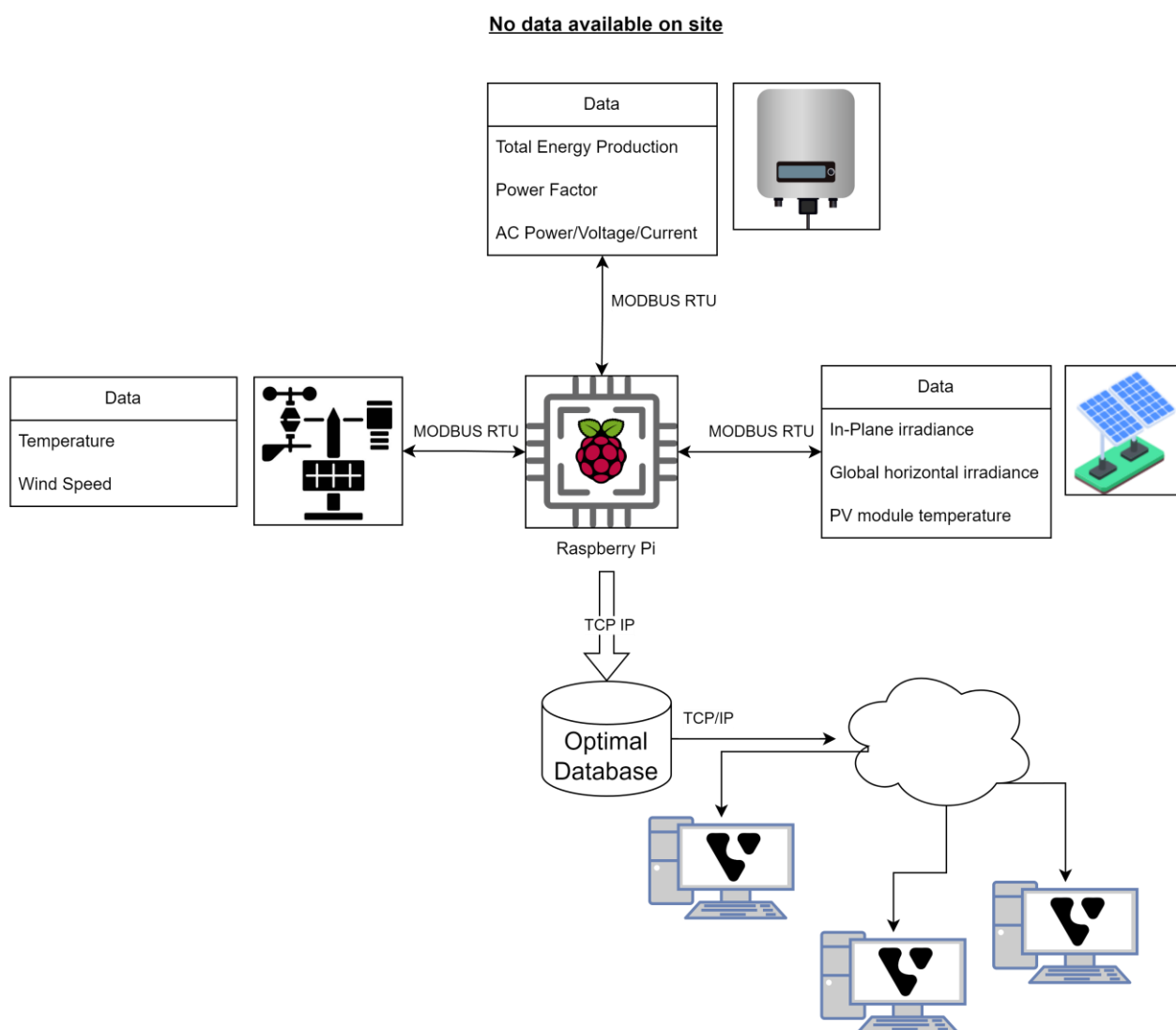


Figure 2.2: Worst-case acquisition system design

#### 2.1.4.3 Modular design – Some data are available on site

The modular design assumes that some of the required data is already available on the site, but additional sensors or components are needed to complete the monitoring system. In this scenario, the system can integrate the existing data infrastructure with additional sensors or components for any missing information.

1. **Sensors:** Depending on the missing data, the system might require a subset of sensors from the worst-case scenario (e.g., irradiance, temperature, or wind speed sensors). See Table 2.1 for the complete list of measurements (sensors) required.

