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

Project Deliverable Report

DELIVERABLE 5.2 – TECHNICAL PROTOCOLS

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List of Abbreviations

Alzahrawy Society	AZS
Bio-Gärtnerei Watzkendorf GmbH	BW
Carbon dioxide	CO_2
Daily Light Integral	DLI
East-West (tracking orientation)	E-W
Ground Coverage Ratio	GCR
Global Horizontal Irradiance	GHI
Greenhouse	GH
Photosynthetically Active Radiation	PAR
Performance Ratio	PR
Photovoltaic	PV
University of Thessaly	UTH
Work Package	WP

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Executive Summary

Deliverable 5.2 presents experience-based technical protocols that support the introduction of the REGACE agrivoltaics greenhouse system in low, medium, and high insolation environments. The protocols are derived from integrated evaluation, monitoring, and modelling activities conducted across REGACE pilot sites and translate observed system behavior into climate-adapted introduction guidance.

Rather than prescribing detailed system design or installation solutions, which are addressed in other dedicated deliverables, notably Deliverable 2.3, this report defines validated operating envelopes, performance expectations, and conditional considerations relevant to early deployment and operation. The protocols are structured around a hierarchical evaluation framework that links geometric (Ground Coverage Ratio), agronomic indicators (Photosynthetically Active Radiation and Daily Light Integral), electrical performance metric, and predictive modelling outputs.

Key outcomes include the identification of insolation-dependent introduction envelopes, clarification of the role of sun-tracking in reducing effective shading, and definition of conditions under which optional measures such as CO_2 enrichment may be beneficial to system performance. By integrating energy, crop, and operational considerations, Deliverable 5.2 provides a transferable, protocol-level framework that enables informed, robust, and replicable system introduction across diverse climatic contexts.

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Introduction

The REGACE project addresses the introduction of agrivoltaics greenhouse systems that combine photovoltaic (PV) generation and, where applicable, CO_2 enrichment with protected crop production. Introducing such systems across diverse climatic regions requires technical guidance that goes beyond component-level design and instead reflects observed system behaviour under real greenhouse operating conditions.

Deliverable 5.2 provides experience-based technical protocols that support the introduction of the REGACE system in low, medium, and high insolation environments. The protocols are derived from the evaluation, monitoring, and modelling activities conducted across REGACE pilot sites and synthesize engineering, agronomic, electrical, and operational insights into climate-adapted introduction guidance.

This deliverable does not prescribe detailed system design or installation solutions, which are out of the scope of this deliverable and are covered in dedicated design and installation deliverables, notably Deliverable 2.3. Instead, it defines validated operating envelopes, performance expectations, and conditional considerations that enable informed and robust system introduction in new deployment contexts. The protocols are intended to support early operation, performance validation, and replication of the system while accounting for climate-dependent trade-offs between energy production, crop performance, and resource efficiency.

Methodological Basis for Protocol Development

Agrivoltaic greenhouse systems operate as coupled agro–energy systems, in which photovoltaic electricity generation, greenhouse microclimate, and crop performance interact dynamically. Therefore, evaluation of such systems requires an integration of several indicators: geometric, agronomic, and electric.

Within the REGACE performance assessment framework, GCR is deliberately positioned as the first evaluation layer, describing the structural and geometric boundary conditions of the system. Subsequent layers incorporate agronomic indicators such as Photosynthetically Active Radiation (PAR) and Daily Light Integral (DLI), which quantify the crop-experienced light environment within the geometric envelope defined by GCR.

This layered approach ensures that engineering design decisions are evaluated in a structured manner, avoiding the conflation of geometric, radiative, and biological effects. By explicitly separating these dimensions, REGACE establishes a transparent and transferable methodology for the assessment and comparison of agrivoltaic greenhouse systems across sites and technologies.

Therefore, the protocol follows a hierarchical structure:

PV Geometry (GCR) → Crop-experienced Light (PAR/DLI) → Energy & Crop Response → Model-supported validation.

Definition of Insolation Regimes for System Introduction

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For protocol application, insolation regimes are classified using annual global horizontal irradiance (GHI) and typical reference DLI levels.

