Design and implementation of a multisensor monitoring system for a pilot agrivoltaic installation in Brazil

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Abstract

Agrivoltaic systems (AVS) offer a promising synergy between agricultural and energy production using photovoltaic (PV) systems; however, their feasibility and scalability rely on the precise monitoring of environmental and technical variables in pilot studies. This work presents the design and instrumentation of a pilot AVS under development in Florianópolis, Brazil (27°S). With a total installed PV capacity of 108 kWp, the system comprises seven different PV configurations and an adjacent control area that is free from shading. A comprehensive network of over 80 sensors is being deployed across the site to monitor environmental, agricultural, and PV variables in real-time. This study employs a comparative multi-case methodology across four AVSs pilots in the Americas, with the UFSC pilot plant serving as a methodological benchmark due to its comprehensive multi-sensor network. This approach identifies key similarities and differences in monitoring strategies, sensor deployment, and data integration across diverse AVS contexts.

Keywords: Agrivoltaic systems (AVS), Photovoltaic Systems, Instrumentation; Monitoring Systems

1. Introduction

Agrivoltaic systems (AVS) enable the simultaneous use of land for both photovoltaic (PV) energy generation and agricultural cultivation, promoting more efficient and sustainable land use. Initially proposed by Adolf Goetzberger and Armin Zastrow in 1981 (Goetzberger; Zastrow, 1981), the concept has gained considerable attention in the last decade due to increasing global demands for renewable energy (RE) and food security (Mamun et al., 2022). Beyond that, AVS are conceived to maximize land-use efficiency, promote more effective utilization of resources, and contribute to sustainable farming practices. By lowering energy expenses and offering partial shielding against extreme heat and water scarcity, they can provide additional resilience for crop production (Warmann; Jenerette; Barron-Gafford, 2024).

Agronomic monitoring represents a central element of AVS (Huang et al., 2023), relying on the deployment of microclimate sensors beneath PV modules. A well-structured sensor network not only supports the scientific analysis of food–energy interactions but also lays the groundwork for practical applications, such as irrigation automation, compliance with land-use regulations, and the quantification of agricultural and energy performance. In regions such as the European Union, commercial AVS projects must demonstrate continued agricultural productivity alongside PV deployment (Vidotto et al., 2024). Therefore, establishing a clear relationship between each sensor and its role in both scientific and operational contexts can enhance the viability of AVS as a sustainable solution for dual land use. Agronomic impacts can include reductions in direct solar radiation, shifts in soil and air temperature, modified evapotranspiration patterns, and consequent effects on plant growth and yield. From an energy standpoint, the presence of vegetation can influence module temperature - potentially improving efficiency - and mitigate soiling through increased humidity. It is imperative to acknowledge the significance of environmental influences, encompassing changes in water consumption patterns, increased biodiversity, and the emergence of distinct microclimatic conditions beneath PV structures (Zainol Abidin; Mahyuddin; Mohd Zainuri, 2021). Accurate monitoring of these interrelated variables is essential for decision-making related to AVS design, operation, and maintenance (O&M).

Despite the growing interest in AVS, there remains a notable scarcity of detailed articles specifying sensor network architectures adapted to the diverse configurations of AVSs, particularly in tropical and subtropical climates. To address this gap, the present study focuses on a pilot AVS currently under development in Florianópolis, Brazil, emphasizing the specification, implementation, and operation and maintenance (O&M) strategy of a comprehensive multi-sensor monitoring framework. The network design was informed by a review of four reference AVS projects

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and customized to capture both agronomic and energy-related variables across distinct structural arrangements. Beyond its scientific contribution, the monitoring strategy proposed here provides insights into the operational requirements necessary for scaling AVSs toward commercial deployment. While most existing projects in Brazil remain limited to experimental or small-scale contexts, large-scale adoption demands robust, scalable, and regulation-compliant monitoring solutions. By embedding this analysis within an international comparative perspective, the study not only characterizes the current state of AVS monitoring but also identifies opportunities for advancing the standardization and effectiveness of sensing networks in both research and practice.

