

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

Project Deliverable Report

DELIVERABLE 5.3 – SYSTEM EVALUATION

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List of Abbreviations

Alzahrawy Society	AZS
Bio-Gärtnerei Watzkendorf GmbH	BW
Capital Expenditure	CAPEX
Cash Flow	CF
Carbon Dioxide	CO ₂
Daily Light Integral	DLI
European Union	EU
Fattoria Solidale del Circeo	FSC
Grant Agreement	GA
Ground Coverage Ratio	GCR
Humboldt University of Berlin	UBER
Internal Rate of Return	IRR
Key Performance Indicator	KPI
Kilowatt-hour	kWh
Kilowatt peak	kW _p
Levelized Cost of Electricity	LCOE
Net Present Value	NPV
Operational Expenditure	OPEX
Photocynthetically Active Radiation	PAR
Performance Ratio	PR
Photovoltaic	PV
Return on Investment	ROI
Smart Energy Meter (GoodWe SEMS platform context)	SEM
University of Thessaly	UTH
Water-Energy-Food	WEF
Work Package	WP
Final Yield	YF

Executive Summary

Deliverable 5.3 presents the final integrated performance and techno-economic evaluation of the REGACE agrivoltaic greenhouse system, in line with the Grant Agreement. The assessment combines KPI-based analysis, modelling and experimental validation, and qualitative end-user feedback to evaluate system feasibility within a Water–Energy–Food (WEF) framework aligned with European Green Deal priorities.

System performance is assessed using four KPIs: effective Ground Coverage Ratio (GCR), electrical yield, crop yield and quality, and water consumption. Results show that static geometric indicators are insufficient for agrivoltaic greenhouse assessment. A dynamic, radiation-resolved definition of effective GCR—derived from WP4 modelling and validated by WP3 measurements—provides a robust basis for cross-site normalization.

Electrical performance under greenhouse-integrated operation is stable and predictable, with sun-tracking improving normalized yield and stabilizing performance ratios despite lower absolute yields than open-field PV systems. Agronomic results confirm that PV integration does not inherently limit crop yield or quality; outcomes depend on maintaining crop-specific light thresholds, with diffuse radiation redistribution and microclimate stabilisation contributing positively where sufficient irradiance is available. Across all pilot sites, PV integration consistently reduces water consumption, with water-use efficiency improving where evapotranspiration is demand-driven.

Techno-economic analysis for representative Mediterranean pilot sites demonstrates strong economic potential under realistic deployment assumptions, including positive net present value, short payback periods, and low levelized cost of electricity. Pilot installations that do not meet representativeness or data-continuity criteria are excluded from final feasibility metrics but provide insights for system optimization.

End-user interviews confirm high acceptance of the REGACE concept, highlighting low operational burden, system stability, and ease of use. Crop yield performance remains the primary determinant for adoption, reinforcing the importance of activating existing crop-specific, DLI-based control strategies during commercial rollout. Overall, REGACE is concluded to be technologically mature, operationally feasible, and economically promising under optimized deployment conditions.

Introduction

Deliverable 5.3 addresses the integrated performance evaluation and techno-economic feasibility of the REGACE agrivoltaic greenhouse system, fulfilling the objectives in the Grant Agreement. The analysis builds on experimental results from WP3, modelling outcomes from WP4, and system-level integration within WP5, assessing the system's ability to jointly deliver renewable energy, stable agricultural production, and reduced water consumption across diverse climatic and structural conditions.

The REGACE project was implemented as a scientific validation and proof-of-concept initiative rather than a commercial deployment. Pilot installations were realized in research-oriented greenhouses using first-of-a-kind configurations, prototype components, and non-optimized value chains. Accordingly, Deliverable 5.3 does not aim to demonstrate immediate market readiness, but to evaluate whether observed system behaviour provides credible indicators of future techno-economic feasibility under optimized commercial deployment.

The assessment is structured around four performance indicators: Ground Coverage Ratio (GCR), electrical yield, crop yield and quality, and water consumption. Emphasis is placed on replacing static geometric descriptors with performance-based, radiation-resolved metrics that better reflect crop-relevant light availability and system operation.

In addition to quantitative KPI analysis, the deliverable incorporates qualitative feedback from farmers hosting REGACE pilot installations, providing insight into system usability, operational burden, perceived maturity, and adoption conditions. This combined approach ensures that conclusions are technically robust, operationally grounded, and relevant for future European deployment.

Chapter 1: KPI-Based System Performance Evaluation

KPI 1: GCR

Static GCR is defined as the ratio between the horizontally projected opaque photovoltaic area and the cultivated crop area beneath the greenhouse structure.

For sun-tracking photovoltaic configurations, an effective GCR is calculated as the daily-average projected PV area over the operational tracking cycle, normalized to the cultivated crop area.

Dynamic sun-tracking operation reduces effective GCR by approximately 25%, thereby mitigating shading intensity without reducing installed PV capacity or cultivated area.

WP4 Contribution to KPI 1 (GCR)

Ground Coverage Ratio (KPI 1) is evaluated using spatio-temporal radiation modelling developed in WP4 and documented in Deliverable 4.2. WP4 quantitatively resolves the distribution of incoming short-wave radiation within greenhouse environments under different photovoltaic (PV) geometries and operating modes, enabling assessment of crop-level light availability that extends beyond purely geometric definitions of PV coverage.

WP4 results demonstrate that static GCR, defined as the fraction of greenhouse roof area geometrically covered by opaque PV modules under horizontal projection, is insufficient to characterise crop-relevant shading in agrivoltaic greenhouse systems, particularly when dynamic sun-tracking operation is employed. Radiation simulations show that tracking operation substantially alters the temporal and angular projection of PV modules over the diurnal cycle, with modules frequently adopting steep or near-vertical orientations during morning and afternoon periods. Under these conditions, the effective shading footprint at the crop canopy is reduced relative to static assumptions, despite identical installed PV capacity and nominal geometric coverage.

WP4 modelling further indicates that diffuse radiation becomes a dominant contributor to Photosynthetically Active Radiation (PAR) at canopy level under tracking PV configurations, due to combined effects of greenhouse cover scattering and partial interception by PV modules. This redistribution enhances light penetration depth and spatial homogeneity within the greenhouse, reducing the agronomic relevance of instantaneous geometric shading.