Table 1. Insolation Regime Classification

Regime	**Annual GHI (kWh m^{-2} yr^{-1})**	**Reference DLI (mol m^{-2} d^{-1})**	**Representative regions**
High	>1700	25–35	Mediterranean, Southern Europe
Medium	1450–1550	18–25	Central Europe
Low	<1100	10–18	Northern Europe

Technical protocols are differentiated according to solar resource availability.
High insolation environments prioritise thermal mitigation and temporal redistribution of excess light.
Medium insolation environments require balanced optimisation between energy yield and crop light availability.
Low insolation environments are light-limited and require conservative geometric design and potential compensation measures.
For each regime, protocols define acceptable GCR envelopes, DLI preservation or redistribution strategies, and validation requirements using predictive simulation.

System Components Considered in Introduction Protocols

The introduction protocols defined in Deliverable 5.2 consider the REGACE agrivoltaic greenhouse system as an integrated operational system and address only those components that directly influence system behaviour during introduction and early operation. These include the photovoltaic (PV) generation system and its operational mode (fixed or sun-tracking), CO_2 enrichment capability as a conditional agronomic support measure, the greenhouse optical and structural context as a boundary condition for radiation transmission, and the monitoring interfaces required to verify protocol compliance.
Components are considered exclusively from a functional and performance perspective, focusing on their interaction and combined impact on geometric shading, crop-experienced light availability, electrical output, and microclimate regulation across different insolation regimes. Detailed system design, component sizing, installation procedures, electrical architecture, and regulatory compliance are outside the scope of this deliverable and are addressed in dedicated design and installation guidelines.

Engineering Performance Envelopes for System Introduction (GCR-Based)

In agrivoltaic greenhouse systems, the Ground Coverage Ratio (GCR) represents a fundamental engineering descriptor used to quantify the geometric interaction between photovoltaic (PV) components and the cultivated area beneath them. GCR is define as the ratio

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between the projected opaque area of the PV elements and the cultivated ground area of the greenhouse.

This definition intentionally focuses on geometry rather than radiative or biological effects, thereby providing a transparent and transferable metric that can be applied across different greenhouse structures, PV layouts, and climatic regions. By isolating the geometric contribution of the PV system, GCR establishes a clear baseline against which more complex agronomic and system-level indicators can later be interpreted. Of note, it does not directly represent crop-experienced light reduction.

Unlike open-field agrivoltaic systems, greenhouse-integrated PV installations introduce additional layers of complexity due to the presence of the greenhouse envelope, structural shading elements, and diffuse radiation pathways. In this context, GCR does not represent a direct measure of crop-experienced light reduction but rather defines the structural shading envelope imposed by the PV installation.

Geometric Interpretation and Validity of GCR Values

A key outcome of the REGACE engineering assessment is the confirmation that GCR values greater than unity are geometrically valid in greenhouse agrivoltaic configurations. This situation arises when the total projected opaque PV area exceeds the cultivated area directly beneath the PV rows, a condition that can occur due to:

- overlapping projections of PV elements at low solar elevations,
- dense PV layouts optimized for energy production,
- structural constraints of greenhouse spans and trusses.

From an engineering standpoint, such values do not imply physical impossibility or excessive shading by default. Instead, they highlight the importance of interpreting GCR strictly as a geometric indicator, decoupled from instantaneous irradiance or biological response.

Fixed horizontal PV configurations were identified as representing a conservative upper bound for geometric shading. In these cases, the projected PV area remains constant throughout the day, leading to higher effective GCR values and limited temporal redistribution of shading.

Limitations of GCR as a Standalone Indicator

While GCR provides a robust geometric baseline, the REGACE analysis clearly demonstrates that GCR alone is insufficient to characterize agrivoltaic greenhouse performance.

Several limitations were identified:

- GCR does not account for the contribution of diffuse radiation, which is particularly relevant in greenhouse environments.
- It does not capture the temporal distribution of shading, which strongly influences crop acclimation and photosynthetic response.
- It cannot represent the moderating effects of greenhouse optics, such as cover transmittance and internal reflections.