## 2. Data Acquisition

- **Raspberry Pi 4:** Like in the worst-case scenario, the Raspberry Pi will be used to collect and transmit the data. It can receive data both from existing site infrastructure and from any newly installed sensors.
  - **Database Server:** To manage and store the data collected, and to make it accessible for real-time visualization in Visualia.
3. **Power Source:** A power source will be needed depending on the sensors being used, but the existing infrastructure may already provide some power options.
  4. **Internet Connection:** As with the other designs, internet connectivity is required for data transmission and remote access to the monitoring system.

Following picture describes this modular data acquisition system design.

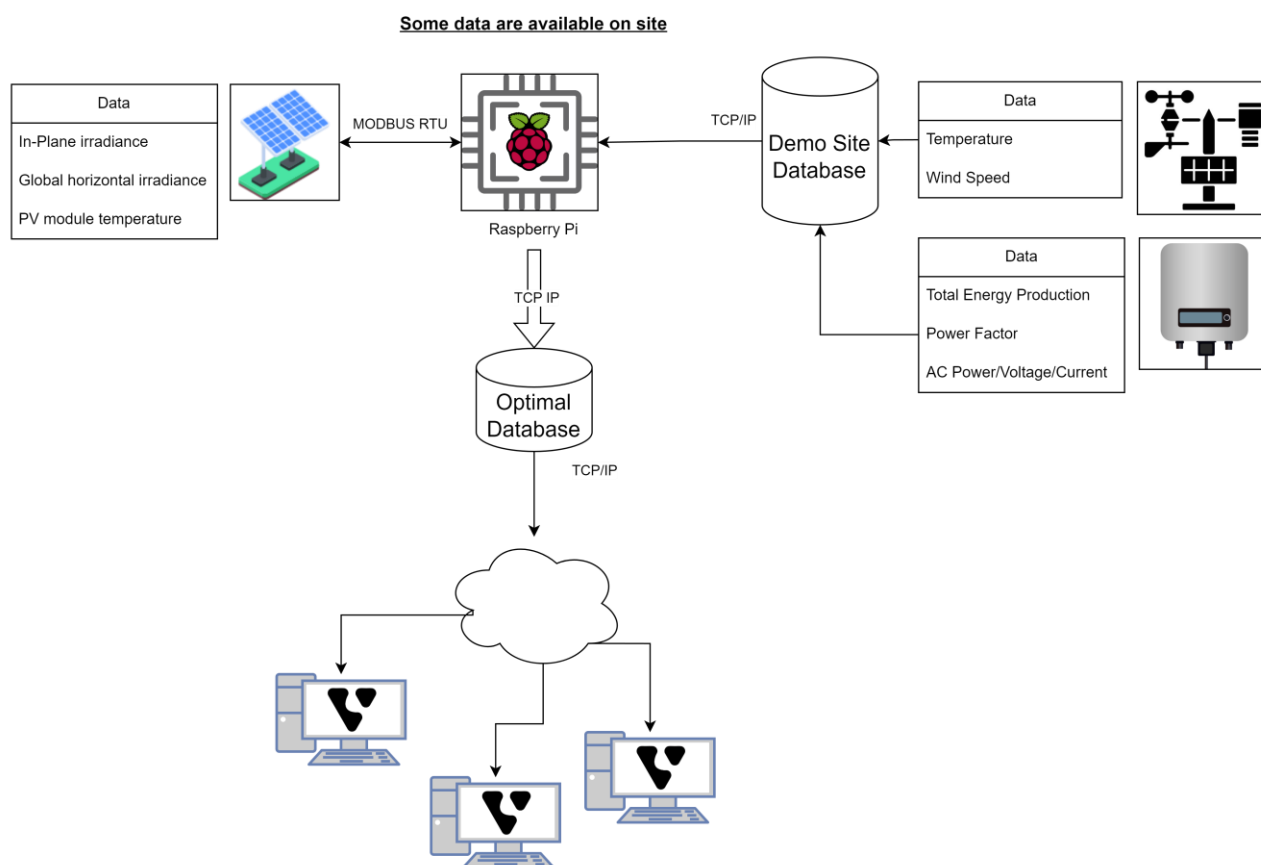


Figure 2.3: Modular data acquisition system design

### 2.1.5 Sensors selected

In accordance with the IEC 61724-1:2021 guidelines for a Class B system, and after analysing various sensor options based on recommendations from SUPSI<sup>1</sup>, recommendation from CEA<sup>2</sup> and our own research, the following choice are made.