2. Methodology

In order to address the research objectives, this study adopts a comparative multi-case methodology centered on four AVSs with distinct configurations and geographical settings. The primary case is the pilot AVS implemented at the Fotovoltaica/UFSC Laboratory in Brazil, which serves as a methodological benchmark given its comprehensive multi-sensor network and experimental design. Complementary data were gathered from three additional AVSs located in Brazil, Mexico, and the United States. These facilities were selected due to their representativeness in scale, structural design, and operational maturity, enabling an examination of diverse monitoring strategies across contrasting socio-environmental and technological contexts. This cross-case approach provides the analytical foundation for identifying both convergences and divergences in sensor deployment, parameter selection, and data integration practices.

2.1. Case Study

This study is based on the design and implementation of a pilot AVS system currently under development in Florianópolis, Brazil (27°S). The system has a total installed capacity of 108 kWp, distributed across seven experimental subzones. Figure 1 illustrates a 3D model of the AVS layout. The PV subsystems include: (1) a fixed-tilt array with semitransparent PV modules (16 kWp); (2) and (3) single-axis trackers with conventional PV modules (16 kWp); (4) and (5) single-axis trackers with semitransparent PV modules (13 kWp); and (6) and (7) vertical arrays (18 kWp and 16 kWp, respectively). An additional control area (C), free from PV shading, was designated to serve as a reference for crop development under natural light conditions.

Figure 1: 3D model of the agrivoltaic system highlighting its seven subsystems.

The agricultural layout comprises 37 planting beds, each measuring 7.5 x 1.5 meters, as shown in Figure 2. Each bed was planted with 96 seedlings of *Lactuca sativa* (lettuce), chosen for its rapid growth cycle and tolerance to partial shading, making it an appropriate crop under AVS conditions. Figure 3 shows the completed AVS as well as the first lettuce planting cycle for initial testing.

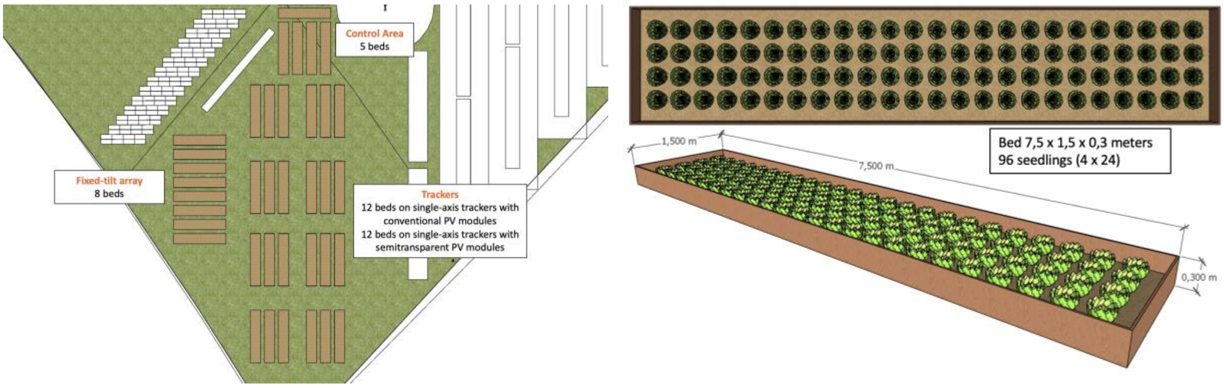

Figure 2: Layout of the pilot AVS at FV/UFSC, showing the distribution of planting beds under fixed-tilt, single-axis tracker PV arrays, and unshaded control area.

Figure 3: Real implementation of the AVS system with the first lettuce plantation cycle.

To define the monitoring strategy and sensor network, this study drew on best practices and technical insights from leading research institutions. Cultivation strategies and sensor configurations were benchmarked through knowledge exchange with the National Renewable Energy Laboratory (NREL) and the Fraunhofer Institute for Solar Energy (ISE), based on their experience with installed AVS systems. Furthermore, a cooperation agreement was established with the Agricultural Research and Rural Extension Company of Santa Catarina (EPAGRI/SC) to support the selection of suitable crops and agronomic sensors.

