REGACE – Crop Responsive Greenhouse Agrivoltaics System with CO2 Enrichment for Higher Yields

Project Deliverable Report

DELIVERABLE 5.1 – VALIDATION COMMON MANUAL OF PROCEDURES AND METHODOLOGIES FOR EVALUATING THE REGACE AGRIVOLTAIC SYSTEM

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	Name	**Organisation**	**Date**	**Signature (initials)**
Coordinator	Prof. Ibrahim Yehia	Alzahrawy Society	2025/01/31	IY
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Executive Summary

The REGACE Validation Manual outlines the comprehensive framework for evaluating the performance, reliability, and efficiency of the REGACE agrivoltaic system with CO_2 enrichment. REGACE integrates renewable energy production with agricultural innovation, ensuring a sustainable and optimized approach to greenhouse farming. Through a structured validation methodology, the project ensures transparency, reproducibility, and adherence to industry standards.

This document establishes the principles governing the validation of key system components, including energy yield assessments, CO_2 enrichment impact on crop productivity, mechanical durability, and environmental effects. Validation procedures are designed to align with international ISO standards and best practices in agrivoltaic research, covering multiple test sites in Israel, Italy, Germany, Greece, and Austria. A well-defined governance framework ensures that responsibilities for data collection, testing protocols, and reporting are clearly assigned to project partners, maintaining accountability throughout the evaluation process.

Testing and data collection leverage cloud-based monitoring systems with automated logging and real-time sensor integration, ensuring accuracy and reliability. Proprietary information, including performance analytics of bifacial PV modules and dynamic tracking mechanisms, is safeguarded while maintaining the project's commitment to knowledge-sharing and Open Science principles.

The long-term sustainability of the REGACE validation framework is also prioritized, with structured post-project data archiving and controlled access to key findings. By implementing a rigorous yet practical validation strategy, REGACE supports scientific collaboration while ensuring technological advancement in agrivoltaics, renewable energy integration, and climate-resilient agricultural systems.

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List of Abbreviations

This section provides a standardized list of abbreviations used throughout the REGACE Validation Manual, ensuring consistency and clarity in project documentation.

Full Name	Abbreviation
Grant Agreement	GA
Consortium Agreement	CA
Project Officer	PO
Data Management Plan	DMP
Project Coordination Team	PCT
Description of Action	DoA
Work Package	WP

Consortium Members and Affiliates

Full Name	Abbreviation
Alzahrawy Society	AZS
Fattoria Solidale Del Circeo Cooperativa Sociale Di Produzione E Lavoro	FSC
Università degli Studi di Roma Tor Vergata	UNITOV
Panepistimio Thessalias	UTH
Humboldt-Universitaet zu Berlin	HU
Tel Aviv University	TAU
Universitaet fuer Bodenkultur Wien	BOKU
Bio-Gaertnerei Watzkendorf GMBH	BW
Interteam Ltd	IT
Agora P.S.v.D. Ltd	AP
Trisolar - Innowadi Group Ltd	TS
Timelex	TL

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Validation Common Manual of Procedures and Methodologies for Evaluating the REGACE Agrivoltaic System

1. Introduction

1.1 Purpose

This manual establishes a standardized framework for evaluating the **REGACE Agrivoltaic Solar System** within greenhouse environments. It outlines methodologies, procedures, and key performance indicators (KPIs) essential for assessing the system's effectiveness in terms of:

- **Energy efficiency**
- **Agricultural productivity**
- **Environmental impact**
- **Economic feasibility**

By adhering to a unified methodology, this manual ensures the reproducibility and reliability of validation results across different test sites.

1.2 The Role of Agrivoltaics in Sustainable Development

Agrivoltaics integrates agricultural production with photovoltaic (PV) energy generation. The REGACE project enhances this synergy by developing innovative agrivoltaic solutions tailored for greenhouse environments, optimizing both energy output and agricultural yields.

The project mitigates conventional competition for land by maximizing land productivity while contributing to Europe's green energy transition. It aligns with sustainability goals, including the **European Green Deal** and climate neutrality objectives for **2050**.

Key Benefits of Agrivoltaics:

- **Efficient Land Utilization**: Dual-purpose land use for both energy and food production.
- **Improved Climate Resilience**: Protection of crops from extreme weather, reducing heat stress and water loss.
- **Enhanced Biodiversity**: Creation of shaded microclimates that support diverse ecosystems.
- **Economic Growth**: Increased financial stability for farmers through energy production and cost savings.

1.3 Scope

This validation report evaluates the REGACE Agrivoltaic Solar System across multiple parameters, including photovoltaic tracking performance, greenhouse microclimate regulation, and CO_2 enrichment system efficiency. A key component of the validation process is to assess the CO_2 delivery system's impact on photosynthesis, crop yield, and overall greenhouse sustainability.

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1.4 Target Audience

This manual is intended for:

- Research institutions in agrivoltaics and renewable energy.
- Greenhouse operators and farm owners adopting the REGACE system.
- Regulatory bodies assessing compliance with EU standards.
- Engineers and technicians responsible for system installation and monitoring.
- Economists and policymakers evaluating financial viability.
- Environmental agencies focused on sustainable land management.

2. System Description

2.1 Overview of the REGACE System

The REGACE project integrates agrivoltaics with advanced CO2 enrichment technologies to enhance electricity production and agricultural yield. The core technology consists of:

- **Bifacial Solar Panels**: High-efficiency panels absorbing sunlight from both sides.
- **Mechanical Tracking System**: Ensuring structural integrity and durability
- **Climate Sensors**: Monitoring temperature, humidity, and CO2 levels in real-time.
- **Automated Control System**: Predictive algorithms adjusting panel angles and CO2 release.
- **CO2 Enrichment System**: Controlled CO2 release to enhance photosynthetic efficiency.

2.2 Best Practices for Agrivoltaic System Implementation

Key best practices include:

- **Site Criteria**: Optimal greenhouse structures and regions with favorable solar radiation levels.
- **Panel Placement Optimization**: Ensuring uniform light distribution.
- **Energy Performance Monitoring**: Smart tracking systems maximizing efficiency.
- **Soil and Water Management**: Evaluating the impact of agrivoltaics on soil moisture retention and irrigation.
- **Economic and Policy Considerations**: Developing business models and regulatory guidelines for agrivoltaic adoption.

2.3 CO_2 Enrichment Technology Overview

The REGACE system integrates a controlled CO_2 *enrichment mechanism to enhance greenhouse productivity. The system includes:*

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- **Automated CO_2 release units**, distributing controlled amounts of CO_2 via vented tubing.
- **Infrared CO_2 sensors**, placed at multiple levels to ensure accurate concentration readings.
- **Automated regulation**, adjusting CO_2 levels dynamically to maintain optimal concentrations between **400-1000 ppm**.
- **Zoned CO_2 delivery**, ensuring uniform distribution across different sections of the greenhouse.

This system is designed to improve photosynthesis rates, leading to **increased plant biomass**, **reduced water loss**, and **enhanced crop yields** while ensuring efficient CO_2 utilization.

3. General Evaluation Methodology

3.1 Validation Protocols

Validation protocols outline standardized methodologies for evaluating system performance, including:

- Installation Qualification (IQ)
- Operational Qualification (OQ)
- Performance Qualification (PQ)

3.2 Field Testing

Field tests measure the system’s real-world performance, including:

- Energy Yield Assessment
- Temperature and Environmental Monitoring
- Impact on Agricultural Productivity
- Albedo Enhancement Strategies

3.3 Risk Assessment

A risk-based approach determines validation priorities, focusing on:

- Product safety and quality impact
- Process complexity
- Regulatory compliance risks

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4. Validation Process for the REGACE System

4.1 Mechanical System Evaluation

Testing includes:

- **Wind Load Testing**: Resistance to high wind speeds under special conditions.
- **Dynamic Mechanical Load (DML) Test**: Assessing mechanical fatigue.
- **Mechanical Flexibility Test**: Examining stress points in dynamic tracking systems.

4.2 PV String Arrangement and Electrical Data Collection

- **Shading Loss Assessment**: Optimizing panel spacing in relation to land coverage ratio.
- **Albedo Impact Measurement**: Evaluating rear-side efficiency under different agricultural ground.
- **MPPT Tracker Considerations**: Optimizing energy output in relation to responsivity requirements.

4.3 Maintenance Procedures

Preventive Maintenance:

- Regular Inspection of PV Panels
- Cleaning Schedule Based on Environmental Conditions
- Electrical Component Inspection

Corrective Maintenance:

- Replacing Faulty Modules
- Repairing or Replacing Actuators
- Fixing Electrical Faults

Emergency Maintenance:

- Severe Weather Response Plans
- Immediate Response to Critical Failures

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Validation Protocol for the Software

1. Purpose

This protocol outlines the steps required to validate the responsive solar tracking software implemented in a greenhouse environment. The software is designed to maximize energy generation by guiding solar panels toward the sun while ensuring that adequate light levels are maintained for plant growth within the greenhouse.