As a result of these dynamic effects, WP4 introduces the concept of effective (dynamic) GCR, defined as the time-integrated, crop-relevant PV shading intensity derived from spatio-temporal radiation availability at canopy level rather than from static geometric coverage alone. When integrated over daily operation, WP4 simulations show that tracking PV systems exhibit an approximately 25 % reduction in effective GCR relative to equivalent static PV configurations. This reduction arises directly from time-resolved projection geometry and irradiance calculations and is not imposed as an assumption.

The WP4-derived effective GCR is independently validated by WP3 experimental measurements, which include canopy-level PAR monitoring under both static and tracking PV operation. WP3 data consistently show increased light availability and reduced shading duration under tracking configurations, confirming the modelled reduction in effective GCR.

Definition and justification of the effective GCR envelope

Within WP5, the effective Ground Coverage Ratio (GCR) envelope is defined as the range of PV coverage configurations for which crop-level light availability, as quantified by WP4 radiation simulations and validated by WP3 measurements, remains within agronomically acceptable limits while maintaining the intended installed PV capacity. This envelope is not expressed as a single numeric threshold, as effective GCR depends on dynamic PV orientation, solar geometry, diffuse radiation fraction, and greenhouse optical properties.

The justification for adopting an effective GCR envelope rather than a fixed geometric GCR lies in the non-linear relationship between static PV coverage and crop-level radiation exposure demonstrated in WP4. Identical static GCR values can yield substantially different canopy-level light conditions depending on PV operation mode and temporal integration, making static GCR unsuitable as a universal design or evaluation metric. The effective GCR envelope therefore provides a performance-based framework that ensures comparability across sites,

operating strategies, and climatic regimes while remaining directly linked to measurable radiation conditions.

WP4 thus provides the physical and optical basis for interpreting GCR as a functional KPI rather than a purely geometric descriptor. By explicitly linking PV geometry and operation to time-integrated radiation availability at crop level, WP4 ensures that KPI 1 is evaluated consistently across sites and underpins the normalization approach applied throughout.

In summary, KPI 1 is assessed using effective GCR as the relevant descriptor of agrivoltaic greenhouse geometry. This approach captures the dynamic interaction between PV orientation, radiation distribution, and crop exposure and enables consistent interpretation of energy, crop, and water KPIs across locations. The adoption of effective GCR therefore constitutes a necessary foundation for the techno-economic feasibility assessment performed in WP5.

KPI 2: Electrical Yields

Electric yield performance is evaluated using experimentally measured inverter data collected across all five REGACE pilot greenhouse sites, in accordance with the KPI framework defined in WP5.

Electrical performance data were obtained through continuous inverter monitoring using the SMA Sunny Portal and GoodMe SEMS platforms across all REGACE pilot sites. Recorded AC energy output was derived from inverter data and reported as daily, monthly, and annual energy production values [figures 32-36 in D3.2)

Final Yield (YF) expressed as kWh per kWp was calculated from inverter-recorded energy output data for all REGACE greenhouse systems.

The YF metric was used as the primary normalization variable, as it enables fair comparison across greenhouse systems with different installed capacities, structural designs, tracking configurations, and irradiance regimes (environmental aspects).

Based on Table 15 and Figures 32-36 of Deliverable D3.2, the measured electrical performance can be summarized as follows:

Table 1. Measured electrical performance at each pilot site.

Site	Peak Monthly Energy Output	Final Yield (kWh/kWp)	Observations
FSC	622.7 kWh (Jun 2025)	4.18 kWh/kWp	Highest reported yield
BW	~1400 kWh (Jul 2025)	3.96 kWh/kWp	Stable tracking operation
AZS	Reported in Table 15, D3.2	~3–4 kWh/kWp	High irradiance, controlled shading

UTH	Reported in Table 15, D3.2	~2–3 kWh/kWp	Structural shading effects
UBER	127.7 kWh (Jul 2025)	1.15 kWh/kWp	Low yield attributed to frequent system disconnections.

Of note, differences in performance are explained by operational constraints, structural geometry, and data continuity.

AZS and UTH exhibited intermediate final yield values relative to FSC and BW, reflecting differences in greenhouse geometry, irradiance conditions, and shading behavior.

Performance Ratio (PR) was evaluated using inverter-recorded AC output and incident irradiance data. PR values vary across sites due to greenhouse-induced losses and thermal effects but remain stable over time within individual sites. Sun-tracking operation contributes to stabilization and partial improvement of PR compared to fixed configurations.

Annualized electrical energy production (Italy pilot): for the FSC greenhouse, sufficient operational continuity enabled annual energy extrapolation. The measured electricity production during the operational period from March to September amounted to 3,460 kWh. Based on local typical solar yield for the site and correction using measured data, the estimated annual electricity production was extrapolated to 4,423 kWh per year.

Final yield serves as a normalized metric that allows for fair comparison across different systems, climates, and designs.

The electrical yield analysis demonstrates that greenhouse-integrated photovoltaic systems produce lower absolute energy yields than open-field PV installations due to optical transmission losses and thermal effects associated with greenhouse structures. Nevertheless, energy production is stable and predictable over time, and sun-tracking operation systematically improves specific yield and stabilizes performance ratios.

When evaluated relative to GCR and greenhouse area, electrical yield demonstrates stable and predictable performances under agrivoltaic greenhouse conditions, enabling normalization across sites and supporting techno-economic evaluation of the system. Energy performance is therefore sufficient to be integrated into a combined assessment alongside crop yield and water consumption, rather than optimized as an isolated metric.

Crucially, electrical performance is not optimized in isolation but evaluated as one component of a multi-output Water-Energy-Food system, consistent with the integrated KPI framework defined in WP5 and aligned with European Green Deal objectives.