Thus, the relationship between GCR and agronomic indicators can be expressed conceptually as:

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$$PAR_{canopy} \neq f(GCR)\ (linear)$$

but rather as:

$$PAR_{canopy} = f\left(GCR, \theta_{sun}, \phi_{diffuse}, C_{GH}\right)$$

where:

- θ_{sun} is solar elevation and azimuth;
- $\phi_{diffuse}$ is the diffuse radiation fraction;
- C_{GH} represents greenhouse optical characteristics.

Therefore, direct inference of crop performance from GCR values alone may lead to misleading conclusions, especially when comparing systems operating under different climatic conditions or control strategies.

Mathematical Definition of Ground Coverage Ratio

Within the REGACE framework, the Ground Coverage Ratio (GCR) is formally defined as:

$$GCR\ = \frac{A_{PV,opaque,proj}}{A_{crop}}$$

where:

- $A_{PV,opaque,proj}$ is the **projected opaque area** of the photovoltaic elements onto the cultivated plane, accounting for panel geometry and solar position;
- A_{crop} is the **cultivated ground area** beneath the PV installation.

This formulation ensures that GCR captures **purely geometric shading effects**, independent of spectral properties, crop characteristics, or climatic conditions.

Static vs. Effective GCR

To distinguish between design geometry and operational behaviour, REGACE introduces the concept of **effective GCR**:

$$GCR_{eff}(t) = \frac{A_{PV,proj(t)}}{A_{crop}}$$

where the projected PV area varies dynamically as a function of time t, particularly under sun-tracking operation.

The **time-averaged effective GCR** over a given evaluation period T is expressed as:

$$\underline{GCR}_{eff}(t) = \frac{1}{T}\int_{T} \quad GCR_{eff(t)}dt$$

This distinction allows direct comparison between:

- fixed PV configurations (constant GCR),
- dynamic tracking systems (time-varying GCR).

Interpretation of GCR > 1

GCR values exceeding unity arise when:

$$A_{PV,opaque,proj}\ >\ A_{crop}$$

This condition is geometrically valid and reflects overlapping PV projections rather than excessive instantaneous shading. Such cases highlight the necessity of interpreting GCR as a structural descriptor, to be subsequently integrated with agronomic indicators

Example GCR Values Across REGACE Configurations

Table 2. Representative static and effective GCR values for selected REGACE greenhouse configurations, illustrating the impact of sun-tracking on geometric shading.

PV Mode	Static GCR	Static GCR	Effective GCR
GH–A	Fixed	1.2	1.2
GH–A	Tracking (E–W)	1.2	0.9
GH–B	Fixed	0.95	0.95
GH–B	Tracking (E–W)	0.95	0.72

The results confirm that sun tracking systematically reduces effective GCR by approximately 25%, irrespective of greenhouse geometry or climatic location.

Insolation-Dependent GCR Design Envelopes

Based on the integrated performance analysis conducted within REGACE, recommended GCR ranges are defined as **climate-dependent design envelopes**, reflecting differences in solar resource availability and radiative composition across low, medium, and high insolation environments:

- **Low insolation environments (GCR ~0.6–0.9):**

  In regions characterized by limited annual irradiance and a higher risk of light limitation, lower GCR values are recommended to preserve crop-experienced DLI. Protocols in these environments prioritize minimization of cumulative shading and robust light availability, particularly during winter and shoulder seasons.

- **Medium insolation environments (GCR ~0.9–1.2):**

  These environments allow balanced optimization between photovoltaic energy yield and agronomic light availability. Moderate GCR values can be deployed without compromising system viability, especially when combined with dynamic control strategies that redistribute shading temporally.

- **High insolation environments (GCR >1.2):**

  In regions with abundant solar resources, higher geometric coverage ratios are feasible from a system-level perspective. However, operation within this envelope requires advanced control strategies and careful validation to manage localized shading effects and thermal loads, ensuring that cumulative DLI remains within acceptable bounds.

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These GCR ranges are not intended as prescriptive limits, but as **climate-specific design envelopes** within which further optimization shall be conducted using integrated agronomic and electrical performance indicators.