The software relies on sensor readings to monitor and regulate the greenhouse climate. These sensors measure light intensity in lux and watts per square meter, humidity, temperature, and CO2 levels. All collected data is transmitted to the cloud, where it is processed and analyzed using a dedicated web platform. This system facilitates real-time monitoring and decision-making to optimize both energy production and greenhouse conditions.

2. Scope

The validation process ensures that the software meets functional, performance, and safety requirements. The protocol applies to the embedded platform controlling the solar tracking system, associated sensors, and actuators.

3. Validation Objectives

The main objectives of this validation process are:

- To verify that the software correctly tracks the sun and adjusts the solar panels accordingly.
- To confirm that the software maintains optimal light levels for plant growth.
- To evaluate the system's responsiveness under various environmental conditions.
- To ensure the system integrates seamlessly with hardware components and performs reliably over time.
- To ensure the system allows professionals to fine-tune parameters to align with specific agricultural yields and demands, ensuring optimal performance and adaptability to varying requirements.

4. Validation Stages

4.1 Requirement Analysis Validation

- **Objective**: Ensure that all functional and non-functional requirements are clearly defined and implemented.
- **Tasks**:
  - Review requirement specifications.
  - Verify that the software meets the following key requirements:
    1. Sun tracking accuracy.

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2. Light level regulation for plant growth.
3. Real-time responsiveness to environmental changes.
4. Integration with sensors and actuators.
5. The system is modular and can be modified and changed due to any constraints and new demands

4.2 Software Validation

- **Objective**: Validate all aspects of the software, including algorithms, data processing, and user interface.
- **Failure analysis**: to detect, analyze, and fix bugs or incorrect behaviors, ensuring consistent and reliable operation over time

4.2.1 Algorithm Validation

- Verify the correctness of the sun-tracking algorithm, ensuring it calculates solar azimuth and elevation angles accurately based on geographic location, date, and time.
- Test the light regulation algorithm to confirm it adjusts panel angles to maintain greenhouse light levels within optimal thresholds for plant growth.
- To shorten the validation time, synthesized random angles can be generated at random times and locations, and these can be tested against the expected panel angles. Similarly, random responsive conditions can be simulated to validate the system's adaptability and responsiveness.

4.2.2 Sensor Data Processing

- Validate the software’s ability to read data from light sensors, solar irradiance sensors, and environmental monitors.
- Ensure that data filtering and error handling mechanisms are in place to manage noisy or missing sensor data.

4.2.3 Actuator Control

- Confirm the software generates precise control signals for actuators to adjust solar panel angles.
- Test actuator calibration procedures and ensure smooth operation without abrupt movements or stalls.
- Test actuator lifetime and power consumption, which can be tested by running the actuator in idle mode for an extended period, based on factory data, to ensure durability and efficiency.

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4.2.4 Real-Time Monitoring and Decision-Making

- Validate that the software operates in real-time, responding to changes in sun position or light conditions within defined time limits.
- Test scenarios such as rapid cloud cover changes and verify that the system adapts promptly to maintain balance between energy generation and plant light needs.
- Validate Data Monitoring and collecting from sensors, backup and saved to the cloud correctly.

4.2.5 User Interface and Configuration

- Verify the functionality of the user interface, ensuring operators can:
  - Monitor real-time system status, including sun position, panel angles, and light levels.
  - Configure parameters such as light thresholds and tracking sensitivity.
  - Access error logs and receive alerts for system faults.
- Ensure the interface is intuitive and provides clear visual feedback on system performance.
- Ensure that the graphical user interface (GUI) is designed to prevent unintended mistakes that could harm the system when operated by unauthorized or non-professional users, ensuring safe and controlled operation.
-

4.3 Unit Testing

- **Objective**: Verify that individual components of the software perform as expected.
- **Tasks**:
  - Test sun position calculation algorithms.
  - Test light intensity monitoring and threshold adjustments.
  - Validate actuator control signals for panel movement.
  - Ensure data collecting algorithms.
  - Validate data collecting and backup when connection is lost.

4.4 Integration Testing

- **Objective**: Ensure proper communication between software modules and hardware components.
- **Tasks**:

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    - Test data flow from sensors to the software.
    - Test data flow from the computer software to the cloud.
    - Test data processing when disconnected from the internet .
    - Verify actuator responses to software commands.
    - Simulate failure scenarios (e.g., sensor failure) and test system behavior.

4.5 System Testing

- **Objective**: Validate the complete system's performance in real-world conditions.
- **Tasks**:
    - Install the system in a test greenhouse.
    - Evaluate sun-tracking accuracy under different weather conditions.
    - Measure light levels within the greenhouse at various times of the day.
    - Test system responsiveness to sudden changes in environmental conditions (e.g., cloud cover).
    - Test the data collecting and uploading to the cloud.
    - Verify power output of the solar panels.

4.6 Performance Testing

- **Objective**: Ensure the system meets performance benchmarks.
- **Tasks**:
    - Measure the system's time to adjust panels in response to sun movement.
    - Test light level consistency and deviation from optimal thresholds.
    - Test times needed for different subtask such as sensor reading or data uploading in real-time.
    - Evaluate energy efficiency of the solar tracking mechanism.

4.7 Safety Testing

- **Objective**: Validate that the system operates safely without causing harm to plants, equipment, or personnel.
- **Tasks**:
    - Test emergency shutdown procedures.
    - Ensure fail-safe mechanisms are functional.

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  - Validate that light levels do not exceed plant tolerance thresholds.

4.8 User Acceptance Testing (UAT)

- **Objective**: Ensure the system meets end-user requirements.
- **Tasks**:
  - Provide training to operators.
  - Conduct testing sessions with greenhouse staff.
  - Collect and address feedback on usability and performance.

5. Success Criteria

The validation will be deemed successful if:

- The system achieves 95% sun-tracking accuracy while maintain the responsivity mechanism.
- Light levels within the greenhouse remain within optimal ranges for plant growth.
- The system responds to environmental changes within short, predefined period.
- No critical safety issues are identified during testing.
- Greenhouse staff confirm ease of use and system reliability.

6. Documentation and Reporting

- Maintain detailed records of all test cases, results, and observations.
- Document any identified issues and corresponding corrective actions.
- Prepare a final validation report summarizing the process and outcomes.

7. Validation Team

The validation team should include:

- Software engineers
- Hardware engineers
- Quality assurance specialists
- Greenhouse operators

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8. Timeline

The validation process will be conducted over a period of X weeks, as follows:

- Requirement Analysis Validation: 1 week
- Software Validation: 2 weeks
- Unit Testing: 2 weeks
- Integration Testing: 2 weeks
- System Testing: 4 weeks
- Performance Testing: 1 week
- Safety Testing: 1 week
- UAT: 2 weeks

9. Approval

The validation process must be approved by the project manager, quality assurance lead, and greenhouse management.

Signature:
Project Manager: ________________________
Date: ________________________

Detailed Validation Protocols

Validation protocols outline standardized methodologies for evaluating system performance, including:

1.1 Purpose of Installation Qualification (IQ)

Installation Qualification (IQ) verifies that all equipment and system components are properly installed according to design specifications and manufacturer recommendations before proceeding to the operational qualification stage.

1.2 Installation Checklist

- Verification of all hardware components, including solar panels, tracking systems, and electrical wiring.
- Inspection of mounting structures for stability and alignment.
- Calibration of climate sensors and environmental monitoring devices.
- Validation of mechanical tracking system movement range and structural integrity.
- Documentation of installation procedures, including photographs and test results.

1.3 Testing Procedures

- Conduct visual and functional checks of all system components.
- Ensure compliance with industry standards (IEC, ISO) for installation safety and stability.
- Perform initial test runs to confirm tracking system response and CO2 enrichment mechanism functionality.
- Log all data in an IQ validation report, including any discrepancies and corrective actions taken.

1.4 Acceptance Criteria

- All components must be installed per technical drawings and specifications.
- Mechanical tracking system must achieve full operational movement range without obstruction.
- Electrical connections must be secure, with no loose wiring or faulty connections.
- Sensor calibration must fall within acceptable tolerance ranges.
- Documentation must be complete and approved before proceeding to Operational Qualification (OQ).

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2- Operational Qualification (OQ)

2.1 Purpose of Operational Qualification (OQ)

Operational Qualification (OQ) verifies that all installed components operate as intended under expected conditions before moving to the performance qualification stage.

