5 DS ANALYSIS AND AI SCENARIOS FOR DS2B IN GREECE

5.1 Context and challenges

The second Greek pilot site, DS2B, is located in Potamia on Tinos Island and is represented by the **Tinos Ecolodge, an off-the-grid eco-tourism facility**. The Ecolodge integrates sustainable practices across all resource flows, including rainwater harvesting, greywater recycling, composting, organic farming, and renewable energy supply. This autonomous system provides a model for sustainable tourism infrastructure in remote and insular Mediterranean contexts, where water scarcity, soil degradation, and high energy costs are pressing challenges.

By combining nature-based and bioeconomy solutions, the Tinos Ecolodge contributes to the WEFE Nexus through water reuse for irrigation, renewable energy generation, organic food production, and the restoration of local ecosystems. Its demonstration value is particularly relevant for promoting sustainable tourism on small islands.

5.2 Top 3 prioritised solutions

During the workshop held in Tinos on 24 June 2023, stakeholders applied the SureNexus MCA tool to evaluate a wide range of NBS and BES. The results show that three solutions scored above the prioritisation threshold of 50, reflecting local priorities for water security, ecosystem resilience, and climate adaptation:

Biochar application was identified as the top-ranked solution. Biochar is a stable, carbon-rich material produced by heating biomass (such as crop residues or pruning waste) in low-oxygen conditions (pyrolysis). When applied to soils, it can improve water retention and fertility, enhance microbial activity, and lock carbon in the ground for long periods, contributing to climate-change mitigation.

Subsurface rainwater harvesting was selected as the second priority. By enabling storage of seasonal rainfall underground, this solution reduces evaporation losses and provides a complementary freshwater source to meet agricultural and domestic needs.

Conservation agriculture reflects its high contribution to soil health, erosion control, and improved water retention. Stakeholders recognised its potential to sustain agricultural productivity while reducing chemical inputs and preserving biodiversity.

For Tinos Ecolodge, considering the importance of soil organic matter and the complementary effects of intercropping on soil fertility, microclimate regulation, and biomass production, an **agroforestry practice based on olive trees combined with mixed legumes and grasses as intercropping species** was selected as a suitable conservation-agriculture approach grounded in a nature-based solution. Agroforestry enhances soil organic matter through continuous biomass inputs, improves water retention, and supports nutrient cycling, while the combination of tree and crop layers increases overall system productivity.

In addition, the biomass generated can be valorized locally, providing a **supplementary renewable energy source** for the Ecolodge and further reinforcing the self-sufficiency of the off-grid system. This integrated approach strengthens the resilience of the agroecosystem and aligns with the WEFE Nexus goals of improving soil health, optimizing water reuse, and promoting low-carbon energy solutions.

However, considering the critical importance of water availability for agriculture and for tourism—particularly in insular environments where freshwater resources are extremely limited—we extend the **analysis of subsurface rainwater harvesting** to encompass a range of techniques inspired by nature-based solutions. These approaches include variations of underground infiltration, including roof and surface rainwater harvesting. soil-moisture conservation practices, fog and residential water harvesting and enhanced groundwater recharge systems, all designed to increase water retention in the landscape and improve the resilience of agroecosystems under drought-prone Mediterranean conditions.

By **comparing different harvesting strategies**, the study aims to identify the most efficient, low-impact methods for capturing, storing, and reusing rainwater in support of sustainable agricultural production on islands such as Tinos.

While desalination provides reliability and independence from rainfall, agroforestry can enhance soil moisture retention and biodiversity, and rainwater harvesting can reduce pressure on centralized water systems and increase household self-sufficiency during peak tourist demand.

Together, these solutions illustrate a portfolio approach: solar desalination ensures baseline supply; salt recovery minimizes waste and creates circular value; agroforestry reinforces ecosystem services; and rainwater harvesting enhances local resilience. This integrated strategy aligns with EU climate adaptation goals and offers a replicable model for other Mediterranean islands facing similar sustainability challenges.