We selected the **Si-RS485TC-2T-v-MB** series from [IMT Technology](#) (see Figure 2.4), primarily for its cost-effectiveness and compliance with the quantity requirements for a Class B system. This reference cell sensor, suitable for POA irradiance measurement, operates by measuring solar irradiation through the short-circuit current of a silicon solar cell, closely mirroring PV module behaviour but with less precision than a thermopile pyranometer. The Modbus RTU protocol enables efficient integration of multiple data points via a single access point. Additionally, it supports:

- **Tmodul-Si** for PV module temperature measurement
- **Vwind-Si** for wind speed monitoring



Figure 2.4: Si-RS485TC-2T-v-MB

The second device chosen is the **WS301-UMB Smart Weather Sensor** from [Lufft](#) (see Figure 2.5), equipped with:

- A Kipp & Zonen thermopile pyranometer for global horizontal irradiance (GHI)
- NTC thermistors for ambient temperature measurement
- A capacitive humidity sensor
- A capacitive pressure sensor

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<sup>1</sup> Some recommendation from SUPSI (Liang): [SUPSI/List of recommended equipment\\_Supsi.docx](#)

<sup>2</sup> Some recommendation from CEA (Brigitte): [CEA/SEAMLESS task 841 CEA.pdf](#)



Figure 2.5: WS301-UMB Smart Weather Sensor

These sensors, while Class B, are suited for standard meteorological tracking. The WS301-UMB also supports Modbus RTU for streamlined data collection.

Other multi-sensor options, such as additional models from Lufft and the **Cabled Vantage Pro2™ Plus** station, were considered but did not provide a better cost-effectiveness ratio for Class B.

For electrical data (energy, voltage, current, power, and power factor), we rely on the inverter, ensuring it supports these measurements and Modbus RTU for unified integration.

For rainfall, we want to use the open-meteo API, which is free for non-commercial use and for less than 10,000 API calls per day.

Table 2.3 illustrates all the required parameters for a Class B system with the corresponding sensors and their costs:

Table 2.3 – Sensor selection

| Parameter                    | Sensor                                                      | Measurement range         |
|------------------------------|-------------------------------------------------------------|---------------------------|
| In-plane irradiance (POA)    | IMT - Si-RS485TC-2T-v -MB                                   | 0...1500 W/m <sup>2</sup> |
| PV module temperature        | IMT - Tmodul-Si                                             | -40...90 °C               |
| Wind speed                   | IMT - Vwind-Si                                              | 0,9...40 m/s              |
| Global horizontal irradiance | WS301-UMB                                                   | 0....2000W/m <sup>2</sup> |
| Ambient air temperature      |                                                             | -40...90 °C               |
| Rainfall                     | <a href="https://open-meteo.com">https://open-meteo.com</a> | /                         |
| Output voltage               | Provided by the Inverter                                    |                           |
| Output current               |                                                             |                           |
| Output power                 |                                                             |                           |
| Output energy                |                                                             |                           |
| Output power factor          |                                                             |                           |

This selection allows us to have a remaining budget for other necessary equipment specific to the demo site, including additional monitoring components like Raspberry Pi, power supply, other supporting devices and installation materials.

If a site already has some sensors, we prefer to connect to them or to the database instead of installing new ones. In this case, we can imagine providing other sensors for other specific measurements if it is necessary or requested for the monitoring.

### 2.1.5.1 Inverter Recommendation

We recommend an **SMA inverter with a Modbus protocol interface** for each demo site. This allows us to test and access all relevant data within Optimal Computing. These inverters give access to other parameters (like the DC voltage, current, power, energy) that can be easily controlled and added to the monitoring system, making them well suited to our needs.

Moreover, having the same type of inverter for all demonstration sites will optimize the cost of constructing the monitoring system by avoiding learning and adapting the system to various inverter providers.

## 2.2 Data logger, communication layer and data storage

In the Figure 2.6 below we illustrate the interconnections between all our monitoring systems, including the possible configurations for each demo site.

The central component of our setup is a Raspberry Pi, which gathers data from all on-site sensors via the Modbus RTU protocol. Modbus was chosen for several key reasons:

- **Reliability and Simplicity:** Modbus RTU is widely used in industrial environments due to its robustness and ease of implementation. It operates efficiently over serial connections, making it especially suited for field environments with simpler and more cost-effective wiring.
- **Interoperability:** As an open standard protocol, Modbus allows for easy integration of sensors and devices from different manufacturers. This flexibility is essential in our case, as we need to seamlessly connect the Raspberry Pi to existing installations.