Agronomic Light Availability Protocols for Introduction (PAR &DLI)

Agronomic performance in agrivoltaic greenhouses depends on how light is redistributed within the greenhouse and perceived at canopy level rather than the geometric shading imposed by PV integration alone. The following section therefore focuses on agronomic performance indicators, specifically PAR and DLI, to quantify the crop-experienced manifestation of geometric shading.

Photosynthetically Active Radiation (PAR) represents instantaneous light availability at canopy level that plants can use for photosynthesis, while Daily Light Integral (DLI) represents cumulative daily exposure of crops to PAR and is the primary agronomic control variable used in these protocols.

REGACE results demonstrate that moderate reductions in DLI under agrivoltaic configurations remain within tolerance ranges (see Deliverable 3.2) for investigated crops, while temporal redistribution of light mitigates potential stress during peak irradiance periods .

Normalized DLI, defined as the ratio between agrivoltaic and reference conditions, is required for protocol validation and cross-climate transferability.

PAR is defined as the portion of the solar spectrum between **400 and 700 nm** that is usable for photosynthesis. In REGACE, PAR is expressed as photon flux density:

$$\int_{400}^{700} E_{\lambda}(t)d\lambda$$

where:

- $E_{\lambda}(t)$ is the spectral irradiance at wavelength λ and time t.

For practical evaluation, PAR is measured in
$\mu mol\ m^{-2}s^{-1}$

PAR measurements were conducted at multiple heights within the greenhouse to capture the vertical light gradient induced by PV shading and structural elements.

Spatial and Temporal Variability of PAR in Greenhouse Agrivoltaics

REGACE measurements demonstrate that PAR distribution within agrivoltaic greenhouses exhibits both spatial and temporal variability:

- Spatial variability arises from:
    - PV row spacing,
    - tracker orientation,
    - greenhouse structural members.
- Temporal variability arises from:
    - solar position,

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  - tracking motion,
  - cloud cover and diffuse radiation fraction.

As a result, instantaneous PAR reductions cannot be directly inferred from static GCR values. Instead, PAR must be interpreted as a dynamic field variable modulated by system operation.

Definition and Calculation of Daily Light Integral (DLI)

The DLI represents the cumulative PAR received over a 24-hour period and is defined as:

$$DLI = \int_0^{24} PAR(t)dt$$

For discretized measurements, DLI is computed as:

$$DLI = \sum_{i=1}^{n} PAR_i \cdot \Delta t$$

where:

- PAR_i is the measured PAR at time interval iii,
- Δt is the measurement time step.

DLI is expressed in:

$$mol\, m^{-2} day^{-1}$$

This metric provides a robust agronomic indicator, as many crops exhibit yield responses that correlate more strongly with DLI than with instantaneous PAR values.

Normalization of Agronomic Indicators

To enable comparison across sites, seasons, and climatic regions, REGACE applies normalized agronomic indicators. Normalised DLI is defined as:

$$DLI_{norm} = \frac{DLI_{AV}}{DLI_{ref}}$$

where:

- DLI_{AV} is the DLI measured under agrivoltaic conditions;
- DLI_{ref} is the reference DLI measured in non-agrivoltaic greenhouse or open-field conditions.

This normalization removes climatic bias and isolates the effect of PV integration on crop-level light availability.

Representative Agronomic Performance Metrics Across REGACE Pilots

Table 3. Normalized PAR and DLI values under agrivoltaic conditions across selected REGACE pilot sites.

Site	**PV Configuration**	**Normalized PAR**	**Normalized DLI**

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UTH	Tracking	0.82	0.88
UTH	Fixed	0.74	0.79
AZS	Tracking	0.85	0.91
BW	Tracking	0.89	0.93

These results confirm that dynamic PV configurations consistently mitigate PAR and DLI reductions relative to fixed installations, particularly in climates with higher diffuse radiation fractions.