2.2. AVS basic sensor network

The AVS basic sensor network was conceived as a multi-layered monitoring architecture capable of integrating photovoltaic, agronomic, and environmental variables into a unified data acquisition framework. Rather than a simple collection of instruments, the network was designed to capture spatial and temporal variability within the experimental plots, ensuring datasets related to radiation distribution, plant physiological response, and microclimatic dynamics could be analyzed in detail, for example. The rationale behind sensor selection followed both scientific imperatives, such as enabling high-resolution studies of plant and operational needs, including the potential for automated control of trackers and irrigation systems in future commercial applications. Table 1 summarizes the multivariable monitoring structure implemented in the system, detailing the sensor types, functions, and their relevance to AVS operation and analysis.

Table 1: Multivariable monitoring structure of an AVS pilot system.

SENSOR TYPE	SENSOR	RELEVANCE TO AVS
PV	PV module temperature	Assesses thermal losses and PV efficiency under different configurations.
PV	Class A pyranometer	Rear e front POA irradiance for energy performance analyses
PV	Class C pyranometer	Rear e front POA irradiance for energy performance analyses
PV	Reference cell	Real-time estimation of actual irradiance received by the modules
Agronomic	PAR sensor	Correlates light availability with plant productivity
Agronomic	NDVI sensor	Enables real-time monitoring of crop health to assess the impact of PV shading on plant development.
Agronomic	Soil sensor	Guide irrigation management and assess water availability for crops.
Agronomic	IRGA	Provides real-time measurements of plant gas exchange, enabling the assessment of photosynthesis and transpiration under PV shading conditions and thus supporting a deeper understanding of crop responses to agrivoltaic microclimates.
Environmental	Temperature and humidity sensor	Measures ambient temperature and humidity to characterize microclimatic conditions under different PV structures.
Environmental	Wind speed sensor	Evaluate the influence on PV cooling and crop microclimate conditions.
Environmental	Atmospheric pressure sensor	Supports local climate characterization and enhances the interpretation of environmental dynamics affecting crops and PV performance.
Environmental	Pluviometer	Measures precipitation to support irrigation management and analyze water availability for crops.
Environmental	Drone/Cameras	Visual monitoring of crop development

2.2. Analysis of different AVS across the Americas

The methodological approach of this study is also based on a comparative analysis of the monitoring strategies implemented in four distinct AVSs. Each site was selected for its representativeness in terms of scale, design, and technological configuration, allowing for the assessment of different approaches to microclimatic and agronomic sensing. Data were collected through field reports, project documentation, and direct communication with system operators, ensuring a consistent basis for comparison across the selected cases.

The analysis focused on identifying the types of sensors installed, the parameters measured (e.g., solar radiation, temperature, soil moisture, relative humidity, crop physiology), and the data acquisition and integration processes. Special attention was given to the granularity and frequency of data collection, as well as to the degree of automation and interoperability of the monitoring platforms. Furthermore, the main difficulties related to the monitoring systems of each AVS were also addressed.

3. Analyses and Results

3.1. FV/UFSC Pilot AVS Sensor Network

The AVS pilot system is equipped with a comprehensive sensor network designed to monitor key variables related to agricultural production, PV performance, and environmental conditions, as illustrated in Figure 4. In total, the monitoring infrastructure will comprise 87 sensors, categorized into three groups: 9 environmental sensors, 28 PV sensors, and 50 agronomic sensors. This classification reflects the multidisciplinary nature of AVS systems, highlighting the importance of integrated monitoring.