Additionally, it can retrieve data from on-site databases and access environmental information from open-source sources through REST APIs. An internal script on the Raspberry Pi collects sensor data every 20 seconds to form samples, which are then aggregated into records every 5 minutes and sent to a database for storage and visualization on a Visualia interface.

For demo sites without internet access, a 4G module will be added to the Raspberry Pi to ensure connectivity.

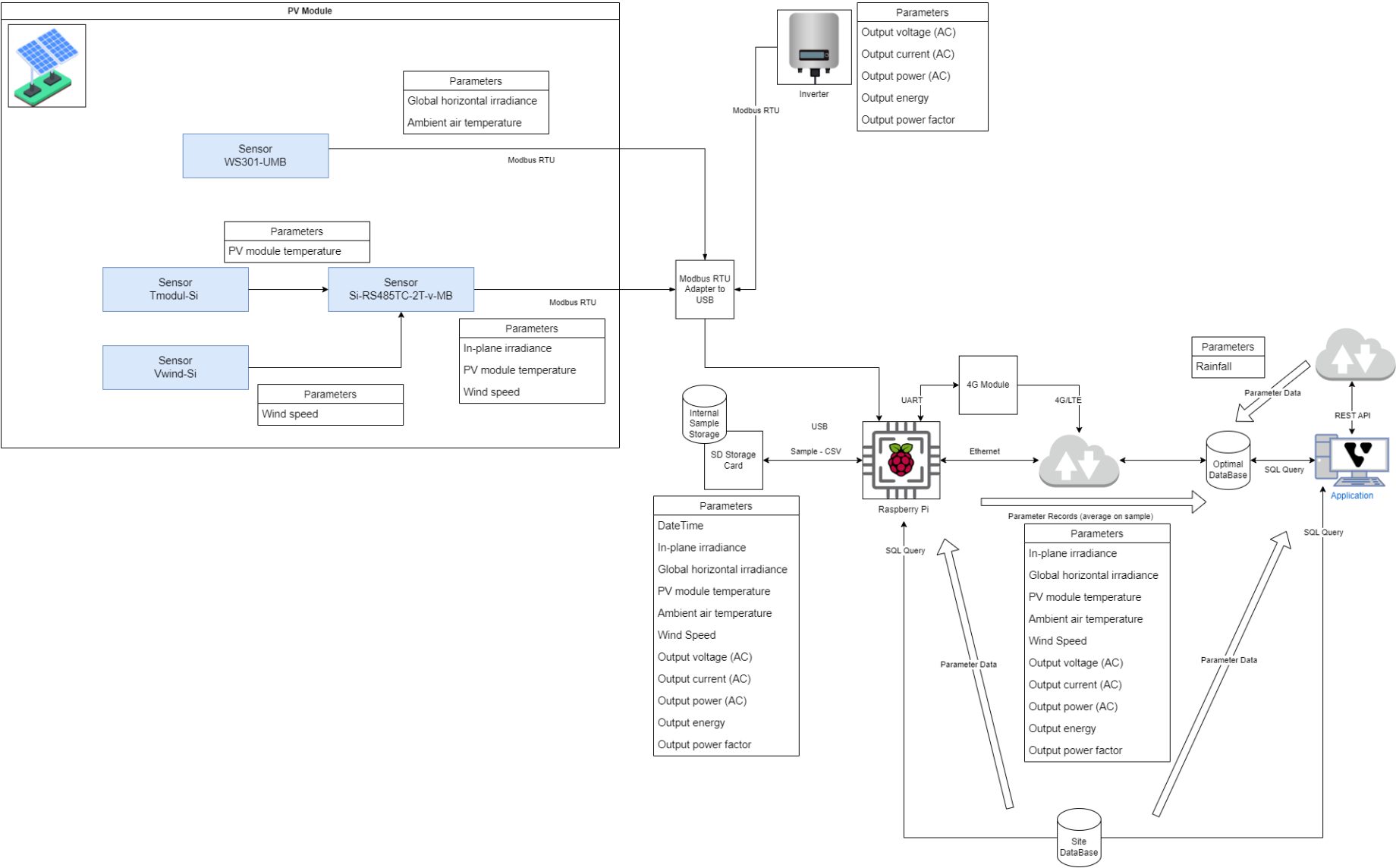


Figure 2.6: Global Implementation Diagram

### 3 CALCULATED QUANTITIES

To assess the performance of photovoltaic systems, certain parameters need to be calculated based on measured data. These calculated quantities provide an overview of total energy production, conversion efficiencies and system losses, enabling comparisons with predicted performance.