5.3 AI scenario results for Water Harvesting Solutions

First, we conducted a **comparative analysis of fog harvesting, rainwater harvesting, and groundwater extraction (**Figure 21), normalizing all results on a per-hectare basis. This initial assessment reveals a clear hierarchy in the resource efficiency of the three water-sourcing strategies:

Rainwater Harvesting (RWH) as the Optimal Solution: RWH emerges as the superior WEFE Nexus technology. It matches the high-water productivity of the groundwater well (approx 4.1 m^3/ha-month) but does so with zero operational energy consumption and zero GHG emissions. It effectively decouples water security from energy dependency.

The "Energy Cost" of Groundwater Well: While the Groundwater Well delivers the same high volume of water as RWH, it imposes a significant parasitic load on the energy system, consuming approximately 2.8 kWh/ha-month and emitting 0.8 $kgCO_2e$/ha-month. This highlights a major trade-off: relying on groundwater well ties water security directly to energy costs and carbon footprint, whereas RWH does not.

Fog Harvesting as a Supplementary Niche: Fog Harvesting shares the sustainability profile of RWH (zero energy, zero GHG), but its specific yield is significantly lower (approx 1.2 m^3/ha-month). With a **yield approximately 70% lower** than the other two methods, Fog Harvesting is best characterized not as a primary water source, but as a supplementary, passive ecological solution for areas where active collection infrastructure is not feasible.

From a Nexus perspective, Rainwater Harvesting represents the most efficient investment, maximizing water yield without incurring the energy penalties associated with Groundwater extraction or the volume limitations of Fog Harvesting.

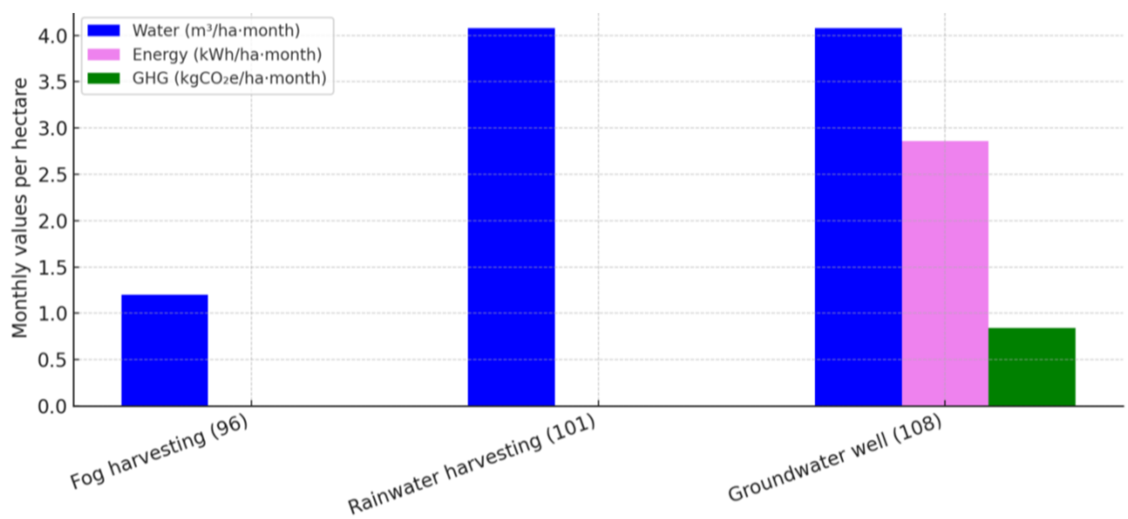

FIGURE 21. COMPARATIVE ANALYSIS OF FOG, RAINWATER HARVESTING AND GROUNDWATER WELL, ON A 2.5 HA BASIS NORMALIZATION.