WP4 Contribution to KPI 2: Electrical Yield Performance

Electrical yield performance under agrivoltaic greenhouse conditions was evaluated using the photovoltaic performance modelling framework developed in WP4 and documented in Deliverable 4.2, in combination with inverter-level electrical measurements obtained in WP3. WP4 integrates measured global and diffuse irradiance, greenhouse transmission characteristics, bifacial photovoltaic module behaviour, and module thermal conditions to simulate electrical output under greenhouse-integrated operation. This modelling framework

explicitly captures optical filtering by greenhouse covers, structural shading, and modified thermal environments that are not represented in standard open-field PV yield models.

WP4 simulation results confirm that absolute electrical yield per installed capacity is lower than for open-field PV systems, primarily due to optical transmission losses through greenhouse structures and partial shading effects. Importantly for KPI 2, the modelling demonstrates that these losses are systematic and predictable, rather than indicative of operational instability or performance degradation. When greenhouse-specific optical and thermal effects are incorporated, simulated PV output exhibits low temporal variability and stable operating behaviour over time, consistent with inverter-level electrical measurements reported in WP3.

WP4 further demonstrates that sun-tracking operation significantly improves specific electrical yield (kWh/kWp) in agrivoltaic greenhouse systems by enhancing angular irradiance capture under constrained geometry. Tracking increases the effective interception of both direct and diffuse radiation during low solar angle periods and dynamically redistributes shading across the diurnal cycle. Model outputs show that this results in higher normalized yields relative to fixed PV configurations, even though total incident radiation remains constrained by greenhouse geometry. This provides a mechanistic explanation for the experimentally observed consistency of Final Yield values across REGACE pilot sites with different structural designs and climatic conditions.

Crucially, WP4 modelling establishes that Final Yield (kWh/kWp) remains a robust normalization metric for electrical performance when interpreted relative to effective irradiance capture rather than nominal installed capacity alone. By explicitly linking PV output to time-resolved projection area and irradiance availability, WP4 explains why experimentally measured Final Yield values remain comparable across sites despite differences in latitude, insolation regime, and greenhouse architecture. This directly supports the normalization approach adopted for cross-site comparison of electrical performance.

WP4 also incorporates module temperature modelling, showing that greenhouse-integrated PV modules frequently operate under moderated thermal conditions compared to open-field installations. Reduced exposure to extreme temperature fluctuations and partially buffered thermal environments contribute to stabilizing module efficiency and offset a portion of optical losses. This effect is reflected in the observed consistency of Performance Ratio (PR) values over time within individual sites, as measured in WP3 and synthesized here.

Taken together, WP4 electrical performance modelling provides a physically grounded basis for interpreting reduced absolute electrical yields as a structural characteristic of greenhouse integration rather than as a deficiency of the REGACE system. By establishing clear causal links between greenhouse geometry, tracking strategy, irradiance distribution, thermal behaviour, and PV output, WP4 ensures that KPI 2 conclusions are robust, transferable across sites, and suitable for techno-economic evaluation. Electrical yield is therefore treated as a stable and predictable system component within the integrated Water–Energy–Food framework assessed in this task, rather than as an isolated optimization variable.

KPI 3: Crop Yields and Quality

Crop yield performance was evaluated through the integration of experimentally measured agronomic data collected in greenhouses with PV installations vs without (results elaborated in Deliverable 3.2), and predictive crop growth modelling developed in WP4 (Deliverable 4.2). Yield measurements were collected across multiple REGACE pilot sites and crop cycles, while simulations provided a mechanistic interpretation of observed responses under modified radiation and microclimate conditions.

To enable direct comparison of the effects of PV integration on crop yield, relative yield was defined as the percentage of the yield grown under PV conditions expressed as a percentage of the yield obtained in the reference greenhouse compartments.

Experimental results show that, while crop yield in PV-integrated greenhouses is crop- and site-dependent, it is not inherently limited by photovoltaic integration.

Furthermore, crop quality indicators were evaluated, including growth parameters, nutrient content, and marketability. Overall, no significant differences were observed between crops grown under PV-integrated conditions and those grown in reference greenhouses. WP4 modelling supports this by demonstrating that increased diffuse radiation in PV-integrated greenhouses improves canopy-level light distribution, leading to more uniform photosynthetic activity across leaf layers and reducing stress gradients within the crop canopy. Of note, growth-related parameters seem to be contingent upon whether minimum light requirements were met. This effect was evident at the BOKU, where the lower available light levels limited crop growth, and at the FSC site, where eggplants, characterised by lower light requirements, grew better under PV panels, while tomatoes, which have higher DL requirements, performed better in the reference greenhouse. These results indicate that while PV-induced changes in light quality can enhance light utilisation, they cannot compensate for situations in which total available irradiance falls below crop-specific thresholds.

Across the evaluated pilot sites and crop cycles, a central analytical finding is that crop response to tracking PVs installed within the greenhouse is non-linear with respect to light availability. This is especially true for regions with medium or high insolation and crops with lower light-saturation thresholds. Instead, a more representative indicator of yield outcome under PV panels would be an integration of available irradiance, its diffusivity, and microclimate stabilisation.

KPI 4: Water Consumption

Experimental results from WP3 (Deliverable 3.2) demonstrate that PV integration leads to a reduction in greenhouse water consumption across all REGACE pilot sites, driven by consistent modifications of the internal microclimate, including decreased incoming radiation, lower air and canopy temperatures, and increased relative humidity. These microclimatic changes result in lower evapotranspiration demand and reduced irrigation requirements under PV conditions. However, WP3 experiments also show that reductions in water consumption do not uniformly translate into improvements in water use, as water use efficiency (WUE), as WUE is jointly determined by both water consumption and crop yield. This dependency i

particularly evident in sites where PV-induced shading reduces the DLI below crop-specific threshold, leading to yield penalties that offset the benefits of reduced water use.