Table 3.1 – Calculated Quantities

| Parameter                         | Symbol     | Units              | Description                                                                                                                     |
|-----------------------------------|------------|--------------------|---------------------------------------------------------------------------------------------------------------------------------|
| In-plane Irradiation              | $H_i$      | kWh/m <sup>2</sup> | Total energy incident in the plane of the array, used as a reference for evaluating expected performance.                       |
| PV array output energy (DC)       | $E_A$      | kWh                | Total DC energy generated by the PV array, measured before inverter conversion, reflecting the raw output from the modules.     |
| Energy output from PV system (AC) | $E_{out}$  | kWh                | AC energy output delivered by the PV system, representing the usable energy post-inverter.                                      |
| Array power rating (DC)           | $P_0$      | kW                 | Combined DC power output of all PV modules under standard test conditions, disregarding rear-side effects for bifacial modules. |
| Array power rating (AC)           | $P_{0,ac}$ | kW                 | The lower value between the array DC power rating $P_0$ and the total inverter capacity, accounting for operating temperatures. |
| PV array energy yield             | $Y_A$      | kWh/kW             | The yield of DC energy per rated kW of PV capacity, providing a measure of the array's energy production efficiency.            |
| Final system yield                | $Y_f$      | kWh/kW             | The yield of AC energy per rated kW of PV capacity, indicating the system's actual energy output.                               |
| Reference yield                   | $Y_r$      | kWh/kW             | Represents the expected sun hours based on front-side in-plane irradiation at reference irradiance.                             |
| Array capture loss                | $L_C$      | kWh/kW             | Represents losses occurring within the array, due to factors like shading and temperature.                                      |
| Array efficiency                  | $\eta_A$   | /                  | Efficiency of the PV array in converting irradiance into DC power.                                                              |
| System efficiency                 | $\eta_f$   | /                  | Overall system efficiency, showing the conversion of irradiance into AC power.                                                  |

Performance metrics evaluate PV system efficiency and losses using either benchmark-based assessments or model-based predictions. Benchmark-based metrics offer direct evaluations, while model-based metrics incorporate detailed modeling to account for system complexities, such as the DC-to-AC ratio.

Table 3.2 – Performance metrics

| Parameter                                       | Symbol              | Units | Description                                                                                                                                                            |
|-------------------------------------------------|---------------------|-------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Performance Ratio                               | $PR$                | /     | Ratio of the system's final yield to reference yield, indicating overall system losses.                                                                                |
| Annual Performance Ratio                        | $PR_{annual}$       | /     | Performance ratio evaluated over an entire year, indicating system efficiency on an annual basis                                                                       |
| 25° C Performance ratio                         | $PR'_{25^{\circ}C}$ | /     | Performance ratio adjusted to a standard module temperature of 25 °C to account for seasonal temperature variation.                                                    |
| Annual-temperature-equivalent performance ratio | $PR'_{annual-eq}$   | /     | Adjusted performance ratio accounting for average annual temperature to approximate annual PR and minimize seasonal temperature effects.                               |
| Power performance index                         | $PPI$               | /     | Compares measured power output to the expected power based on a detailed performance model, useful for model-based assessments.                                        |
| Energy performance index                        | $EPI$               | /     | Compares measured energy output to the expected energy based on a performance model, aiding in energy efficiency evaluations.                                          |
| Baseline power performance index                | $BPPI$              | /     | Ratio of measured power to a predicted baseline output, supporting performance guarantees by referencing predicted values                                              |
| Baseline energy performance index               | $BEPI$              | /     | Compares measured energy output to a baseline prediction, supporting guarantee evaluations by assessing baseline energy performance relative to modelled expectations. |

See ANNEX I: FORMULA for the way how to calculate these values.

## 4 QUANTITIES SELECTION PER DEMONSTRATION SITE TYPE

This section defines the Key Performance Indicators (KPIs) and monitoring strategy for each type of demonstration site. For every site, we ensure compliance with Class B monitoring requirements (as outlined in section 2.1.1) and use the selected equipment (Table 2.3). This setup allows us to derive the Calculated Quantities (Table 3.1), and Performance Metrics (Table 3.2) required for a robust performance assessment.

The following subsections detail the specific monitoring strategy for each category of Integrated Photovoltaics (IPV), including site-specific adaptations where necessary.