2.2 OQ Testing Procedures

- Validation of tracking system movement accuracy and alignment.
- Testing of bifacial solar panels under varying light conditions.
- Assessment of CO2 enrichment system functionality and uniform distribution.
- Performance verification of climate sensors, data logging, and automated control systems.
- Load testing on electrical connections and MPPT tracker efficiency.

2.3 Acceptance Criteria

- All tracking systems must align correctly within ±1° accuracy.
- Solar panels must reach expected power output efficiency.
- CO2 enrichment system must maintain levels within predefined tolerances.
- Climate sensors must show consistent and accurate real-time readings.
- Automated control systems must respond correctly to predefined environmental changes.

3. Performance Qualification (PQ)

3.1 Purpose of Performance Qualification (PQ)

Performance Qualification (PQ) ensures that the installed and operational components perform reliably and consistently under expected real-world conditions, meeting all predefined performance criteria.

3.2 PQ Testing Procedures

- Continuous monitoring of energy yield over multiple seasonal cycles.
- Evaluation of greenhouse climate control effectiveness, including temperature and humidity regulation.
- Assessment of CO2 enrichment impact on crop growth and yield.
- Analysis of mechanical tracking system performance under different environmental conditions.

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- Long-term durability and reliability testing of photovoltaic panels and mounting structures.

3.3 Acceptance Criteria

- Solar panels must maintain at least 95% of expected efficiency over the validation period.
- Climate sensors must maintain ±2% accuracy in all environmental measurements.
- CO2 enrichment system must sustain consistent distribution levels within 5% variation of target concentrations.
- Tracking system must remain functional with zero critical failures over a 12-month testing phase.
- Overall system uptime should be above 98% to ensure continuous energy and agricultural productivity.

Sensor Calibration:

- Bi-weekly calibration of **CO_2 sensors** to maintain ±5% accuracy.
- Comparative analysis of **measured vs. expected CO_2 levels**.

CO_2 Distribution Testing:

- Measure CO_2 levels at **three different heights** (top, middle, bottom).
- Monitor uniformity of CO_2 dispersion across the greenhouse.

Crop Response Analysis:

- Monitor **stomatal conductance** and **photosynthetic rates** weekly.
- Track **biomass accumulation** (g/m^2) and **chlorophyll fluorescence**.

Leakage Assessment:

- Check for unintended CO_2 escape points in ventilation areas.
- Assess **CO_2 retention efficiency** compared to standard greenhouse conditions.

4.0 Field Testing

Field tests measure the system's real-world performance, including:

Energy Yield data collection - Measurement of energy generation over time.

- The electrical yields of the photovoltaic system of the responsive tracking systems with and without CO_2 enrichment added to the greenhouse will be measured in all henhouse sites. The electrical measurement protocol for the PV systems installed on the tracking systems inside the greenhouses as part of the REGACE project will be as follows.

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- 1- **Electrical data measurement at system level using the inverter installed at each location**. All installation locations will include an inverter as part of the PV system installed. The data from the inverter will form part of the data collection method for the project. The same inverter type will be used in all locations to ensure ease of data collection and analysis. In addition, each tracker installation will include some additional light and module temperature sensors to evaluate the PV performance in each location. The inverters installed at all installation sites will provide the following data for each string connected to the inverter (with and without CO_2 if tested):

  - Output (kWh),
  - Power at maximum power point (P_{mpp}) (W),
  - Current at maximum power point (I_{mpp}) (A),
  - Voltage at maximum power point (V_{mpp}) (V),
  - short circuit current (I_{sc}) and open circuit voltage (V_{oc}) (V).

This data will be collected continuously for specified intervals from each inverter. This data will be accessible on the inverter portal and downloaded periodically by Al-Zahrawy team to analyses the data. The data measurements interval by all inverters is 5 minutes and stored in the inverter web-box as excel file.

The Regace system employs the SMA Sunny Tripower inverter, a three-phase device designed for residential and small commercial photovoltaic applications. This inverter offers a nominal AC output power of 5-15kW and achieves a maximum efficiency of 98.3%. It supports a maximum DC input voltage of 250-600 V and operates within a wide MPP voltage range, enhancing its adaptability to various solar array configurations. The Sunny Tripower is equipped with dual Maximum Power Point Tracking (MPPT) inputs, allowing for optimal energy harvesting from solar panels under diverse conditions. Additionally, the inverter features integrated SMA Smart Connected service for proactive monitoring and maintenance, ensuring reliable and efficient operation throughout its service life.
The SMA inverter provides comprehensive electrical data to monitor and optimize the performance of your photovoltaic (PV) system. Through its integrated web interface and connectivity features, users can access real-time and historical data, including:

- **Input (DC) Data**:
  - ❖ Voltage (V)
  - ❖ Current (A)
  - ❖ Power (W)
- **Output (AC) Data**:
  - ❖ Voltage (V)
  - ❖ Current (A)
  - ❖ Power (W)
  - ❖ Frequency (Hz)
  - ❖ Power Factor

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- **Energy Generation**:
  - ❖ Daily, monthly, and total energy produced (kWh)
- **Efficiency Metrics**:
  - ❖ Inverter efficiency (%)
- **Operational Status**:
  - ❖ Temperature readings
  - ❖ Event logs
  - ❖ System alerts

These data points are accessible via SMA's Sunny Portal or locally through the inverter's web interface, providing valuable insights for effective system management.

- 2- Electrical data measurement at Panel level, to understand the PV performance in a greenhouse environment in more detail measurements will be carried out on panel level using the existing measurement tools at AZ:
  - Current-voltage (I-V) curves,
  - Open circuit voltage,
  - Short circuit current,
  - maximum power point,
  - Panel efficiency,
  - fill factor,
  - panel temperature
  - incident irradiance (on both sides of the bifacial modules).

These measurements will be taken every 2 minutes, except for the I-V curve measurements that will be taken every 10 minutes. The I-V measurement system includes loads attached to the measured modules, to keep the PV modules at maximum power point in between measurements. The measured panel will be configured as the following:

Greenhouse with CO2 Enrichment:

- ❖ Two PV panels mounted on the tracking system inside the Greenhouse
- ❖ One Fix panel inside the greenhouse oriented to south direction at tilt angle 0˚.
- ❖ One Panel mounted on the tracking system outside the Greenhouse
- ❖ One Fix panel outside the greenhouse oriented to south direction at tilt angle 0˚.

Greenhouse without CO2 Enrichment:

- ❖ One PV panels mounted on the tracking system inside the Greenhouse
- ❖ One Fix panel inside the greenhouse oriented to south direction at tilt angle 0˚.
- ❖ One Panel mounted on the tracking system outside the Greenhouse
- ❖ One Fix panel outside the greenhouse oriented to south direction at tilt angle 0˚.

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This configuration enables us to compare the energy production for each greenhouse refer to the responsivity mode of each greenhouse. The PV panels will be monitored throughout the project over a period of 24 months, to evaluate their annual performance as well as their diurnal performance throughout the year. The effect of temperature, irradiance and humidity on the panels will also be investigated using the microclimate data collected from the AZS greenhouses.

4.2- Temperature Impact on PV Panels and Greenhouse Systems

To assess the influence of photovoltaic (PV) panels on temperature distribution within greenhouses and their impact on plant growth, energy efficiency, and overall system performance.

Methodology

4.2.1 Data Collection

- Thermal imaging with an infrared camera inside and outside the AZ greenhouse site.
- Continuous temperature monitoring of air, panel surfaces, soil, and crop levels.
- Comparative analysis between greenhouses with and without PV panels, including solar tracking and non-tracking systems.

4.2.2 Key Parameters Measured

4.2.3 Panel Temperature: PV panels inside the greenhouse exhibit temperatures **5°C higher** than those outside.

4.2.4 Air Temperature: The temperature outside the greenhouse is 20°C lower than panel temperatures.

4.2.5 Crop-Level Temperature: Greenhouses with PV panels show a 7°C lower crop-level temperature than those without.

4.3 CO_2 Concentration Stability: Sensors monitor fluctuations in CO_2 levels every 10 minutes.

Crop Yield Impact: Weekly tracking of fruit count, leaf expansion rate, and chlorophyll content.
Environmental Efficiency: Measure water savings due to reduced transpiration in CO_2-enriched plants.
System Energy Usage: Monitor power consumption per kg of yield increase to evaluate efficiency.
Comparative Growth Studies: Test different crops (lettuce, basil, tomatoes) under CO_2 vs. control conditions, recording yield per square meter.