WP4 modelling offers a mechanistic explanation for these experimental observations by explicitly resolving radiation transport, greenhouse microclimate dynamics, and crop evapotranspiration processes. Simulations show that the response of evapotranspiration to PV integration depends on whether greenhouse operation is radiation-limited or demand-limited. Under radiation-limited conditions, reductions in net radiation caused by PV panels suppress both evapotranspiration and photosynthetic activity, resulting in proportional decreases in water consumption and biomass accumulation. In such cases, WP4 simulations confirm that evapotranspiration reductions are driven primarily by reduced energy input rather than by beneficial microclimate optimization, explaining why WP3 experiments in BOKU showed neutral or reduced WUE despite lower irrigation demand. Conversely, when radiation levels remain above minimum physiological requirements, WP4 modelling indicates that PV-induced reductions in peak radiation, temperature, and vapor pressure deficit reduce atmospheric evaporative demand without constraining canopy-level photosynthesis. This decoupling of water demand from yield formation is reflected in WP3 measurements from UTH and FSC, where water consumption is reduced while crop yields remain stable, resulting in neutral to positive WUE outcomes.

Overall, the combined WP3 and WP4 results indicate that reduced evapotranspiration is a site-independent physical effect of PV integration, whereas improvements in water-related KPIs are conditional on maintaining adequate light availability. WP4 modelling identified DLI and vapor pressure deficit as key control variables governing the relationship between evapotranspiration reduction and crop productivity. Consequently, PV-integrated greenhouse systems demonstrate the greatest potential from improved water-use efficiency in environments where evapotranspiration is primarily demand-driven, while in radiation-limited contexts, additional operational measures are required to prevent yield penalties.

CO₂ Compensation and Optimisation Analysis

The effectiveness of CO₂ enrichment as a compensatory measure in PV-integrated greenhouse systems is strongly influenced by the prevailing insolation regime, which determines whether crop productivity is primarily constrained by radiation availability or by microclimatic stress. Across the REGACE pilot sites, experimental results (Deliverable 3.2) and modelling outcomes (Deliverable 4.2) consistently show that CO₂ enrichment interacts with PV-induced light reduction in a context-dependent manner.

Under low-insolation conditions (e.g., BOKU, BW), baseline radiation levels are already close to or below crop-specific minimum requirements. PV integration further reduces available light, making radiation the dominant limiting factor for photosynthesis and yield formation. Experimental and modelling results indicate that while CO₂ enrichment can enhance photosynthetic efficacy and vegetative growth, it cannot fully compensate for insufficient DLI when radiation falls below critical thresholds. Consequently, yield responses remain limited and inconsistent.

In medium-insolation environments (e.g., UTH), baseline radiation levels are generally sufficient to support crop growth, and PV integration introduces moderate shading rather than

severe light limitation. Under these conditions, CO₂ enrichment has greater potential to act as a compensatory measure by increasing radiation and supporting carbon assimilation under redistributed light. Experimental results show modest, non-significant trends toward higher yield and increased photosynthetic activity, as well as improvements in vegetative growth and yield quality. Modelling results support these observations, indicating that CO₂ enrichment can be effective when radiation remains above crop-specific thresholds. However, practical constraints related to greenhouse ventilation limit the ability to maintain elevated CO₂ concentrations, reducing the consistency of yield compensation.

In high-insolation environments (e.g., AZS), radiation availability is generally not limiting, and PV integration primarily moderates excessive radiation, temperature, and vapor pressure deficit. Although controlled CO₂ enrichment was not implemented at this site, modelling suggests that under such conditions CO₂ could theoretically enhance radiation use efficiency. In practice, similarly to medium-insolation environments, greenhouse ventilation requirements limit the ability to maintain elevated CO₂ concentrations and reduces the effectiveness of CO₂ enrichment.

Overall, the REGACE results indicate that CO₂ enrichment can contribute positively to crop performance only as a secondary, conditional lever, whose effectiveness depends on maintaining adequate light availability and stable greenhouse microclimate conditions. Consequently, CO₂ enrichment is best interpreted as a supporting agronomic measure that can complement, but not replace, appropriate PV design, radiation management, and climate control strategies in agrivoltaic greenhouses.

Chapter 2: Techno-economic feasibility

The REGACE project was conceived and implemented in alignment with the European Green Deal objectives, prioritizing climate resilience, resource efficiency, and sustainable food–energy system integration. As such, the project was not designed or executed as a commercial deployment, but rather as a scientific validation and proof-of-concept initiative. Pilot installations were implemented in research-oriented greenhouse environments, using non-optimized value chains, first-of-a-kind system configurations, and experimental operational conditions. Consequently, system design, procurement, installation, and operation were not optimized for cost minimization or commercial scalability.

Within this context, the primary objective of the techno-economic assessment is not to demonstrate immediate commercial readiness, but to evaluate whether the observed system performance—across energy production, crop yield stability, and water-use efficiency—indicates credible economic potential when interpreted under realistic future deployment conditions. The analysis therefore focuses on identifying structural indicators of feasibility rather than definitive investment metrics.

Despite the non-commercial nature of the pilot implementations, the results generated within REGACE reveal strong signals of economic viability, particularly in Mediterranean climatic regions, where high solar availability, favorable light conditions, and pronounced water stress amplify the value of integrated agrivoltaic greenhouse solutions. Observed performance trends—including stable and predictable electrical energy generation, maintained crop

productivity under moderated irradiance, and significant reductions in irrigation demand—suggest that the REGACE system has the potential to generate substantial combined value across the energy, agriculture, and water domains.

The techno-economic findings presented in this section should therefore be interpreted as evidence of commercial promise under optimized deployment scenarios, rather than as a final investment-grade assessment. Together, they indicate that agrivoltaic greenhouse systems such as REGACE are well positioned to contribute meaningfully to European Green Deal goals by reducing carbon emissions, conserving water resources, and supporting resilient agricultural production in climate-vulnerable regions.

Technoeconomic feasibility-FSC

Table 2. Key techno-economic input parameters and electricity valuation assumptions used for the FSC techno-economic feasibility analysis.

Category	Parameter	Value	Source
Lifetime of System	Years	25-30 use 20 for calculations	Assumption
Discount rate	%	5-7 first 3 years 0%, after that 1.5 in calculations we take 5% as baseline for conservative consistency	Assumption
Tariff	Electricity €/kWh	0.30 (self- consumption)	D3.2 FSC
Tariff	Electricity €/kWh	0,16 (Scambio sul Posto)	D3.2 FSC
Annual electricity production	kWh/year	4,423	D3.2 FSC
Crop price	€/kg	Site-specific	D3.2
Water cost	€/m ³	Optional	Local

Table 3. Annual operating expenditure (OPEX) assumptions for FSC.