### 4.1 Adaptive Strategy

To ensure a **cost-effective and efficient** monitoring framework, the implementation follows these principles:

- **Leverage existing infrastructure** whenever possible to **reduce costs** and avoid redundant sensor deployment.
- **Adopt a modular sensor setup**, prioritizing key performance measurements while considering budget constraints.
- **Integrate with existing databases** when available; otherwise, deploy independent sensors to collect data.

This approach ensures a **flexible yet standardized** monitoring system, enabling **robust data acquisition** while optimizing available resources.

## 4.2 BIPV – Building integrated Photovoltaics

The monitoring strategy for BIPV demonstration sites is designed to capture essential performance parameters while adapting to site-specific constraints.

The approach follows the general methodology defined in this document, with a focus on:

- Solar resource assessment (Plane of Array irradiance – POA, Global Horizontal Irradiance – GHI)
- Temperature effects (PV module temperature)
- Electrical performance (voltage, current, power, energy, power factor)
- Environmental conditions (wind speed, rainfall, ambient air temperature)

Whenever possible, existing monitoring infrastructure is leveraged to avoid redundancy and reduce costs. If required, additional sensors are deployed following the modular framework described in Section 2

### 4.2.1 Deployment per site

Table 4.1 – BIPV Deployment per site

| Demo N° | Description                                                  | Context & Existing Infrastructure              | Additional Monitoring Requirements                                             |
|---------|--------------------------------------------------------------|------------------------------------------------|--------------------------------------------------------------------------------|
| 1       | Residential building retrofit                                | No existing monitoring system                  | Full installation of Class B sensors (Worst-Case Design)                       |
| 2       | Residential building retrofit                                | No existing monitoring system                  | Identical setup to Demo 1, with support from 3S for data access                |
| 3       | Facade retrofit in an office building                        | No existing monitoring system.                 | POA irradiance sensors for four module orientations (N, S, E, W)               |
| 4       | Roof integration over a residential single-dwelling building | No existing monitoring system                  | Identical setup to Demo 1                                                      |
| 5       | FACT experimental building                                   | SCADA-based monitoring system already in place | No additional hardware is needed; all data will be provided by the site owner. |

### 4.3 IIPV - Infrastructure integrated Photovoltaics

The monitoring strategy for IIPV demonstration sites is designed to capture essential performance parameters while adapting to site-specific constraints.

The approach follows the general methodology defined in this document, with a focus on:

- Solar resource assessment (Plane of Array irradiance - POA, Global Horizontal Irradiance - GHI)
- Temperature effects (PV module temperature)
- Electrical performance (voltage, current, power, energy, power factor)
- Environmental conditions (wind speed, rainfall, ambient air temperature)
- Acoustic Performance (Noise level monitoring for PV-integrated noise barriers)

Where possible, existing monitoring infrastructure and weather data sources are leveraged to minimize costs and avoid redundancy.

#### 4.3.1 Deployment per site

Table 4.2 - IIPV Deployment per site

| Demo N° | Description                                                   | Context & Existing Infrastructure                                               | Additional Monitoring Requirements                                                                                                |
|---------|---------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| 6       | PVNB at Bizkaia Connected Corridor living lab (Noise Barrier) | Weather data available from TEC (1 km from site). AC/DC electrical data needed. | Full installation (Worst-Case Scenario)<br>Noise level monitoring (front & back of barrier) + integration with inverter cloud API |

## 4.4 AGRI – Agriculture Photovoltaics

The monitoring strategy for AGRI demonstration sites is designed to capture essential performance parameters while adapting to site-specific constraints.

The approach follows the general methodology defined in this document, with a focus on:

- Solar resource assessment (Plane of Array irradiance – POA, Global Horizontal Irradiance – GHI)
- Temperature effects (PV module temperature)
- Electrical performance (voltage, current, power, energy, power factor)
- Environmental conditions (wind speed, rainfall, ambient air temperature)
- Agronomic Monitoring (Soil moisture, soil temperature, photosynthetically active radiation under PV panels)

Where possible, existing monitoring infrastructure and weather data sources are leveraged to minimize costs and avoid redundancy.