Findings

4.3.1 PV panels significantly influence temperature distribution within the greenhouse.

4.3.2 Tracking Panels: Higher temperatures in the upper greenhouse space and lower near the ground due to enhanced solar absorption.

4.3.3 Fixed Panels: More uniform temperature distribution, with lower temperatures at the upper level but higher near the ground.

4.3.4 External Influence: Panels outside the greenhouse are the hottest, indicating that the greenhouse structure provides some thermal regulation.

The presence and configuration of PV panels impact greenhouse microclimate by altering heat absorption, air circulation, and temperature gradients. These findings are critical for optimizing greenhouse energy efficiency while maintaining optimal growing conditions for crops. Further validation will involve extended monitoring across different seasons and locations.

5.0 Impact of PV Systems on Greenhouse Performance

Objective

To validate the impact of PV integration on greenhouse energy efficiency, crop growth, and environmental parameters across different sites.

5.1 Methodology

1. **Comparative Site Analysis:**
    - Evaluation of PV system performance at multiple locations (AZ, Circeo, Humboldt, Watzkendorf, Buko, and Kfar Qare').
    - Analysis of the influence of greenhouse orientation, plastic cover type, and environmental conditions on energy production.
2. **Key Parameters Measured:**
    - **Light Distribution:**
        - COMSOL sun radiation simulations confirm effective light diffusion in tunnel greenhouses.
        - Sensor data from Kfar Qare' and Italy indicate adequate light levels even under PV panels, ensuring optimal plant growth.
    - **Temperature Variations:**
        - Thermal imaging reveals that PV panels create temperature gradients, with hotter air near the panels and cooler air near the ground.
        - Tracking systems intensify this effect but contribute to a **7°C reduction in crop-level temperature** inside greenhouses.
    - **CO2 Concentration:**

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        - Kfar Qare' shows CO2 fluctuations linked to shading effects from PV panels.
        - Italy's open greenhouse structure maintains stable CO2 levels (~400 ppm), while enclosed sites reach up to **450 ppm**, impacting photosynthesis rates.
    - **Power Production & Efficiency:**
        - Circeo site data shows a seasonal increase in energy output from February to April 2024.
        - Kfar Qare' achieves higher overall energy production due to greater panel coverage and favourable light conditions.
        - Tracking systems **boost energy production by over 20%**, demonstrating their efficiency in optimizing power yield.

5.2 Findings & Implications

- **PV systems significantly alter greenhouse microclimates**, affecting light penetration, heat distribution, and CO2 levels.
- **Seasonal and structural factors** (greenhouse design, shading, and climate conditions) influence energy output and crop environment.
- **Tracking PV panels improve energy efficiency but require optimization** to balance heat management and crop growth conditions.

5.3 Next Steps

- **Advanced sensor analysis** to refine energy-crop balance strategies.
- **Long-term seasonal studies** to optimize agrivoltaic designs.
- **Development of best practices** for sustainable energy integration in greenhouse agriculture.

By continuously refining PV-greenhouse interactions, the REGACE project validation will maximize renewable energy efficiency while ensuring optimal crop productivity, fostering sustainable agrivoltaic solutions.

4.2- Technical Methods for PV String Arrangement and Constraints for Grid-Connected Inverters

To ensure optimal power generation, **PV string arrangements** must be carefully planned while considering **grid-connected inverter constraints**. Below are the key methods, constraints, and best practices for **PV string design and management** for the REGACE agrivoltaic system.

4.2.1 Influence of PV String Arrangement on Power Yield: Key Considerations

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No 101096056.

PV panels are typically connected in **series (strings) and parallel (arrays)** to achieve the required voltage and current levels. The arrangement must optimize power output while avoiding **shading losses, voltage mismatches, and inverter inefficiencies**. Greenhouse structure affect and cover can affect the light distribution on the frontside of the Bifacial solar panels causing partial shading or unequal light distribution on panel frontside. This phenomenon led to different power generation on each panel (different current and voltage). During simulating our PV incorporated greenhouses in terms of light distribution, the crucial mentioned non uniform light distribution caused by azimuthal illumination have led to lowering the energy production in the single string configuration. Solving this effect has been subjected to several areas of study; (1) electrical line engineering and (2) panel configuration. Through these improvements, electrical bottlenecks can be minimized, ensuring more consistent current flow, higher efficiency, and increased overall power output.

4.2.2 Optimal String Length Design

- The number of panels in a string is determined based on:
    - **Inverter Input Voltage Range** (typically 250V - 600V DC for utility-scale systems).
    - **Open Circuit Voltage (Voc)** of the module.
    - **Temperature Coefficients** (colder temperatures increase Voc, requiring safety margins).
    - **Maximum Power Point Tracking (MPPT) capability** of the inverter.

Formula for Maximum String Size:

$$N_{max} = \frac{V_{DCmax}}{V_{oc} \times (1 + T_{coefficient})}$$

Where:

- N_{max} = Maximum number of modules per string.
- VDC_{max} = Maximum inverter DC voltage.
- V_{oc} = Open-circuit voltage of one module.
- $T_{coefficient}$ = Temperature coefficient for voltage expansion.

Formula for Minimum String Size:

$$N_{min} = \frac{V_{DCmin}}{V_{mpp} \times (1 - T_{coefficient})}$$

Where:

- N_{min} = Minimum number of modules per string.
- VDC_{min} = Minimum inverter startup voltage.
- V_{mpp} = Voltage at maximum power point.

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4.2.3 Series vs. Parallel Connections

- **Series Connection:** Increases voltage while keeping current the same.
- **Parallel Connection:** Increases current while keeping voltage constant.

4.2.4 Managing Bifacial PV Panel Strings

- **String Orientation & Albedo Consideration:** To optimize the energy yield from bifacial PV panels, careful consideration must be given to panel orientation and albedo effects. The intensity and direction of albedo radiation depend on factors such as ground surface properties, crop type, and crop height. Selecting the appropriate ground material and arrangement can significantly enhance the amount of sunlight scattered or reflected onto the rear side of the panels, thus improving overall system efficiency. our greenhouse at TRDC, initial crop planting was conducted using regular soil with an average albedo of 0.25-0.30. As part of our ongoing optimization efforts, a new planting trial was implemented in which the soil was covered with white agricultural plastic film, increasing the albedo effect to 0.4-0.45. This modification has demonstrated a measurable improvement in rear-side energy gain, contributing to higher overall system performance. Future studies will continue to refine ground surface treatments and crop arrangements to maximize bifacial module efficiency within agrivoltaic systems.
- **Shading Avoidance:** Proper row spacing is essential to minimize shading caused by greenhouse structures and panel coverage. The distance between panel rows directly influences the land-to-solar system area ratio, impacting the overall light distribution and shading percentage within the greenhouse. Maintaining an optimal **coverage ratio** ensures maximum energy production while preventing panels from shading one another during critical morning and evening hours. When the coverage percentage exceeds 50%, careful design adjustments must be made to prevent self-shading effects. If panel rows are positioned too closely, early morning and late afternoon sunlight may be obstructed, leading to power losses. Implementing an optimized row spacing strategy ensures consistent light exposure to both the front and rear sides of the bifacial panels, enhancing overall system efficiency while maintaining a balanced agricultural microclimate.
- **String Length Consistency:** Keep strings with similar shading conditions to avoid mismatch losses.

4.2.5 Wiring and Electrical System Validation

- **Actuator Polarity Check:** Verify that actuators are connected in the correct polarity (+ and - are correctly aligned).
- **PV Panel Circuit Inspection:** Measure subcircuit voltage to confirm correct connections and prevent potential short circuits.

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- **Sensor Signal Integrity:** Test the sensor cable connections to ensure consistent signal transmission to the control system.
- **Electrical Signal Continuity:** Validate the electrical signal path from power sources to system components.
- **Motor Signal Verification:** Ensure motor signals are functioning correctly and actuators are receiving proper input.
- **Electronic Component Testing:** Before installing any new electronic components (such as actuators), perform an individual functionality test to prevent system-wide faults.

4.2.6 Electronics & Control System Validation

- **Pre-Installation Component Testing:** Before full system integration, verify that all electronic components function correctly.
- **Inverter Performance Monitoring:** Ensure SMA inverters provide accurate readings for PV voltage, current, frequency, power factor, and efficiency metrics.
- **Sensor Calibration:** Regularly test environmental sensors (such as light, wind, and temperature sensors) for accuracy and recalibrate if necessary.

4.2.5 Grid-Connected Inverter Constraints

MPPT Tracker Considerations: Modern inverters come equipped with multiple Maximum Power Point Tracking (MPPT) inputs, allowing for flexibility in string orientation and energy optimization. In the REGACE project, most inverters have two MPPT inputs, except for the Watzkendorf greenhouse, where the inverter features four MPPT inputs.