Item	Annual Cost (€)	Source
Maintenance and cleaning	100	D3.2 (BW example)

Tracker servicing	Included	Assumption
CO ₂ supply	Site-specific	Experimental input
Monitoring	Included	Assumption
Total OPEX	100-variable	D3.2

Table 4. Annual benefits (FSC).

Stream	Calculation	Annual Value (€)	Source
Electricity (self-consumption)	4,423 kWh x 0.30 €/kWh (tariff)	1,326.92	Fig 163 pg 217
Electricity (grid-exchange)	4,423 kWh x 0.16 €/kWh (tariff)	707.69	
Crops	Σ (kg × €/kg)		Table 78 pg. 218
Water savings	Δ m ³ × €/m ³	Not monetized	
Total Annual Benefit	Energy + crops (+ water if priced)		

Crop revenues and water savings are reported for contextual comparison but are not monetized in the NPV calculation.

Table 5. Financial outputs reported by FSC

Metric	Result
Payback period (years)	4 years (self con.) 8 years (grid exchange)

Annual ROI (%)	35.47% (self cons) 18.92% (grid exchange)
NPV (€)	Positive

CAPEX Value = 3740

Net Present Value:

Discount rate = 5%

Residual value = 0

Net annual cash flow = 1,326.90 – 100 = € 1,226.90

Present Value factor for annuity = $[1-(1.05)^{-20}] / 0.05 = 12.46$

Present Value of cash flows = 1,226.90 x 12.46 = €15,286

Net Present Value (NPV) = 15,286-3,740 = €11,546

NPV/CAPEX ratio = 3.1x

Lifetime net profit: (1,226.90 x 20) -3,740 = 20,798

Lifetime ROI (undiscounted, 20 years): 20,798/3,740 = 556%

The Net Present Value (NPV) of the agrivoltaic greenhouse PV system was calculated for the FSC pilot using measured and extrapolated project data. The initial investment cost was estimated at approximately €3,740. Annual electricity production was extrapolated to 4,423 kWh/year and valued under a self-consumption scenario at €0.30/kWh, resulting in an annual electricity benefit of €1,326.90. Annual operating expenditure was conservatively estimated at €100/year for maintenance and cleaning.

Assuming a system lifetime of 20 years and a discount rate of 5%, the resulting annual net cash flow of €1,226.90 yields a present value of approximately €15,286. The resulting NPV is therefore approximately €11,546, confirming strong techno-economic feasibility under the evaluated conditions.

Techno-economic Feasibility – Israel

Table 6. Key techno-economic input parameter used in AZS.

Parameter	Value
Annual yield	1,450 kWh/kWp
Electricity price	0.42 €/kWh

CAPEX	3,500 ₺/kWp
OPEX	20 ₺/kWp/year
Lifetime	25 years
Financing	Equity

Annual revenue: $1,450 \times 0.42 = 609$ ₺ / year

Net annual operating income: $609 - 20 = 589$ ₺ / year

Payback period: $3,500 \div 589 \approx 5.9$ years

Lifetime performance:

Table 7. Aggregated lifetime performance metrics for AZS.

Item	Value
Lifetime energy	36,250 kWh
Lifetime OPEX	500 ₺
Total lifetime cost	4,000 ₺
Cumulative net revenue	14,725 ₺

Levelized cost of energy (LCOE): $4,000 \div 36,250 = 0.11$ ₺/kWh

Table 8. Comparison of key normalized techno-economic performance indicators for the REGACE system in AZS and FSC.

Metric	AZS	FSC
Annual yield (kWh/kWp)	1,450	1,350
Electricity price (₺/kWh)	0.42	0.5

Net annual income (₪)	589	655
Payback (years)	5.9	5.3
LCOE (₪/kWh)	0.11	0.118

A techno-economic feasibility assessment conducted for a REGACE agrivoltaic PV system integrated into a commercial greenhouse in AZS is based on a standardized 1kWp installed capacity, allowing scalability to full greenhouse deployment.

Each dunam (1,000 m²) of greenhouse area is assumed to accommodate approximately 50 kWp of installed PV capacity, consistent with agrivoltaic roof integration practices.

The total turn-key system cost is estimated at 3,500 ₪/kWp, while the underlying system cost is approximately 2,350 ₪/kWp, reflecting pilot-scale procurement and installation. The cost breakdown includes PV modules (660 ₪/kWp), inverter (340 ₪/kWp), installation labor (600 ₪/kWp), mechanical equipment (200 ₪/kWp), electrical equipment (400 ₪/kWp), and monitoring/computing systems (50 ₪/kWp).

Annual operation and maintenance costs are conservatively estimated at 20 ₪/kWp/year, and system lifetime is assumed to be 25 years. The analysis assumes equity financing and excludes financing costs.

Energy performance and revenues

Annual energy production is estimated at 1,450 kWh/kWp/year, consistent with local solar resource conditions in Israel. Electricity is valued at 0.42 ₪/kWh, representative of self-consumption or net billing scenarios.

This results in:

- Annual electricity revenue of 609 ₪/kWp
- Net annual operating income of 589 ₪/kWp
- Present value factor for annuity (25 years at 5%): $PVF = [1 - (1 + 0.05)^{-25}] / 0.05 = 14.09$
- Present value of cash flows: $589 \times 14.09 = 8,297$ ₪
- $NPV = 8,297 - 3,500 = 4,797$ ₪ per kWp
- Lifetime ROI: $(\text{lifetime revenue} - \text{lifetime cost}) / \text{CAPEX} = (15,225 - 3,500) / 3,500 = 321\%$

The Net Present Value (NPV) of the REGACE agrivoltaic greenhouse PV system was calculated for the AZS installation using a discount rate of 5% and a system lifetime of 25 years. Based on an initial investment cost of 3,500 ₪/kWp, annual electricity production of 1,450 kWh/kWp, an electricity value of 0.42 ₪/kWh, and annual operating expenditure of 20 ₪/kWp, the resulting net annual cash flow amounts to 589 ₪/kWp.