The **analysis of the five water-management scenarios (S3 to S7) at Tinos Ecolodge** provides a detailed comparison of how the lodge integrates multiple water sources and treatment methods to balance water availability, energy demand, and carbon footprint. In this case, to normalize the results, we make a **comparison on a 500 m2 comparable harvesting surface for all solutions**. This area was selected because is the real harvest catchemt area that is used by Tinos Ecolodge.

The results shown in Figure 22, Figure 23 and Figure 24 establish a clear hierarchy of sustainability and demonstrate how the project successfully combines environmental performance with opportunities for more resilient and economically viable resource management.

Rainwater harvesting (S3) emerges as the most efficient and sustainable option, supplying approximately 10 m³ of water per month with zero energy consumption and zero GHG emissions. This scenario represents an ideal Nexus configuration in which water provision is fully decoupled from energy use, allowing the Ecolodge to secure a baseline water supply without operational costs or carbon impacts. Its simplicity and low-impact nature make it an excellent fit for decentralized systems and eco-tourism operations.

The **groundwater well scenario (S4)** delivers a similar water volume but introduces moderate energy use (7–8 kWh/month) and associated emissions (2–3 kg CO_2e/month). This reveals the energy intensity of water extraction and the direct dependency between groundwater availability, electricity consumption, and the carbon footprint. Such reliance may become problematic in small island environments where aquifers are vulnerable to depletion and saline intrusion.

The **subsurface rainwater harvesting scenario** (S5) also performs well, providing around 9 m³ of water with negligible energy use and no measurable GHG emissions. Subsurface rainwater harvesting yields slightly less recoverable water compared to residential rainwater harvesting (S3) because **a portion of the captured water is naturally lost or redistributed within the soil matrix before it becomes available for extraction or reuse**. Unlike rooftop or hard-surface residential systems, where nearly all rainfall can be directed into a storage tank with minimal losses, subsurface systems interact directly with the soil and therefore undergo several hydrological processes that reduce the final volume of water that can be collected. In this case, the lower water yield is explained by the following mechanisms:

i. **Infiltration and Percolation Losses**. Water entering a subsurface system infiltrates the soil and may percolate beyond the root zone or storage zone, becoming part of deeper groundwater layers. Although this supports long-term aquifer recharge, it reduces the short-term volume available for direct use.
ii. **Soil Moisture Retention**. A fraction of the harvested water remains stored as soil moisture, bound to soil particles through capillary forces. This moisture enhances plant growth and ecosystem health, but it is not extractable as a direct water supply.
iii. **Lateral Movement and Subsurface Flow**. Depending on the soil structure and slope, a portion of infiltrated water may move laterally, contributing to slow interflow rather than accumulating in the designated storage area.
iv. **Evaporation from the Upper Soil Layer**. Although much lower than evaporation from an open lagoon, some water is still lost through soil-surface evaporation, especially in shallow infiltration trenches or during dry, windy conditions typical of Mediterranean islands.
v. **Hydraulic Inefficiencies**. Subsurface systems require water to saturate part of the soil profile before effective storage begins. Initial wetting reduces the amount of water that can be recovered during early rainfall events.

As a passive underground treatment or recharge system, it recycles water for irrigation or ecosystem support without increasing energy demand. This strongly reinforces the Food and Ecosystem dimensions of the WEFE Nexus, contributing to soil moisture, vegetation health, and local ecological stability.

The **lagoon scenario (s6),** when **evaporation losses** are accounted for, results in a net negative water balance (~–7 m^3/month). Although lagoon systems provide ecological benefits and low-energy wastewater treatment, the trade-off in a Mediterranean island context is significant: valuable water is lost to the atmosphere. Specially with the scenarious of continuos increasing of temperature for the Mediterranean area, this confirms that open-surface treatment systems may not be viable under increasing drought pressure and should be reconsidered for arid and semi-arid environments.

Finally, the **combined system (s7)**—integrating rainwater harvesting with groundwater extraction—achieves the highest water output, approximately 20 m^3 per month. Notably, it does so without increasing energy or GHG levels beyond those of the well-only scenario. This demonstrates a strong synergy within the Nexus: the passive, zero-carbon contribution of rainwater harvesting effectively offsets the environmental costs of groundwater pumping. As a result, the combined configuration offers a more resilient and balanced water portfolio, making it a strategic option when maximizing water security is the primary objective.