Coupling Engineering and Agrivoltaic Indicators

To link engineering design with agronomic response, REGACE introduces the concept of effective light availability normalized by geometric coverage.
The effective agronomic light efficiency η_{night} is defined as:

$$\eta_{night} = \frac{DLI_{AV}}{DLI_{ref} \cdot \left(1 - \underline{GCR_{ref}}\right)}$$

where:

- DLI_{AV} is the measured DLI under agrivoltaic conditions;
- DLI_{ref} is the reference DLI;
- $\underline{GCR_{ref}}$ is the time-averaged effective GCR.

Values of η_{night} greater than unity indicate compensation effects due to diffuse radiation enhancement and temporal shading redistribution.

CO_2 Enrichment Considerations for System Introduction

CO_2 enrichment is considered within the REGACE system as a secondary, context-dependent agronomic measure whose effectiveness depends on insolation regime, radiation availability, and greenhouse operating constraints. Evidence from REGACE pilot sites and integrated analysis reported in Deliverable 5.3 shows that CO_2 enrichment cannot act as a universal compensatory mechanism for photovoltaic-induved light reduction, but may provide incremental benefits under specific conditions.

In low insolation environments, crop productivity is primarily radiation-limited, with cumulative DLI often near minimum crop thresholds. Under these conditions, CO_2 enrichment cannot compensate for insufficient light and should not be relied upon during system introduction. In medium insolation environments, where baseline radiation is sufficient and PV integration introduces moderate shading, CO_2 enrichment may enhance radiation use efficiency under redistributed light. However, benefits are constrained by ventilation requirements that limit sustained enrichment. In high insolation environments, PV integration primarily mitigates excess radiation and thermal stress. While CO_2 could theoretically improve efficiency, practical feasibility is similarly limited by ventilation demand and should be regarded as optional.

Across all regimes, CO_2 enrichment cannot substitute for appropriate PV geometry, radiation management, or climate control. Its use during system introduction should therefore be

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considered after geometric (GCR) and radiative (PAR/DLI) conditions fall within validated introduction envelopes, and as a complementary measure rather than a determinant of feasibility.

Electrical Performance Indicators Supporting System Introduction

Electrical performance indicators are used within Deliverable 5.2 to support the introduction of the REGACE agrivoltaics greenhouse system across different insolation environments by verifying that PV operations remain stable, predictable, and compatible with greenhouse-integrated conditions.
Electrical performance is evaluated using standard photovoltaic indicators, including:

- **Final yield** $Y_f\,[kWh/kWp]$, representing the measured energy output of the system PV system normalied to installed capacity.
- **Reference yield** $Y_r\,[kWh/kWp]$, representing the theoretical energy output derived from measured irradiance under reference conditions.
- **Performance ratio** (PR).

The performance ratio is defined as:

$$PR = \frac{Y_f}{Y_r}$$

These indicators are calculated using monitored electrical energy production and irradiance data collected at the REGACE pilot sites and are reported in normalized form to enable comparison across locations, seasons, and insolation regimes.
Within the system introduction framework, the PR is interpreted in conjunction with agronomic and geometric indicators, rather than as a standalone metric. In particular, PR values are assessed alongside GCR, PAR, and DLI to ensure that electrical performance is evaluatedin the context of greenhouse-specific shading dynamics, seasonal variability, and optical effects. This integrated interpretation avoids misleading conclusions that may arise when electrical indicators are considered independently of climatic or agronomic conditions.
Results from REGACE pilot sites demonstrate stable electrical performance consistent with expectations for PV systems operating under comparable climatic conditions.
Electrical performance therefore does not represent a limiting factor for system introduction in low, medium, or high insolation environments, provided operation remains within the protocol-defined introduction envelopes, and serves as supporting evidence for system readiness alongside agronomic and operational assessments.

Integrated System Behaviour Across Insolation Regimes

Across all climatic contexts, dynamic PV operation modifies both the quantity and temporal distribution of radiation within the greenhouse, influencing crop physiology, evapotranspiration, and electrical output simultaneously. Deliverable 5.3 confirms that static

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geometric descriptors are insufficient to capture these interactions. Instead, integrated interpretation of GCR, PAR, DLI, electric yield, and water consumption is required to characterize system behaviour readily.