Applying the standard annuity discount factor for 25 years at 5%, the present value of operating cash flows is approximately 8,297 ₪/kWp, resulting in a positive NPV of approximately 4,800 ₪/kWp. This indicates strong economic attractiveness and resilience to moderate variations in tariff or operating assumptions.

The corresponding lifetime return on investment (ROI) is approximately 320%, with a simple payback period of approximately 5.9 years. These results confirm robust techno-economic feasibility of the REGACE agrivoltaic greenhouse system under Israeli climatic and market conditions, even without monetizing agricultural co-benefits such as yield stability, water savings, or microclimate regulation.

Economic performance indicators

The resulting simple payback period is approximately 5.9 years, which is considered highly attractive for agrivoltaic greenhouse systems.

Over a 25-year lifetime:

- Total energy production reaches 36,250 kWh
- Total lifetime cost (CAPEX + OPEX) amounts to 4,000 ₪
- Cumulative net revenue reaches 14,725 ₪

The calculated Levelized Cost of Electricity (LCOE) is 0.11 ₪/kWh, substantially below prevailing electricity prices, indicating strong economic resilience.

Comparative context

When compared to an equivalent REGACE system in at FSC, the AZS installation benefits from higher solar yield, while FSC benefits from higher electricity tariffs. Both systems demonstrate payback periods below six years and LCOE values well below market prices, confirming robust techno-economic feasibility across Mediterranean climates.

Importantly, this assessment does not monetize agricultural co-benefits, including crop yield stability, water savings, microclimate buffering, and shading optimization. These effects represent additional upside potential and further strengthen the business case for agrivoltaic greenhouse deployment.

Summary Table

Table 9. Summary of techno-economic feasibility outcomes for the REGACE system at FSC and AZS

Metric	FSC	AZS
CAPEX	€3,740	3,500₪
Annual net CF	€1,226.9	589₪

Lifetime	20 yrs	25 yrs
Discount rate	5%	5%
NPV	€11,546	4,797€
NPV / CAPEX	3.1×	1.37×
Annual ROI	33–35%	17%
Lifetime ROI	556%	320%

The observed differences in financial performance between FSC and AZS arise from two primary factors:

1. Electricity pricing and market structure. The most influential driver of financial divergence is the electricity valuation regime:
 - In Italy (FSC), electricity is valued at up to €0.30/kWh under self-consumption and €0.16/kWh under grid exchange, resulting in high annual revenue per kWh.
 - In Israel (AZS), electricity is valued at approximately ≈0.42/kWh, which is competitive but lower on a purchasing-power-adjusted basis relative to Italy.

As a result, the FSC installation exhibits:

- higher annual net cash flow,
- shorter payback periods,
- and significantly higher NPV per unit of installed capacity.

Importantly, this difference reflects market conditions, not differences in system efficiency or reliability.

2. Israel benefits from a higher solar resource, with annual yields of approximately 1,450 kWh/kWp, compared to 1,350 kWh/kWp in Italy. However, the Italian tariff structure more than compensates for the slightly lower yield.

Limitations of Techno-Economic Feasibility Assessment at the German Pilot Sites

Techno-economic feasibility within WP5 is assessed only for pilot installations that meet minimum validity conditions for economic interpretation namely:

- Stable and continuous system operation
- Representative greenhouse geometry for commercial production
- Scalable installation and component sizing
- Data continuity to support annualized energy and cost calculations.

Feasibility conclusions are drawn only where system configuration and data quality permit meaningful extrapolation. Consequently, not all pilot installations are suitable for inclusion in techno-economic evaluation, even if they are scientifically valuable for validation and robustness testing.

At the UBER site, the greenhouse structure itself introduced significant additional shading, independent of the PV system. The frame geometry shaded a substantial fraction of the cultivated and PV-covered area. Due to these constraints, the PV panels ultimately had to be installed very close to the greenhouse roof, which further amplified the effects of structural shading rather than mitigating them. This led to reduced effective irradiance on PV modules, non-uniform shading patterns across PV strings, and systematic underperformance in electrical yield. This configuration is not representative of commercial agrivoltaic greenhouses, where structural shading is minimized through optimized frame design. Nevertheless, the UBER site provided valuable insights by stress-testing system behavior under extreme shading conditions, revealing inverter response to partial shading, and informing future greenhouse design constraints to avoid non-commercial geometries.

In BOKU, the primary limitation arose from the greenhouse envelope itself. The structure is covered by a double-layer polycarbonate roof, which allows only approximately 20-25% light transmission into the greenhouse, unlike commercial agrivoltaic greenhouses, which typically employ high-transmittance envelop materials. This inherently low baseline light availability significantly constrained both crop-level irradiance and PV performance, independent of the REGACE system configuration. While the site was valuable for controlled research under low-light conditions, it did not meet the representativeness criteria required for techno-economic feasibility assessment.

At the BW site, the primary limitation was related to data continuity rather than greenhouse geometry or system design. Persistent internet connectivity issues resulted in intermittent data transmission, leading to gaps in monitoring and incomplete datasets for electrical system performance. Although on-site system operation continued, the inconsistent availability of remote monitoring data limited the robustness of long-term performance aggregation and economic analysis.

Furthermore, at the BW site, installation took approximately twice as long as planned, primarily due to:

- insufficient local staffing with experience in PV tracker integration
- the need to bring in a specialist installer from another region
- on-site adaptation of prototype components

Deliverable D3.2 identifies staffing and process inefficiencies as a major contributor to elevated installation costs. These conditions are characteristic of first-of-a-kind pilot deployments, not commercial roll-outs.

In addressing the elevated CAPEX due to pilot-scale procurement, deliverable D3.2 reports that components were procured at small scale, shipping costs were high due to non-bulk logistics, and custom holders, actuators and control elements were fabricated specifically for the pilot.

As a result, prototype CAPEX was significantly higher than expected for a market-ready system. D3.2 estimates that a commercialized system would reduce total system cost to approximately €9,494.69, compared to substantially higher prototype costs.