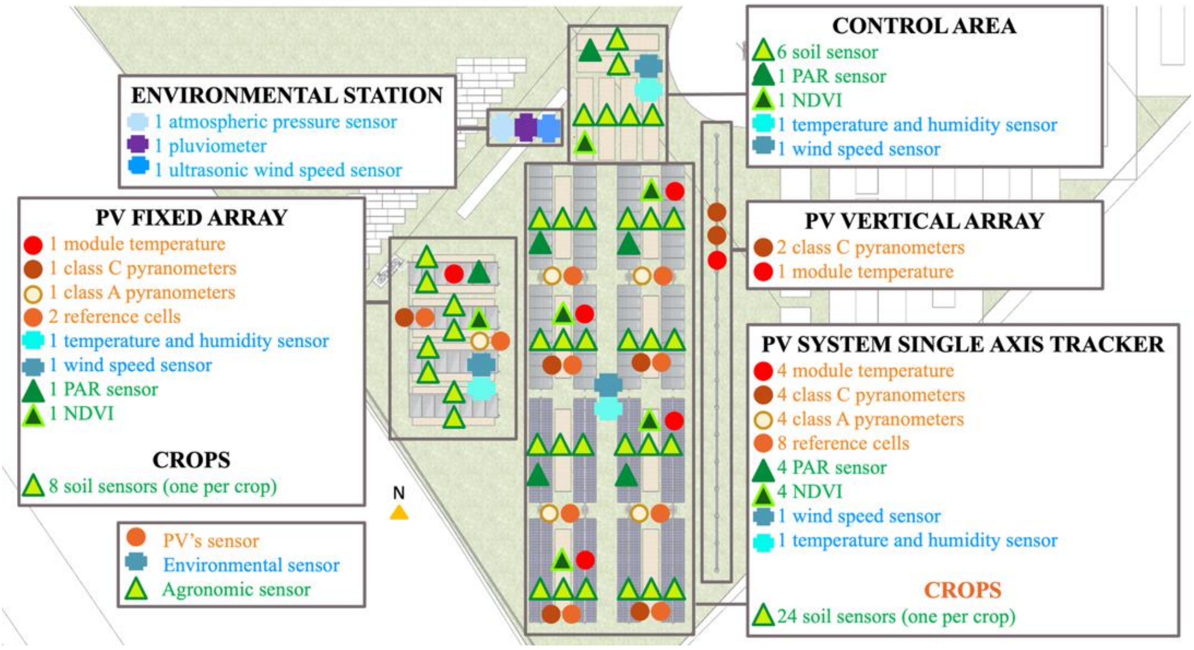

Figure 4: Photovoltaic, environmental, and agronomic sensors installed at the FV-UFSC AVS pilot.

In addition to presenting the types of sensors and their functions, the FV/UFSC sensor network can be better understood by detailing the operational architecture and data acquisition processes. Each sensor category was selected not only for its capacity to measure specific variables, but also for its role in enabling integrated analyses across agronomic, photovoltaic, and environmental domains. The network design prioritizes redundancy in key measurements, such as irradiance and soil conditions, in order to ensure reliability under field conditions where sensor drift or temporary failures may occur. Furthermore, the placement and distribution of sensors follow a spatial strategy aligned with crop rows and PV structures, allowing the system to capture microclimatic variability across shaded and non-shaded zones.

The collected data will be integrated into a control system capable of adjusting the tilt of solar trackers based on agronomic parameters. This approach aims to optimize light availability and microclimate conditions for crop development across various growth stages. By tailoring the tracker positioning in response to plant needs, the system aims to enhance the synergy between food and energy production. The expected outcomes of this project include the establishment of a high-resolution, real-time monitoring framework capable of generating integrated datasets that reflect the dynamic interactions between PV shading, crop development, and environmental conditions. The comprehensive sensor network is anticipated to enable more accurate assessments of crop performance under different PV configurations and provide a robust foundation for optimizing energy-agriculture synergies. Additionally, the data collected will support the development of adaptive control algorithms for solar trackers based on agronomic feedback, aiming to maximize both crop yield and energy output.

3.2. Comparison with other facilities

To provide geographical and technical context for the comparative analysis, Figure 5 illustrates the location of the AVSs included in this study, distributed across Brazil (Florianópolis and Rio Largo (Ferreira Junior et al., 2025)), Mexico (San Miguel Topilejo) and United States (Golden). These sites were selected for their representativeness in terms of scale, structural design, and monitoring strategies. Complementarily, Table 2 summarizes the main characteristics of each facility, including installed capacity, system configuration, and module specifications. Together, the geographic distribution and system descriptions offer a comprehensive overview of the diversity of AVS implementations across different climatic and socio-technical contexts, supporting the subsequent comparative evaluation of their monitoring approaches. Table 3 provides a comparative overview of the sensor networks implemented across the four AVS facilities, highlighting the types of sensors, their specific applications, and their deployment at each site.