### 4.4.1 Deployment per site

Table 4.3 – AGRI Deployment per site

| Demo N° | Description                                        | Context & Existing Infrastructure                                               | Additional Monitoring Requirements                                                                                                              |
|---------|----------------------------------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|
| 8       | Customized glass-glass module for open agriculture | AC/DC electrical data available from AKU0. No climate data currently collected. | Full installation (Worst-Case Scenario) without WS301-UMB replaced by 2 Quantum Sensors PAR (front & back) + 3 soil moisture sensors in 3 zones |
| 9       | Lightweight PV over tunnel multi-span greenhouse   | No existing weather monitoring.                                                 | Full installation (Worst-Case Scenario) without WS301-UMB, replaced by 2 Quantum Sensors PAR (front & back)                                     |

## 4.5 VIPV – Vehicle integrated Photovoltaic

VIPV monitoring focuses on energy generation efficiency, considering environmental factors and vehicle-specific constraints:

- Solar Resource Assessment (POA irradiance, GHI irradiance)
- Temperature Effects (PV module temperature)
- Electrical Performance: DC voltage, current, power, energy (no AC data needed)
- Environmental Conditions (Static Vehicle Only): Wind speed, rainfall, ambient air temperature
- Operational Conditions: Vehicle motion status (stationary vs. moving)

Whenever possible, existing vehicle sensors and embedded monitoring systems are used to minimize additional hardware installation.

### 4.5.1 Deployment per site

Table 4.4 – VIPV Deployment per site

| Demo N° | Description                                         | Context & Existing Infrastructure                                            | Additional Monitoring Requirements                                                                                                                         |
|---------|-----------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 7a      | integration over a car with PV on the roof          | The car is equipped with internal sensors. DC energy data already available. | No additional hardware is needed; all data will be provided via structured database access.                                                                |
| 7b      | Integration on a truck with PV on top and on a side | No existing monitoring, system                                               | Full installation (Worst-Case Scenario) without WS301-UMB. POA irradiance and PV back-face temperature for each PV side.<br><br>GPS module (nice to have). |

## 5 CONCLUSIONS

This document presents a comprehensive, adaptable monitoring framework for evaluating photovoltaic (PV) performance across diverse demonstration sites. By leveraging the IEC 61724-1 standards and adopting a cost-effective Class B monitoring approach, the framework ensures accurate, real-world performance tracking while remaining adaptable to site-specific constraints.

### **Key Takeaways:**

- **Tailored Monitoring Strategies:** Each IPV type (BIPV, IIPV, AGRI-PV, VIPV) has a customized approach to ensure relevant data is collected efficiently.
- **Modular & Cost-Effective Design:** The monitoring system balances cost and performance, prioritizing existing infrastructure integration while adding necessary sensors only when required.
- **Real-Time & Embedded Data Collection:** Where possible, data is retrieved directly from existing site databases and equipment, reducing redundancy and enhancing efficiency.
- **Scalability & Future Adaptation:** The flexibility of the framework allows for adjustments based on future field data, ensuring long-term reliability and relevance.

### **Next Steps:**

As the SEAMLESS-PV project progresses, additional site-specific information will be incorporated to refine the monitoring system. Future iterations may involve:

- Adjustments in sensor placement or type, depending on real-world performance.
- Enhancements in data acquisition frequency based on actual site conditions and constraints.
- Integration of additional KPIs if new performance metrics become necessary for deeper analysis.

In summary, this document provides a strong foundation for reliable performance monitoring across all IPV applications while maintaining the flexibility to adapt and improve as new insights emerge.

## 6 REFERENCES

[1]

CENELEC, 2021. *Photovoltaic system performance - Part 1: Monitoring (IEC 61724-1:2021)*, Brussels: CENELEC.

## 7 ANNEX I: Formula

The formulas below calculate cumulative quantities over a reporting period by summing values recorded during each interval. Each interval  $k$  has a specific duration,  $t_k$ , measured consistently to ensure correct unit outcomes. By multiplying a given quantity (such as average power) by the interval duration, the result for each interval is obtained. Summing these interval values across all intervals ( $\sum k$ ) provides the total for the reporting period.

Indicator  $i$  represents one or more modules monitored on a photovoltaic system. In our specific case,  $i$  corresponds to the entire PV installation.

All formulas are taken from CENELEC, 2021. *Photovoltaic system performance - Part 1: Monitoring (IEC 61724-1:2021)*, Brussels: CENELEC.