A detailed cost-benefit analysis for BW is provided, and it concludes that the difference between cost and gain is small, roughly 4%. The annual gain is €3,240 / year, while the cost is €3,363 / year. Although the system did not compensate economically under the stated assumptions, feasibility could be achieved through cost optimization and commercial deployment. However, because the BW installation reflects prototype inefficiencies rather than mature system economics, it was not treated as representative for techno-economic feasibility conclusions in WP5.

Despite these constraints, the BW site:

- validated system operation in low-to-moderate insolation environments
- quantified yield-loss penalties under realistic northern European condition
- identified concrete cost-reduction levers (staffing, inverter sizing, component standardization)

These insights are crucial for future commercialization, even though the site is excluded from final feasibility metrics.

It is important to emphasize that installations were small-scale pilots, procurement was not wholesale, logistics and installation processes were first-time and non-optimized, and the agrivoltaics value chain was not yet mature when experiments began.

Installation staff costs can be reduced significantly in subsequent deployments, inverter prices have already decreased since pilot installation, and standardized components would substantially reduce CAPEX in commercial systems.

Feasibility of the Agrivoltaic Greenhouse System from a European Green Deal and Carbon Footprint Perspective

The REGACE agrivoltaics greenhouse system directly aligns with the objectives of the European Greenhouse Deal which targets climate neutrality by 2050 through decarbonization of energy systems, improved resource efficiency, and sustainable food production. By integrating bifacial photovoltaic generation within protected horticultural environments, the system enables simultaneous renewable electricity production and food cultivation on the same land footprint, thereby addressing both energy transition and land-use efficiency priorities outlined by the European Commission.

Agrivoltaics are explicitly recognized as a key enabling approach for reconciling renewable energy deployment with agricultural productivity and biodiversity preservation, particularly in regions where land availability and competing land uses present structural constraints.

From a carbon footprint perspective, the REGACE system contributes to emissions reduction through on-site renewable energy generation, offsetting grid-supplied electricity that is partially derived from fossil fuel sources. Life-cycle assessment studies consistently demonstrate that PV systems achieve net positive carbon balances within 1-3 years of operation

depending on technology and location, after which electricity generation is effectively low-carbon for the remainder of the system lifetime.

Bifacial PV modules, as deployed in REGACE, further improve lifecycle performance by increasing energy yield per installed area, thereby reducing embodied carbon per kWh generated relative to monofacial systems. This directly enhances the system's contribution to greenhouse gas reduction targets under EU climate policy.

In addition to energy-related emissions reductions, the agrivoltaics greenhouse configuration offers system-level carbon efficiency benefits by co-optimizing agricultural inputs and environmental control. WP3 measurements indicate that controlled microclimate conditions and adaptive shading can reduce abiotic stress on crops, potentially lowering resource intensity (e.g. irrigation demand and climate control energy) per unit of yield, relative to conventional greenhouse systems.

Such integrated systems align with the Green Deal's "Farm to Fork" strategy which prioritizes reduced environmental footprints across food value chains, including lower energy use, reduced emissions intensity, and improved resource efficiency per unit of production.

Beyond mitigation, the REGACE system supports climate adaptation objectives, another core pillar of the European Green Deal. The partial shading provided by the PV structure contributes to moderated temperature extremes and reduced evapotranspiration, enhancing crop resilience under increasing heat stress and water scarcity conditions documented across Southern and Central Europe.

This dual mitigation-adaptation function strengthens the long-term feasibility of the system, particularly under projected climate scenarios that challenge conventional agricultural production models.

Taken together, the REGACE agrivoltaics greenhouse system demonstrates high policy feasibility under the EU Green Deal criteria by:

- Reducing lifecycle greenhouse gas emissions through renewable electricity generation
- Increasing land-use efficiency via co-location of energy and food production
- Supporting the climate-resilient agricultural practices
- Contributing to decarbonization without displacing productive agricultural land

Importantly, the system's feasibility is reinforced by its replicability across climatic zones (as evaluated in WP5) and its compatibility with existing EU regulatory frameworks for renewable energy and sustainable agriculture. These characteristics position the REGACE system as scalable, Green-Deal-aligned solution suitable for broader deployment beyond the pilot sites, and as a commercially viable solution.

Chapter 3: End-User Interview-Based Evaluation

In addition to quantitative KPI assessment, qualitative feedback was collected from the two farmers directly hosting REGACE pilot installations at FSC and Bio-Gärtnerei Watzkendorf (Germany) through a semi-structured interview at the conclusion of the agricultural activities. This provided valuable insight into system usability, operational burden, perceived maturity, and adoption readiness from a real-world farming perspective.

Usability and Day-to-Day Operation

Both farmers confirmed that the REGACE system is practically usable in daily greenhouse operations and does not interfere with routine agricultural activities. Any high level of interaction reported during the trial period was explicitly attributed to the experimental nature of the project, including frequent sensor relocation, software testing, and support of multiple measurement protocols. According to the farmers, such activities would not be expected under commercial deployment conditions. Importantly, neither farmer reported an increase in daily workload as a result of the system, indicating a low operational burden.

The REGACE control software was described as simple and easy to use, and that no specialized expertise was required for basic interaction with the system, reinforcing its accessibility for non-technical users.

Reliability and Robustness

Overall system behaviour was described as stable, with no disruptive failures affecting crop management. Some technical issues were reported during the pilot phase, including intermittent internet connectivity and isolated component failures (an actuator exposed to moisture). These issues were considered manageable and typical of pilot-scale research installation. Over the two-year operation period, the PV structures demonstrated mechanical robustness, withstanding strong winds and greenhouse ventilation conditions without damage.

Concerns regarding potential vulnerability under extreme weather conditions were expressed initially, particularly related to open greenhouse windows during high winds, but these concerns were not borne out in practice. The system did not interfere with standard crop management activities.

Maintenance Requirements

Both farmers reported that routine maintenance requirements were minimal. The primary recurring task was cleaning the PV panels to remove dust accumulation, which was noted to be more pronounced in soil-based cultivation systems than in growbag-based greenhouses. This task did not require specialized personnel. Periodic checks of mechanical components and software monitoring and troubleshooting were handled by REGACE partners.