In low insolation environments, system behaviour is predominantly radiation-limited. Under these conditions, integrated system benefits depend on preserving agronomic light availability, and introduction protocols must prioritise conservative operating envelopes.

In medium insolation environments, the system exhibits the most balanced and robust interated behavior. Radiation availability is sufficient to sustain crop productivity, while PV-induced shading moderates peak irradiance and stabilises microclimatic conditions. Sun tracking reduces effective GCR, stabilises electrical performance, and redistributes light without inducing yield penalties. Water consumption is consistently reduced while maintaining crop output, resulting in neutral to positive water-use efficiency. These environments provide the most transferable conditions for system introduction.

I high insolation environments, is dominated by mitigation of excess radiation and thermal stress rather than light preservation. PV integration reduces canopy temperature, vapour pressure deficit, and evapotranspiration demand while maintaining adequate DLI. Electrical yields benefit from high solar availability, and water savings are most pronounced due to demand-driven evapotranspiration reduction.

Across all regimes, sun-tracking operation emerges as a key integrative mechanism, reducing effective GCR, stabilizing electrical output, and redistributing radiation in ways that mitigate agronomic stress. These regime-specific interaction patterns provide the empirical basis for defining differentiated system introduction protocols in Deliverable 5.2.

Predictive Modelling Support for System Introduction

The predictive simulation model developed in WP4 provides a digital representation of the agrivoltaic greenhouse system, incorporating:

- solar geometry and irradiance decomposition;
- PV module orientation and tracking logic;
- greenhouse optical properties;
- spatial and temporal light distribution.

Model outputs include simulated PAR, DLI, and energy yield, which are compared against measured values to assess model validity.

The deviation between measured and simulated values is quantified as:

$$\Delta X = \frac{X_{meas} - X_{sim}}{X_{sim}}$$

where X represents PAR, DLI, or energy yield.

Across REGACE pilot sites, deviations were found to remain within acceptable uncertainty ranges, confirming the suitability of the model for system-level interpretation.

Cross-Site Integrated Performance Comparison

Table 4. Integrated performance assessment framework adopted in REGACE, linking geometric, agronomic

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and electrical indicators with predictive modelling.

Site	**PV Mode**	**PR (avg.)**	**Normalised DLI**	**ηlight\eta_{\mathrm{light}}ηlight**
UTH	Tracking	0.66	0.88	1.05
AZS	Tracking	0.69	0.91	1.08
BW	Tracking	0.71	0.93	1.1

The results demonstrate that, despite climatic differences, integrated agrivoltaic systems exhibit stable electrical performance, moderate DLI reductions, and light-use efficiencies close to or exceeding unity.

Predictive simulation tools developed in WP4 are integral to the technical protocols. Models provide a validated digital representation of agrivoltaic greenhouse systems, incorporating solar geometry, PV behaviour, greenhouse optics, and light distribution.
Within the protocols, predictive modelling is used to:

- validate GCR and DLI compatibility under local climatic conditions,
- assess fixed versus tracking configurations,
- extrapolate performance to untested regions,
- reduce deployment risk prior to installation.

Model validation against measured REGACE data confirms suitability for protocol-level decision support.

Introduction Protocols by Insolation Regime

High Insolation Environments

High insolation environments are characterized by abundant direct radiation and frequent peak irradiance conditions. In these contexts, system introduction protocols prioritize thermal mitigation and temporal redistribution of excess radiation rather than strict preservation of cumulative DLI. PV integration can therefore be used as an active shading and climate moderation strategy, reducing canopy heat stress and, in some cases, replacing conventional shading nets.

Table 5. High Insolation Introduction Protocol Parameters

Parameter	**Recommended range**	**Rationale**
Static GCR	0.9–1.3	High solar availability allows increased coverage
Effective GCR	≤1.0	Controlled through tracking operation
Normalized DLI	≥0.85	Moderate reduction acceptable

Tracking	Strongly recommended	Enables temporal redistribution of shading

Medium Insolation Environments

Medium insolation environments require a balanced optimization between energy generation and crop light availability. Radiation levels are generally sufficient to sustain crop growth, but excessive shading may induce performance penalties if not properly managed. Introduction protocols therefore aim to maintain stable DLI while enabling meaningful energy production through controlled PV operation.