Table 7.1 - Formulas

| Parameter                         | Symbol     | Units              | Formula                                                                                                                                                              |
|-----------------------------------|------------|--------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| In-plane Irradiation              | $H_i$      | kWh/m <sup>2</sup> | $H_i = \sum_k G_{i,k} * t_k$                                                                                                                                         |
| PV array output energy (DC)       | $E_A$      | kWh                | $E_A = \sum_k P_{A,k} * t_k$                                                                                                                                         |
| Energy output from PV system (AC) | $E_{out}$  | kWh                | $E_{out} = \sum_k P_{out,k} * t_k$                                                                                                                                   |
| Array power rating (DC)           | $P_0$      | kW                 | $P_0 = \sum P_{i,STC}$ <p><math>P_{i,STC}</math> is the rated power of each module under normal test conditions (STC)</p>                                            |
| Array power rating (AC)           | $P_{0,ac}$ | kW                 | $P_{0,ac} = \min(P_0, \sum P_{j,AC})$ <p><math>P_{j,AC}</math> is the AC power rating of each inverter, usually determined at a specified operating temperature.</p> |
| PV array energy yield             | $Y_A$      | kWh/kW             | $Y_A = \frac{E_A}{P_0}$                                                                                                                                              |
| Final system yield                | $Y_f$      | kWh/kW             | $Y_f = \frac{E_{out}}{P_0}$                                                                                                                                          |
| Reference yield                   | $Y_r$      | kWh/kW             | $Y_r = \frac{H_i}{G_{i,ref}}$                                                                                                                                        |
| Array capture loss                | $L_C$      | kWh/kW             | $L_C = Y_r - Y_A$                                                                                                                                                    |
| Array efficiency                  | $\eta_A$   | /                  | $\eta_A = \frac{E_A}{H_i * A_a}$ <p><math>A_a</math> is the total surface area of the PV module</p>                                                                  |

|                                                 |                    |   |                                                                                                                                                                                                                                                                      |
|-------------------------------------------------|--------------------|---|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| System efficiency                               | $\eta_f$           | / | $\eta_f = \frac{E_{out}}{H_i * A_a}$ <p><math>A_a</math> is the total surface area of the PV module</p>                                                                                                                                                              |
| Performance Ratio                               | $PR$               | / | $PR = \frac{Y_f}{Y_r} = \frac{\sum_k P_{out,k} * t_k}{\sum_k \frac{P_0 * G_{i,k} * t_k}{G_{i,ref}}}$                                                                                                                                                                 |
| Annual Performance Ratio                        | $PR_{annual}$      | / | is the performance ratio from Equation of $PR$ evaluated over a monitoring period of one year.                                                                                                                                                                       |
| 25° C Performance ratio                         | $PR'_{25^\circ C}$ | / | $PR'_{25^\circ C} = \frac{\sum_k P_{out,k} * t_k}{\sum_k \frac{(C_{k,25^\circ C} * P_0) * G_{i,k} * t_k}{G_{i,ref}}}$ $C_{k,25^\circ C} = 1 + \gamma * (T_{mod,k} - 25^\circ C)$ <p><math>\gamma</math> is the temperature coefficient relative to maximum power</p> |
| Annual-temperature-equivalent performance ratio | $PR'_{annual-eq}$  | / | $PR'_{annual-eq} = \frac{\sum_k P_{out,k} * t_k}{\sum_k \frac{(C_{k,annual} * P_0) * G_{i,k} * t_k}{G_{i,ref}}}$ $C_{k,annual} = 1 + \gamma * (T_{mod,k} - T_{mod,annual-avg})$ <p><math>\gamma</math> is the temperature coefficient relative to maximum power</p>  |
| Power performance index                         | $PPI$              | / | $PPI = \frac{\sum_k P_{out,k} * t_k}{\sum_k P_{expected,k} * t_k}$                                                                                                                                                                                                   |
| Energy performance index                        | $EPI$              | / | $EPI = \frac{\sum_k E_{out,k} * t_k}{\sum_k E_{expected,k} * t_k}$                                                                                                                                                                                                   |
| Baseline power performance index                | $BPPI$             | / | $BPPI = \frac{\sum_k P_{out,k} * t_k}{\sum_k P_{predicted,k} * t_k}$                                                                                                                                                                                                 |
| Baseline energy performance index               | $BEPI$             | / | $BEPI = \frac{\sum_k E_{out,k} * t_k}{\sum_k E_{predicted,k} * t_k}$                                                                                                                                                                                                 |

NB :

**Expected** power or energy refers to the output predicted by the performance model using **historical weather data** for the monitoring period. This is typically used to establish a baseline of typical performance under usual or averaged environmental conditions.

**Predicted** power or energy, on the other hand, is calculated using **actual, real-time weather data** from the monitoring period. It represents the performance the system should achieve given the specific environmental conditions experienced during that period.



# Seamless-PV



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