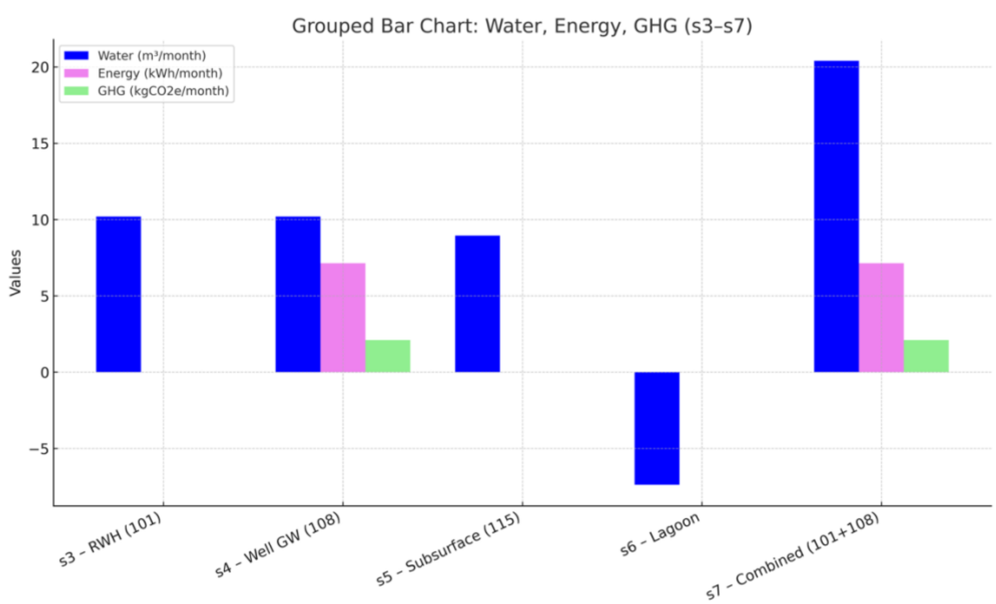

FIGURE 22. WATER HARVESTING AND SOURCING TECHNOLOGIES

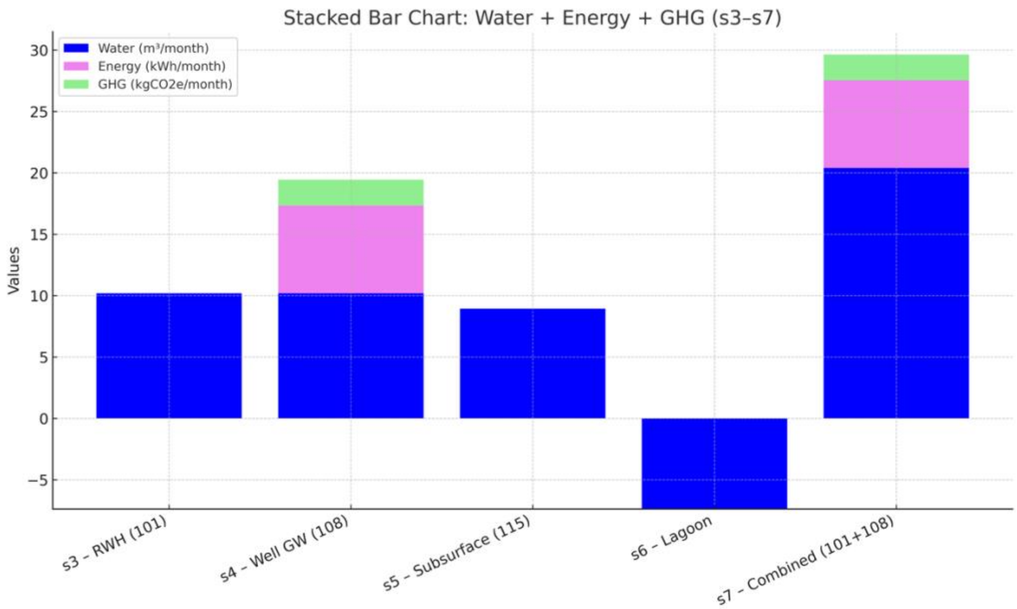

FIGURE 23. STACKED BAR COMPÀRING THE WATER HARVESTING AND SOURCING TECHNOLOGIES TESTED.