Table 6. Medium Insolation Introduction Protocol Parameters

Parameter	**Recommended range**	**Rationale**
Static GCR	0.8–1.1	Balanced trade-off between energy and crops
Effective GCR	≤0.9	Preserves crop-experienced DLI
Normalized DLI	0.85–0.95	Supports stable crop performance
Tracking	Recommended	Improves integrated system performance

Low Insolation Environments

Low insolation environments are light-limited and highly sensitive to additional shading. In these contexts, introduction protocols prioritize preservation of crop light availability over energy density. Conservative PV coverage and careful control of effective shading are required to avoid cumulative DLI deficits that may compromise crop productivity.

Table 7. Low Insolation Introduction Protocol Parameters.

Parameter	**Recommended range**	**Rationale**
Static GCR	0.6–0.8	Minimises structural shading
Effective GCR	≤0.75	Limits cumulative light loss
Normalized DLI	≥0.90	High preservation required
Tracking	Optional but beneficial	Adds operational flexibility

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Compensation	Supplemental lighting (if needed)	Mitigates light deficits

System Introduction: Operational Considerations and Workflow

Operational experience from REGACE pilot sites indicates that the agrivoltaics greenhouse system can be introduced with low operational burden and without disruption to routine greenhouse activities. System behaviour during early operation was stable, with any issues observed primarily attributable to pilot-scale conditions rather than intrinsic system limitations. From an end-user perspective, crop performance is the primary determinant of adoption, while ease of use, robustness, and compatibility with existing workflows are key enabling factors.
Accordingly, system introduction should follow a simple, monitoring-driven workflow:

(i) Classify the site by insolation regime.
(ii) Select an appropriate operating envelope for PV operation and light availability
(iii) Define crop-specific DLI targets.
(iv) Validate the configuration using predictive simulation where available
(v) Deploy the system with early stage monitoring of agronomic and electrical indicators.

This approach supports operational confidence, early performance validation, and replicable system introduction across greenhouse typologies and climatic contexts.

Limitations and Conditions of Applicability

The protocols in this deliverable are derived from REGACE pilot-scale experience across diverse climatic and operational conditions. While the insolation-based framework supports transferability, system behavior may vary with site-specific factors such as greenhouse geometry, optical properties, ventilation capacity, crop requirements, and local management practices.

The REGACE pilots were designed for research an validation rather than commercial optimization. Therefore, the defined operating envelopes represent validated feasibility ranges rather than guaranteed performance outcomes. Optional measures, such as CO_2 enrichment, are subject to operational constraints that may limit applicability under certain conditions. The protocols should thus be applied as guiding technical frameworks to support informed system introduction, with site-specific assessment required prior to large-scale deployment.

Conclusion

Deliverable 5.2 establishes a coherent set of technical protocols that enable the climate-adapted introduction of the REGACE agrivoltaics greenhouse system. Building on pilot-scale experience and validated modelling tools, the deliverable demonstrates that system performance and suitability for introduction cannot be assessed through isolated indicators but

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must be interpreted through an integrated framework combining geometric, agronomic, electrical, and operational dimensions.

The results confirm that differentiated introduction protocols are required across low, medium, and high insolation environments, with distinct priorities ranging from light preservation in radiation-limited contexts to thermal mitigation and resource-use optimization under high solar availability. Sun-tracking operation consistently emerges as a key enabling mechanism, reducing effective shading and stabilizing integrated system behaviour, while CO_2 enrichment is identified as a secondary, context-dependent measure rather than a primary determinant of feasibility.

By defining validated operating envelopes and clear conditions of applicability, Deliverable 5.2 supports early operation, performance validation, and replication of the REGACE system without duplicating design- or installation-focused guidance. The protocols presented herein provide a robust technical basis for future deployments and contribute to the broader objective of advancing agrivoltaics greenhouse systems as integrated, climate-responsive solutions for sustainable food and energy production.

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