This configuration allows for strategic distribution of PV strings, optimizing energy generation and greenhouse functionality. One MPPT input is designated for a greenhouse with PV panels and CO_2 enrichment, while the other is used for a greenhouse without CO_2 enrichment. This setup facilitates different panel tilt angles simultaneously, adapting to diverse lighting and agricultural conditions within the same installation.

By independently monitoring and analyzing the MPPT input for each greenhouse system, researchers can fine-tune performance parameters, ensuring that each segment operates at its optimal efficiency. The ability to manage independent MPPT channels further enhances energy harvesting potential, mitigates power losses, and allows for detailed performance comparisons between greenhouses under different environmental conditions.

- **Strings with different orientations should be assigned to different MPPT inputs**.

A. Maximum DC Input Voltage & Current

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- The total **Voc of a string must never exceed the inverter's maximum DC input voltage**.
- The total **short-circuit current (Isc) must remain within the inverter’s current limits**.

B. Harmonics and Power Quality

- Large PV systems must comply with **grid harmonic limits** (IEC 61000-3-2).
- Improper string configuration can cause harmonic distortion, reducing efficiency.

C. Reactive Power Control

- Some inverters require **reactive power support (VAR compensation)**.
- Improper string design may lead to voltage instability.

D. Anti-Islanding and Grid Compliance

- Must follow **IEEE 1547** & **IEC 61727** anti-islanding standards.
- PV strings should be arranged to ensure stable power delivery without fluctuations.

4.2.6 Best Practices for PV String Arrangement

4.2.7 String Management for Bifacial Panels

1. **Avoid Partial Shading:** Use bypass diodes and proper row spacing.
2. **Account for Temperature Variations:** Plan for cold-weather voltage increases.
3. **Use MPPT Optimization:** Assign separate MPPT channels for different orientations.
4. **Maintain String Voltage Consistency:** Ensure uniformity across strings to prevent mismatch losses.

4.2.8 Inverter Connection Optimization

- **Balance Strings Across MPPT Inputs:** Prevent power loss due to uneven input conditions.
- **Central vs. String Inverters:**
    - **Central Inverters:** Require longer, uniform strings.
    - **String Inverters:** Allow flexibility with different orientations.
- **Oversizing Inverter Inputs:** Keep inverter DC-to-AC ratio within 1.1 - 1.3 for higher efficiency.

4.2.9. Loss Minimization Strategies

- **Use PV combiner boxes** to manage multiple strings efficiently.
- **Use thicker cables** to reduce **voltage drop losses**.

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- **Avoid crossing different albedo zones** in the same MPPT input.

5. Conclusion

To achieve **optimal power generation** in the REGACE agrivoltaic system, PV string arrangement must:

- Be designed based on **inverter voltage and MPPT capabilities**.
- Avoid **shading losses** by proper row spacing and orientation.
- Maintain **uniform string configurations** to prevent mismatches.
- Consider **bifacial panel effects and albedo variations**.
- Align with **grid connection standards** to ensure compliance

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3.3 Risk Assessment

A **risk-based approach** determines validation priorities, focusing on:

- **Product safety and quality impact**
- **Process complexity**
- **Regulatory compliance risks**

4. Validation Process for the REGACE System

4.1 Mechanical System Evaluation

- **Wind Load Testing**: The Trisolar solar system in the REGACE project is installed within a greenhouse, which provides protection against wind loads under normal conditions. However, it is essential to consider wind load impacts on the structural system in two critical scenarios:

✓ **In Case of Greenhouse Structural Failure**: If the greenhouse structure is damaged or collapses, the solar panels will be directly exposed to wind forces. This scenario necessitates evaluating the load-bearing capacity and resilience of the mounting system to prevent panel detachment or damage.

✓ **During Greenhouse Cover Replacement**: When replacing the greenhouse's plastic covering, the panels may be temporarily exposed to strong winds. This requires an assessment of short-term wind resistance and proper anchoring mechanisms to maintain stability during maintenance operations.

✓ **To ensure the system's durability and reliability** in these conditions, wind tunnel testing, computational fluid dynamics (CFD) simulations, and real-world stress testing should be performed. These evaluations will contribute to the optimization of mounting structures, reinforcement strategies, and operational guidelines for managing extreme wind conditions effectively.

- **Mechanical Stability and Impact on Greenhouse Structure**: Performance under stress, durability over time, maintenance requirements. The. The Dynamic Mechanical Load (DML) **Test** – Assesses mechanical fatigue over repeated stress cycles.
  - **Impact on Greenhouse Structure** – Measures any deformation or stress induced on greenhouse components.
  - **Mechanical Flexibility Test** – Examines stress points and deformation in dynamic tracking systems.

4.2 Durability Testing of Mechanical Parts

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  - **Corrosion Resistance Test** – Simulates environmental exposure to moisture and chemical elements.
  - **Long-Term Wear Analysis** – Evaluates degradation of moving parts over time.
  - **Actuator Stress Testing** – Validates the endurance of the tracking system's motor and actuator under continuous operation.
  - **Vibration Testing** – Simulates mechanical fatigue under operational vibrations.
  - **Base Profile Alignment:** Verify that the base profile is installed at the correct height at multiple locations, ensuring proper integration with greenhouse connectors. This step should be performed during initial installation and checked periodically.
  - **Structural Fastening:** Ensure that all screws and bolts are securely tightened, with appropriate spacing between rotators in each greenhouse section.

- **Swing Arm Stability:** Confirm that swing arms are securely positioned with no unwanted movement or looseness.
- **Alignment of Panel Profiles:** Inspect the alignment of solar panel profiles after installation and make necessary adjustments to ensure optimal performance.
- **System Clearance & Movement Check:** After the installation of all components, including actuators, test the full range of motion in both directions. Ensure that no part of the system interferes with movement or greenhouse elements. Adjust as necessary.
- **Panel Voltage Verification:** Confirm that each installed solar panel provides a proper voltage reading, ensuring electrical functionality.

Section 4.3 - CO_2 Enrichment Validation

1. Objectives

The primary objectives of CO_2 system validation are:

1. **To ensure precise CO_2 concentration control** (400-1000 ppm range).
2. **To assess the impact on plant growth and photosynthetic efficiency**.
3. **To monitor uniformity of CO_2 distribution** across greenhouse sections.
4. **To evaluate system energy consumption vs. productivity gains**.
5. **To determine environmental sustainability and CO_2 retention efficiency**.

2. CO_2 System Components and Testing Scope

The CO_2 enrichment system consists of:

- **Automated CO_2 Injection System**: Releases CO_2 in predefined concentrations.
- **CO_2 Sensors**: Measure real-time concentration levels at different zones.

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- **Ventilation and Air Circulation Units**: Maintain even CO_2 distribution.
- **Crop Monitoring Stations**: Measure plant physiological responses.

Scope of Validation

- Short-term impact on **photosynthesis and growth rates**.
- Long-term **crop yield improvements**.
- **Energy consumption analysis** for CO_2 injection.
- **Leakage and distribution consistency** assessments.

3. Validation Standards and Compliance

The validation follows internationally recognized **ISO standards**:

- **ISO 20998-1:2006** – CO_2 measurement in closed environments.
- **ISO 14064-2** – Guidelines for greenhouse gas validation.
- **ISO 8756:2004** – Air quality CO_2 concentration measurement.
- **ISO 18621:2015** – Plant response to elevated CO_2 conditions.

4. CO_2 Validation Testing Protocols

4.1 CO_2 Concentration and Distribution Monitoring

- **Hourly CO_2 concentration measurements** at different greenhouse levels (**top, middle, bottom**).
- Use **infrared CO_2 sensors** (calibrated every 14 days) for accurate ppm readings.
- Maintain CO_2 levels between **400-1000 ppm**, adjusting flow rates dynamically.
- **Check leakage points** to prevent CO_2 losses outside the greenhouse.

4.2 Plant Growth and Photosynthesis Impact Assessment

- **Measure chlorophyll fluorescence (Fv/Fm ratio)** to determine photosynthetic efficiency.
- **Monitor stomatal conductance and leaf gas exchange** using infrared gas analyzers.
- Record **biomass accumulation (g/m^2)** and **leaf expansion rate** weekly.
- Compare **CO_2-enriched vs. non-enriched** crop yields.

4.3 CO_2 Energy and Cost Efficiency

- Track **power consumption** of CO_2 injectors per kg of crop yield increase.
- Evaluate **ROI (Return on Investment)** based on **additional revenue per CO_2-treated crop unit**.

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- Assess **water use reduction** due to improved plant gas exchange efficiency.