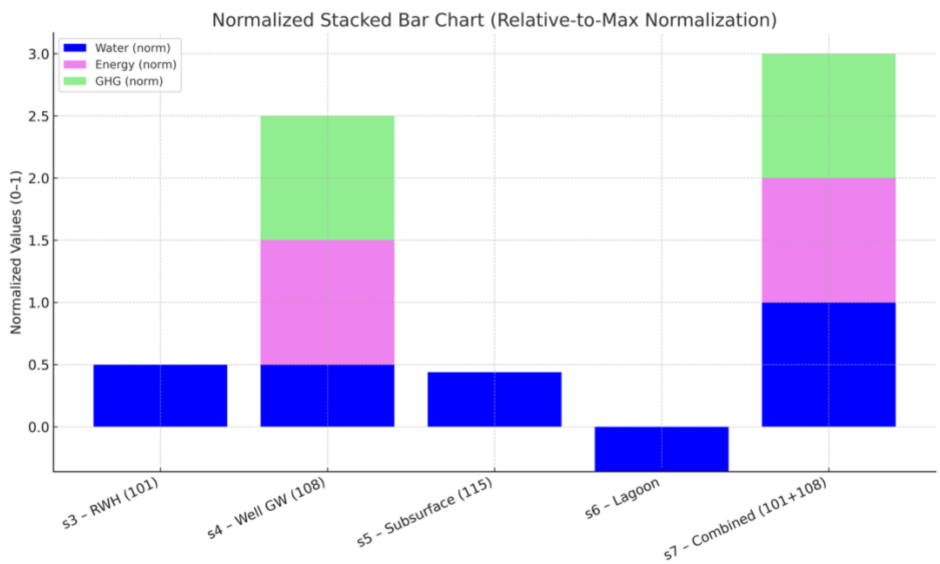

FIGURE 24. STACKED BAR COMPARING THE WATER HARVESTING AND SOURCING TECHNOLOGIES TESTED WITH A RELATIVE TO MAX NORMALIZATION.

Overall, the analysis shows that **rainwater harvesting systems (S3 and S5) should be prioritized due to their superior environmental performance and low operational cost**, while the combined system (s7) provides the most robust supply when larger volumes are needed. In contrast, the lagoon scenario (s6) should be excluded from future planning because of its substantial evaporation-driven losses.

Together, these findings validate the broader project goal of aligning environmental sustainability with innovative water management opportunities for island communities.

Error! Reference source not found. presents the **MCDA scoring for the four water-harvesting and reuse scenarios** (S3–S7)**, comparing their performance across three individual criteria: Water availability, Energy consumption, and GHG emissions.** The visualization highlights the strong contrast between low-impact nature-based systems and more energy-dependent alternatives.

Rainwater harvesting (S3) and subsurface harvesting (S5) achieve the highest scores, shown in bright green, across Energy and GHG criteria because they operate without electricity and produce no emissions. Both scenarios also perform well in Water, making them the most environmentally efficient strategies. **Groundwater extraction** (S4) scores lower due to its dependency on electricity for pumping, which increases both energy use and emissions, reflected by yellow and red cells in the Energy and GHG columns.