Figure 5: Geographic distribution of the AVS pilots evaluated in this study, located in Brazil (Florianópolis and Rio Largo), Mexico (San Miguel Topilejo), and United States (Golden).

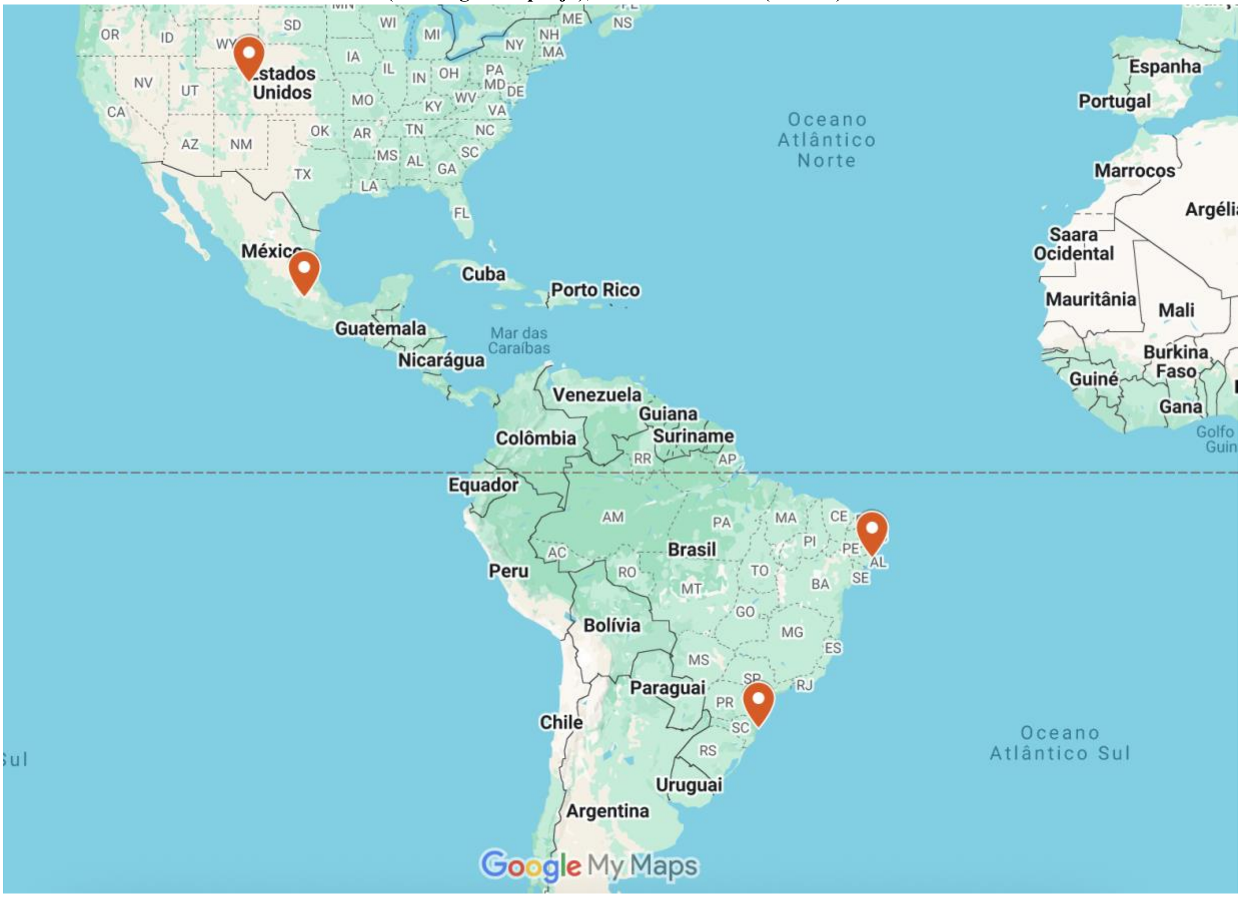

Table 2: Main characteristics of the AVS pilots evaluated in this study.