4.4 Environmental and Sustainability Metrics

- Determine **CO_2 retention efficiency** within greenhouse.
- Measure **external leakage and absorption into greenhouse structure**.
- Compare agrivoltaic CO_2 use to **natural atmospheric CO_2 absorption rates**.

5. Data Collection and Reporting

- **Daily Logs**: CO_2 levels, energy use, and plant physiological data.
- **Weekly Reports**: Growth metrics, yield comparison, and efficiency scores.
- **Monthly Review**: System optimization recommendations and sustainability assessment.

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5.0 Sample: Test Report for Mechanical Tracking System in Solar Energy Systems

Prepared according to ISO 9060: Solar Energy – Methods for Assessing the Durability of Components of Solar Tracking Systems

5.1 General Information

Date of Report:

- **Date:** 28/10/2024

Testing Laboratory:

- **Laboratory Name:** Triangle R&D center - Zahrawy society
- **Accreditation:** ISO/IEC 17025 accredited (No)
- **Address:** Kfar Kari, Israel 3007500, P.O.Box 2167
- **Contact Information:** inf.trdc@gmail.com, +972-4-635-7011

Test Engineer(s):

- **Engineer Name(s):** Raoof Korabi
- **Title:** Trisolar Mechanical Engineer
- **Qualifications:** Msc. Mechanical Engineering

5.2 Description of the Tested System

System Identification:

- **System Name:** Trisolar Experimental PV Mechanical tracking system
- **Manufacturer:** Trisolar
- **Type of System:** Single-axis
- **Model Number/Serial Number:** linear Actuator model

5.3 Components Tested:

- **Primary Components:** Actuators, Rotation supports (SHS bearings), Structure supports, Panel holders, Actuator swing arms.
- **Materials:** steel frames, steel brackets, aluminium panel holders, steel rotation supports
- **System Specifications:**

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    - **Maximum Load Capacity:** tested for 30 panel modules each weighing 33 kg
    - **Operational Movement Range:** -60 deg to 60 deg
    - **Tracking Speed:** [60 degrees per minute]

5.3 Test Methodology

Standards and Procedures:

- **Standard Used:** ISO 9060
- **Test Procedure:** Detailed testing procedures followed per ISO 9060 for mechanical systems
    - **Cyclic Load Testing**: Simulated repetitive movement and loads over time.
    - **Wind Load Testing**: No wind loads are excreted on the system, due to positioning inside the greenhouse.
    - **Wear and Lubrication Test**: Evaluation of mechanical wear and lubrication sufficiency.
    - **Alignment and Tracking Accuracy Test**: Test for alignment deviation and accuracy degradation over time.

Test Equipment Used:

- **Equipment Type:** No equipment was used, system was run for 383 cycles

5.4 Test Conditions

Environmental Conditions:

- **Temperature Range Tested:** [15-40°C range]
- **Humidity Levels Tested:** [20-80%]
- **Wind Load Simulation:** no wind load applied

Load Cycles:

- **Number of Cycles Tested:** 383
- **Load Applied per Cycle:** weight of 30 panel modules each weighing 33 Kg
- **Cycle Duration:** each cycle lasted 2 mins, with 30 min break in between cycles (avoid overheating actuator according to manufacturer's data sheets)

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5.5 Test Results

Mechanical Fatigue Testing:

- **Cycles Completed:** 383
- **Observed Fatigue Issues:**

  loosening of 4 screw was observed, 1 on a rotation connector (one of 2 holding the profile in place with no danger of part falling)
  3 screws holding the panel holder ears were loosened as well, mitigated with springes in the new design
  3 panel holder ear rubber seals have fell off due to the screws loosening.
- **Failure Mode (if applicable):** [Description of failure point, if any]

Wear and Lubrication Test Results:

- **Observed Wear:** No excessive wear in bearings, joints, or actuators was observed
- **Lubrication Effectiveness:** No lubricant is applied in the system

Tracking Accuracy Results:

- **Initial Accuracy:** initial accuracy stands at 2-3 degrees
- **Final Accuracy after Test:** no visible change has been viewed (2-3 degrees of accuracy)
- **Deviation:** No deviation in alignment was viewed

5.6 Conclusion

Summary of Results:

- **Overall System Performance:** overall the system has performed well, with minimal signed of wear and fatigue, but more tests with higher cycle counts should be performed to simulate longer system lifespan. Moreover, the many of the required tests for the panels have not been performed at this stage and should be repeated by an accredited independent lab, in addition to the other required tests to meet ISO 10991
- **Key Observations:** system had minimal signs of wear

Compliance with ISO 9060:

- **Pass/Fail Criteria:** was not tested for compliance with ISO 9060
- **Specific Recommendations:** Repeat experiment by an accredited lab with all the measures

System Life Expectancy:

- **Estimated Operational Lifetime:** under normal operating conditions, the system's lifespan without any maintenance should be around 1 year or more, yet due to the relative

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low number of cycles the system went through during the experiment and for safety reasons, we recommend performing a visual inspection of the system after each growing season to see if anything is out of place. Moreover, we recommend performing maintenance for all components every 6-8 months according to a guide that will be provided to all users

Figures:

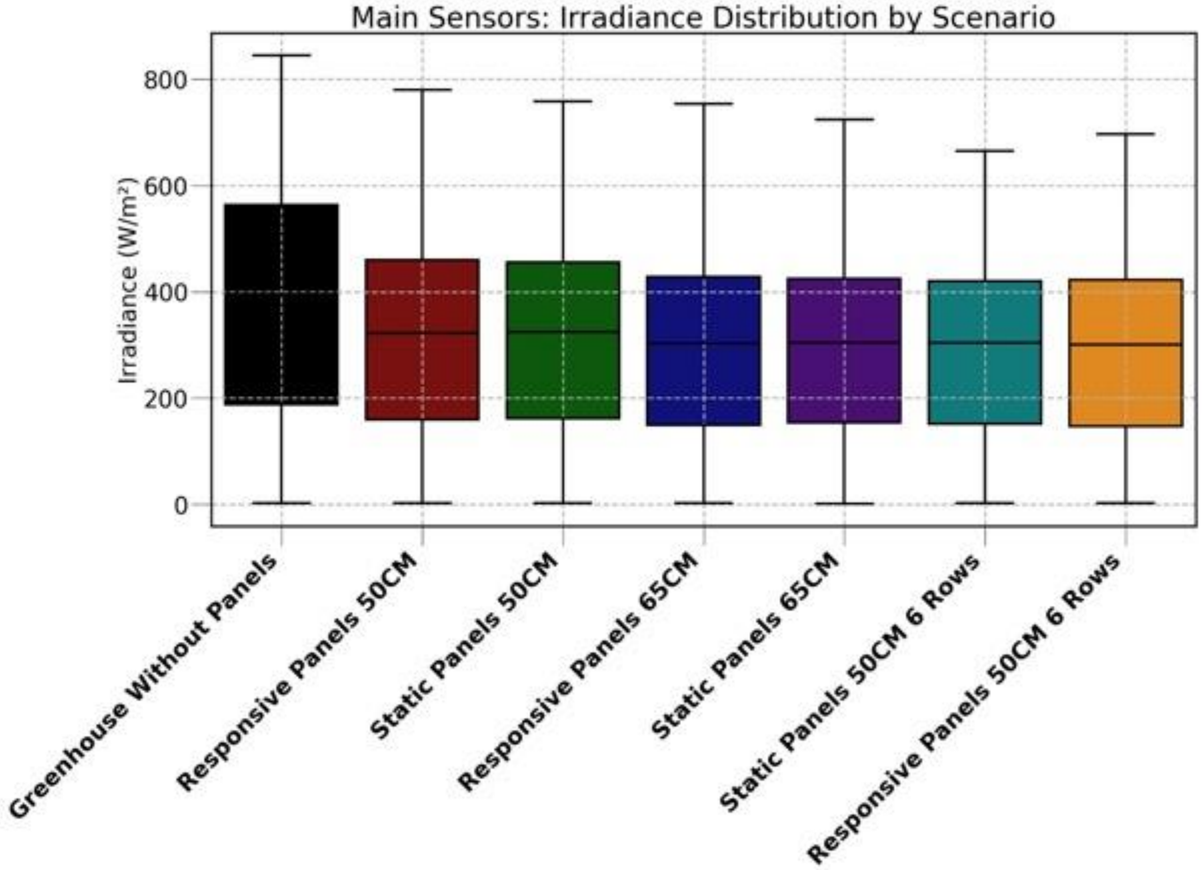

Figure 1. Irradiance whole year distribution in different PV configurations

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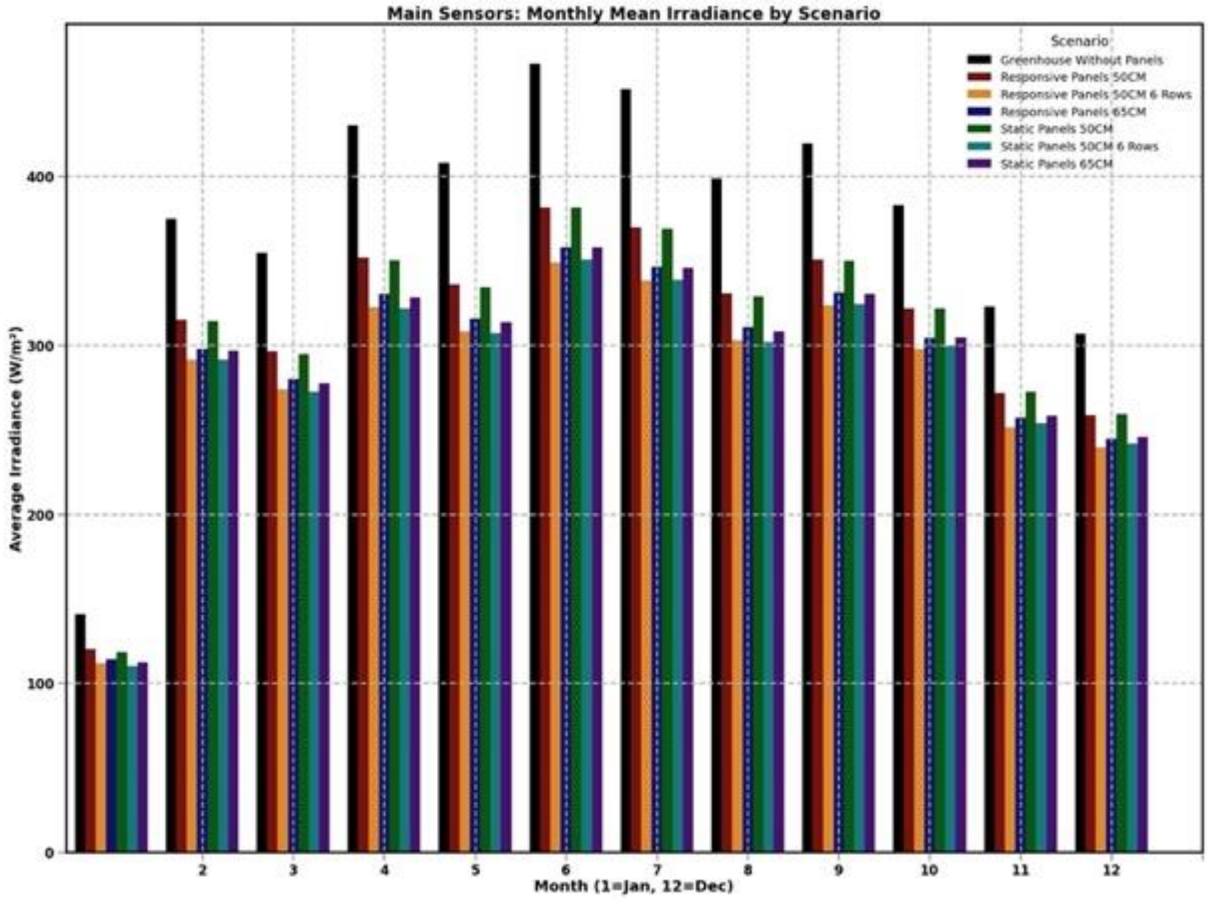

Figure 2. Detailed by month from Figure 1.