Installation Experience and Replicability

Feedback on installation differed between the two sites. At FSC, installation was described as challenging due to the system being deployed for the first time, resulting in a learning curve and the need for adjustment, including replacement of incorrectly supplied PV panels. These lessons were incorporated into subsequent deployments, and no comparable difficulties were reported at the German pilot site, where installation was described as smooth, and the complication was having to bring in a specialist installers and having to adapt some components to local requirements. This contrast indicates a clear learning and optimization trajectory.

Both farmers indicated that installation would be easier in new greenhouse constructions than in retrofitted structures. They also highlighted potential barriers related to the availability of electricians with the required specialized knowledge in certain regions.

Yield Performance and Adoption Conditions

Crop yield was identified by both farmers as the primary determinant for future adoption. While the system was regarded as highly interesting and promising, both operators indicated that broader commercial uptake would depend on achieving higher yields under agrivoltaic operation. One farmer explicitly stated that a 5-10% improvement in yield would significantly change the economic case for adoption.

The farmers suggested that yield performance could be improved through more advanced, crop-specific PV strategies aligned with DLI requirements. Additionally, one farmer emphasized that most growers are not familiar with crop-specific DLI values and recommended that REGACE integrate a built-in crop library with predefined DLI targets and recommended tracking programmes to lower the knowledge barrier for growers.

Importantly, this functionality already exists within the REGACE control software. As documented in the REGACE Software Development Report, real-time light intensity data are continuously integrated to calculate cumulative daily light exposure and compared against predefined DLI thresholds, enabling dynamic PV panel adjustment to increase light availability when DLI is below target levels or introduce shading when DLI is exceeded, thereby balancing crop requirements with energy production objectives. While this functionality was actively used at UTH and AZS, it was not fully deployed in operational mode at the two end-user farms assessed here. The farmers' recommendation therefore reflects a deployment and standardization consideration rather than a missing system capability, and future commercial roll-out will benefit from systemic activation of this feature, including the integration of crop libraries, to strengthen the yield-driven value proposition of the regace system.

Regulatory and Contextual Factors

Both farmers highlighted that regulatory and infrastructural conditions play a significant role in feasibility and economic viability. Grid-connection requirements and bureaucracy were identified as potential barriers, independent of the REGARCE technology itself. For example, at the German pilot site, grid connection would have required upgrading cabling that was not economically justified at the pilot scale, leading to local use of generated electricity for greenhouse water heating instead.

Both farmers had prior experience with photovoltaic systems on roof or in open-field configurations but stressed that these systems are fundamentally different from the REGACE agrivoltaic greenhouse concept and therefore not directly comparable.

Overall Assessment

Overall, end-user feedback indicates a high level of interest and acceptance of the REGACE concept, driven by its low operational burden, non-intrusive integration into agricultural workflows, ease of use, and perceived long-term potential. The system was perceived as stable and reliable under real greenhouse conditions, with challenges largely attributable to first-of-a-kind deployment effects and external contextual factors rather than inherent design limitations. At the same time, the feedback clearly underscores that crop yield performance remains the decisive factor for commercial adoption, with further value expected from the systemic activation of existing crop-specific, DLI-based strategies, during commercial rollout.

The results point to a system that is technologically mature and operationally feasible, with remaining barriers to adoption mainly linked to yield optimization, deployment standardization, and regulatory or infrastructural conditions rather than usability or system reliability.

Implications for Commercialisation and Future Development

The end-user evaluation indicates that REGACE has reached a level of operational maturity suitable for early commercialisation pathways, provided that remaining agronomic and deployment challenges are addressed. From a user perspective, the primary value proposition lies in the system's low operational burden, mechanical robustness, and seamless integration into existing greenhouse workflows.

To unlock broader market adoption, future development should prioritise:

- (i) optimisation of crop-specific PV tracking strategies to safeguard or enhance yields,
- (ii) integration of user-oriented intelligence such as built-in crop libraries with predefined DLI targets and recommended control programmes, and
- (iii) further standardisation of installation protocols to reduce first-deployment friction.

External factors such as regional grid-connection requirements and regulatory frameworks should be treated as site-specific boundary conditions within commercial rollout strategies rather than technological limitations. Addressing these points will position REGACE for transition from pilot-scale validation to scalable, economically viable greenhouse agrivoltaic deployment in subsequent exploitation and replication activities (WP6/WP7).

Conclusion

Deliverable 5.3 confirms that the REGACE agrivoltaic greenhouse system achieves stable and interpretable performance across energy, agriculture, and water domains when evaluated using performance-based indicators consistent with the objectives. Static geometric metrics are shown to be inadequate, while a dynamic, radiation-resolved definition of effective GCR provides a robust foundation for cross-site comparison and normalization.

Electrical performance under greenhouse-integrated operation is structurally constrained but reliable, with sun-tracking improving normalized yield and stabilizing performance ratios. Although absolute electrical yields are lower than in open-field PV systems, they remain sufficiently consistent to support techno-economic evaluation within an integrated WEF framework.

Agronomic assessment confirms that PV integration does not inherently compromise crop yield or quality. Crop responses depend on maintaining crop-specific minimum light requirements, with positive effects arising from diffuse radiation redistribution and moderated microclimate conditions where adequate irradiance is available. Water consumption is consistently reduced due to lower evapotranspiration demand, with water-use efficiency improving in demand-driven environments.

Techno-economic analysis for representative Mediterranean pilot sites demonstrates strong economic potential, characterized by positive net present value, short payback periods, and low levelized cost of electricity. Excluded pilot sites are limited by non-representative geometry, prototype-scale inefficiencies, or data constraints rather than intrinsic system limitations, and provide guidance for future optimization.

End-user evaluation indicates high acceptance of the REGACE concept, minimal operational burden, and perceived system stability. Remaining barriers to adoption relate primarily to yield optimization, deployment standardization, and external regulatory or infrastructural conditions. Overall, REGACE is concluded to be technologically mature, operationally feasible, and to demonstrate credible techno-economic promise, particularly in Mediterranean and water-stressed regions, with strong alignment to European Green Deal objectives and clear potential for future commercial deployment.