CATEGORY	FV/UFSC	UFAL	IER	NREL - BARN
LOCATION	Florianópolis - Brazil	Rio Largo – Brazil	San Miguel Topilejo – Mexico	Golden - USA
INSTALLED CAPACITY	108 kWp	71.4 kWp	39.36 kWp	45 kWp
PV MOUNTING TYPE	Vertical, fixed-tilt and single-axis trackers	Fixed-tilt	Fixed-tilt	Single-axis trackers
NUMBER OF CROP BEDS	38	-	30	-
CROPS	Lettuce	Sugarcane	Red onion, white onion, Italian lettuce, sangria lettuce, cauliflower, chard, broccoli, leek, green cabbage and red cabbage.	2022-2024: Kale, Tomato 1, Tomato 2, Basil, Chard, Pepper, Poblano Pepper, Carrots 2025: Cabbage (Early), Broccoli (Destiny), Cilantro, Cucumbers (Pickling Bush), Carrots (Bolero), Beets (Red Ace), Peppers (Hungarian Wax), Tomatoes (Bella Rosa), Basil (Genevese)
DATA INTEGRATION PLATFORM	Dedicated datalogger	Dedicated datalogger	Dedicated datalogger	Dedicated datalogger

Table 3: Sensor network composition across the four evaluated AVS facilities, indicating sensor types of units installed at each site.

SENSOR TYPE	SENSOR	FV/UFSC	UFAL	NREL	IER
PV	PV module temperature	✓	✓	✓	✓
PV	Class A pyranometer	✓		✓	
PV	Class C pyranometer	✓	✓	✓	✓
PV	Reference cell or module	✓		✓	✓
Agronomic	PAR sensor	✓	✓	✓	✓
Agronomic	NDVI sensor	✓			
Agronomic	Soil sensor	✓	✓	✓	✓
Agronomic	IRGA	✓			
Environmental	Temperature and humidity sensor	✓	✓	✓	✓
Environmental	Wind speed sensor	✓	✓	✓	✓
Environmental	Atmospheric pressure sensor	✓		✓	✓
Environmental	Pluviometer	✓		✓	✓
Environmental	Camera	✓		✓	

The results reveal substantial heterogeneity in monitoring strategies: while FV/UFSC employs the most comprehensive network, including advanced agronomic instruments such as NDVI sensors, soil sensors, and an IRGA, other facilities adopt more streamlined configurations. UFAL, for instance, emphasizes basic PV and agronomic measurements, whereas NREL and IER focus primarily on environmental and PV-related variables, reflecting different research priorities and operational objectives. This diversity reflects the pilot-nature of current AVS initiatives, where each site tailors its monitoring approach and sensor deployment to local climatic conditions, technical capabilities, and scientific goals. while efforts to establish standardized monitoring frameworks for commercial AVSs are still ongoing.

4. Conclusions

This article presents the design and implementation of a multisensor monitoring system for a pilot AVS, deployed at the Fotovoltaica/UFSC laboratory in Florianopolis, Brazil. As demonstrated in this comparative analysis, there is currently no standardized framework for sensor deployment across AVSs. The monitored facilities differ significantly in both the type and number of instruments employed, reflecting site-specific objectives and resource constraints rather than a harmonized approach. This variability is inherent to the experimental nature of the pilots but underscores a fundamental challenge for the field: the absence of a consistent methodology complicates data comparability, limits cross-site benchmarking and hinders the development of universally applicable performance metrics for AVSs.

In this context, the present work contributes to establishing the foundations for a more coherent monitoring strategy by mapping existing practices and highlighting their divergences. By systematically documenting sensor choices, agronomic parameters, and environmental variables, this article provides a reference point for future studies and initiatives seeking to advance standardization. Ultimately, such efforts are essential for improving the reliability of agrivoltaic research, fostering knowledge exchange between institutions, and supporting the development of guidelines that can accelerate the global deployment of AVSs as a sustainable solution for food–energy–water integration.

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