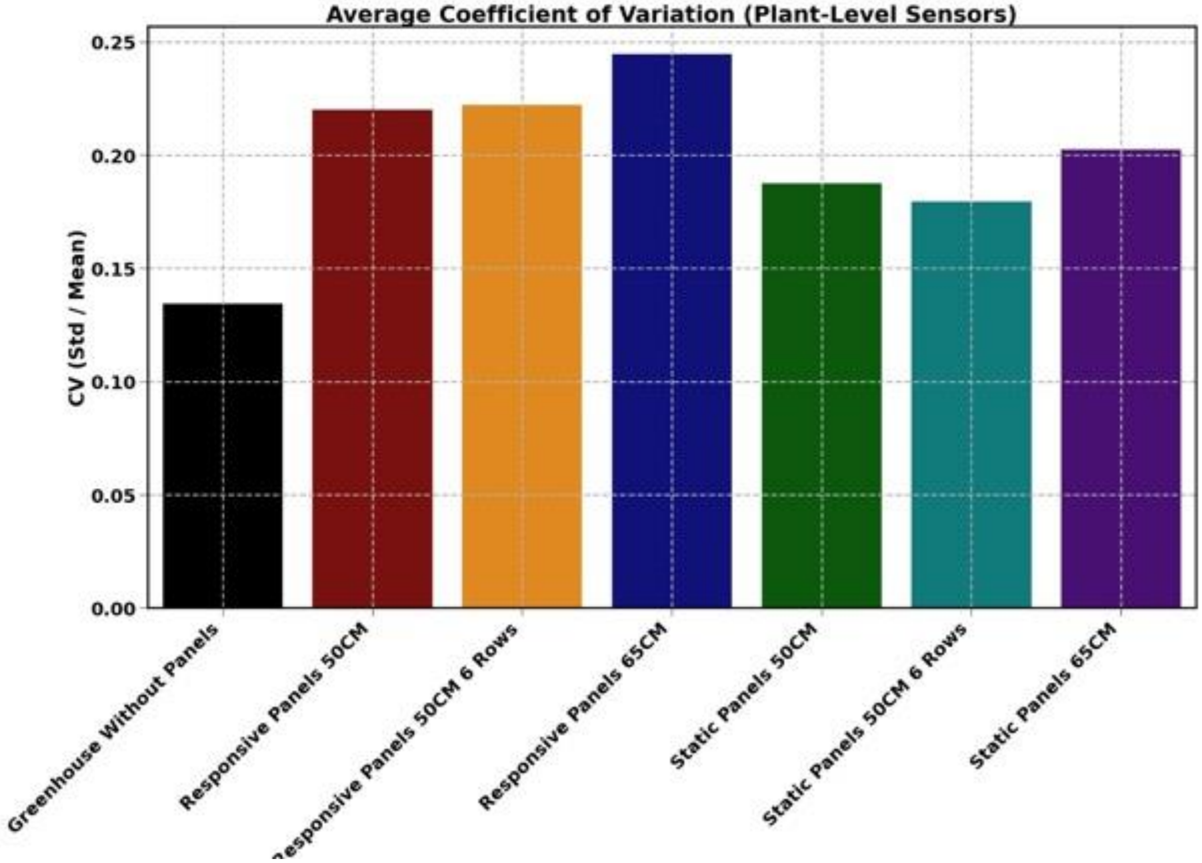

Figure 3. light distributionat the plant level in different scenarios

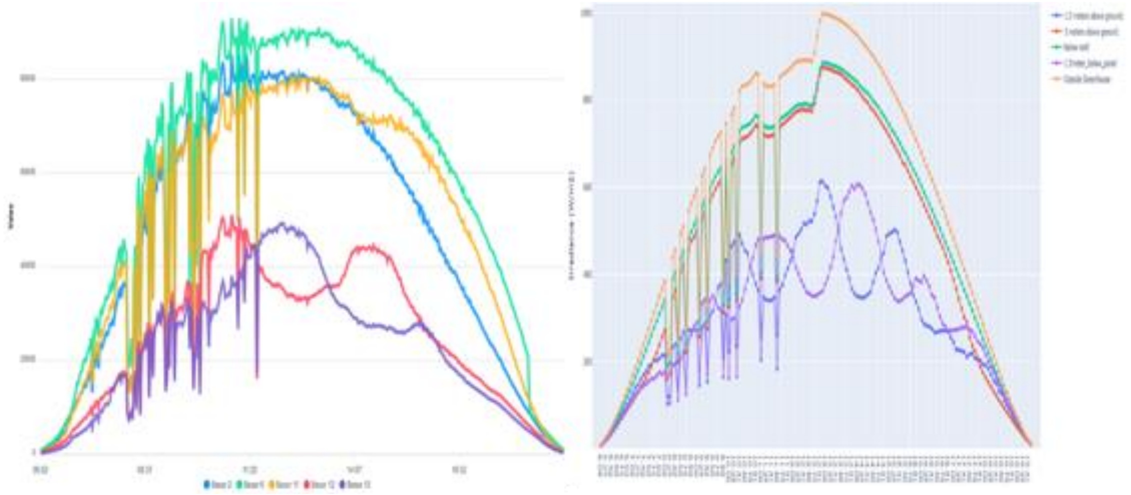

Figure 4. Validation of light sensors vs simulations

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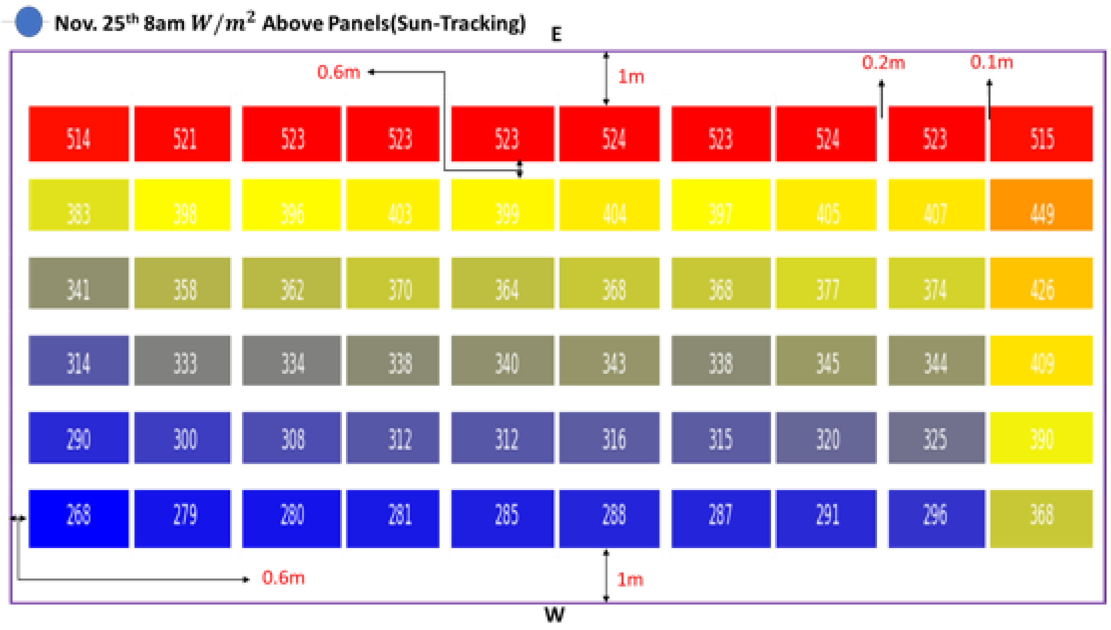
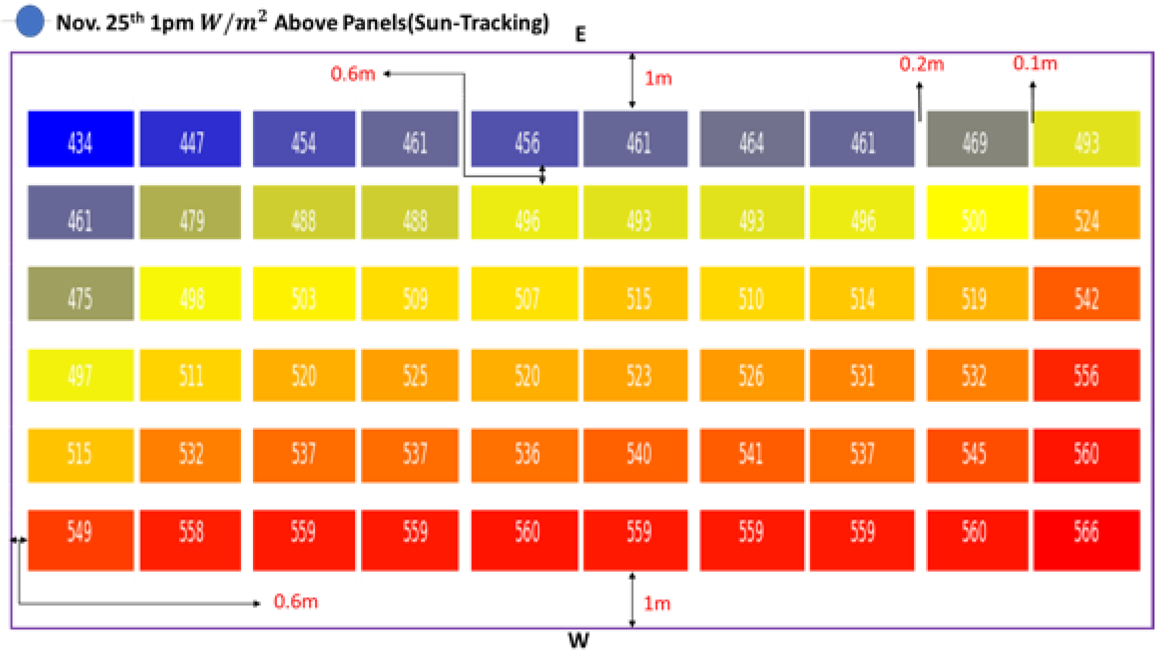


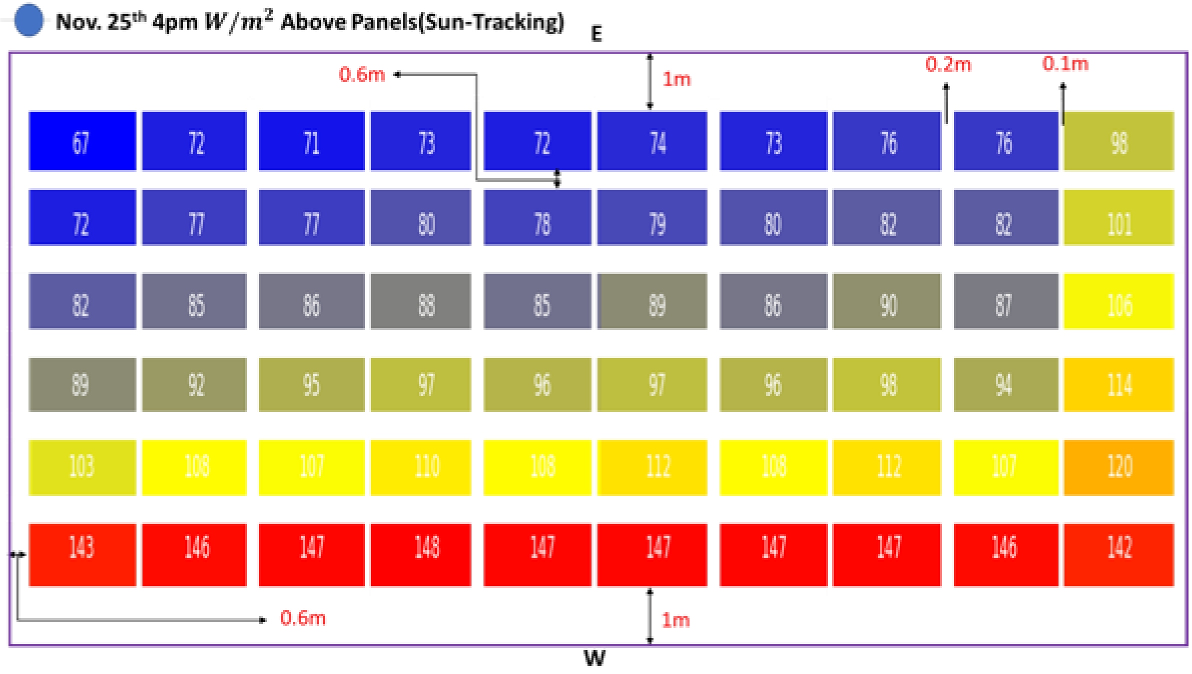
514	521	523	523	523	524	523	524	523	515
383	398	396	403	399	404	397	405	407	449
341	358	362	370	364	368	368	377	374	426
314	333	334	338	340	343	338	345	344	409
290	300	308	312	312	316	315	320	325	390
268	279	280	281	285	288	287	291	296	368

Figure 5Light distribution on panels 8:am



434	447	454	461	456	461	464	461	469	493
461	479	488	488	496	493	493	496	500	524
475	498	503	509	507	515	510	514	519	542
497	511	520	525	520	523	526	531	532	556
515	532	537	537	536	540	541	537	545	560
549	558	559	559	560	559	559	559	560	566

Figure 6. light distribution on panels 1:pm



67	72	71	73	72	74	73	76	76	98
72	77	77	80	78	79	80	82	82	101
82	85	86	88	85	89	86	90	87	106
89	92	95	97	96	97	96	98	94	114
103	108	107	110	108	112	108	112	107	120
143	146	147	148	147	147	147	147	146	142

Figure 7. Light distribution on panels 4pm