The lagoon scenario (S6) reveals a critical trade-off**: while its Energy and GHG performance is excellent (green),** the negative water balance caused by evaporation produces a very low Water score (orange–red). **This confirms that open-surface water systems may significantly reduce usable water volumes in drought-prone regions with high temperatures. While the lagoon supports biodiversity and aesthetics (key for eco-tourism), it acts as a water sink. Nexus planning must account for this loss in the overall water budget.**

In contrast, the **combined scenario (S7)** maximizes water availability, obtaining the highest Water score, but exhibits lower sustainability in Energy and GHG due to reliance on groundwater pumping.

Overall, Figure 25 shows that nature-based and passive systems (S3 and S5) achieve the best environmental performance, while mixed systems (S7) increase water security at the cost of higher operational impacts.

Error! Reference source not found. applies weighting schemes (Balanced, Environmental, and Water Priority) to the MCDA results, providing an integrated sustainability ranking of the scenarios. The results illustrate how different policy priorities influence the decision-making process while maintaining consistent trends.

Under **Balanced weighting, rainwater harvesting (S3) and subsurface harvesting (s5) emerge as the preferred solutions**, reflecting their excellent environmental performance and moderate water contributions. These systems obtain the highest composite scores, particularly under Environmental weighting, where their zero-emission, zero-energy characteristics dominate the scoring.

The lagoon scenario (S6) improves under Environmental weighting due to its very low energy and GHG footprint, but its poor water performance prevents it from becoming a top-ranked option. Groundwater extraction (S4) maintains intermediate scores across all weightings, indicating that while it provides stable water output, its energy dependence limits its sustainability.

Under Water Priority weighting, the combined system (S7) becomes the leading option with the highest score, confirming that it is the best strategy for maximizing total water availability. However, its lower environmental performance remains evident, reinforcing that increased water supply comes at the cost of higher energy use and GHG emissions.

Overall, Error! Reference source not found. **demonstrates that S3 and S5 dominate under environmental criteria, while S7 becomes the optimal solution when water quantity is the priority. These results clearly reveal the trade-offs and synergies within the WEFE Nexus and support informed, context-dependent decision-making for island water management.**

Social & Economic Integration. Local residents and tourists often view passive technologies (rainwater, subsurface reuse) as non-intrusive and responsible. The "economic opportunities" arise from combined solution (S7). By securing a larger volume of water (~20 m3) efficiently, the lodge can support more guests or extended seasons without incurring prohibitive energy costs, directly boosting business viability.

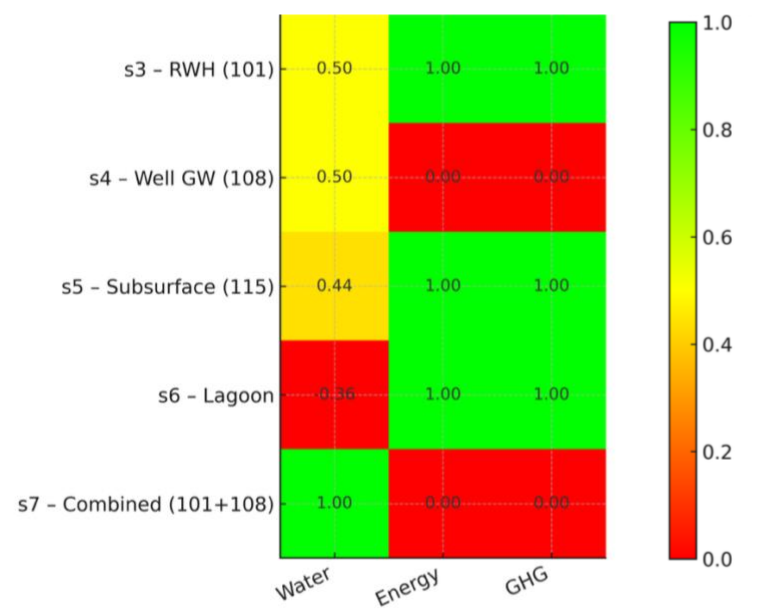

FIGURE 25. MCDA HEATMAP FOR S3 TO S7 WATER HARVESTING SOLUTIONS.

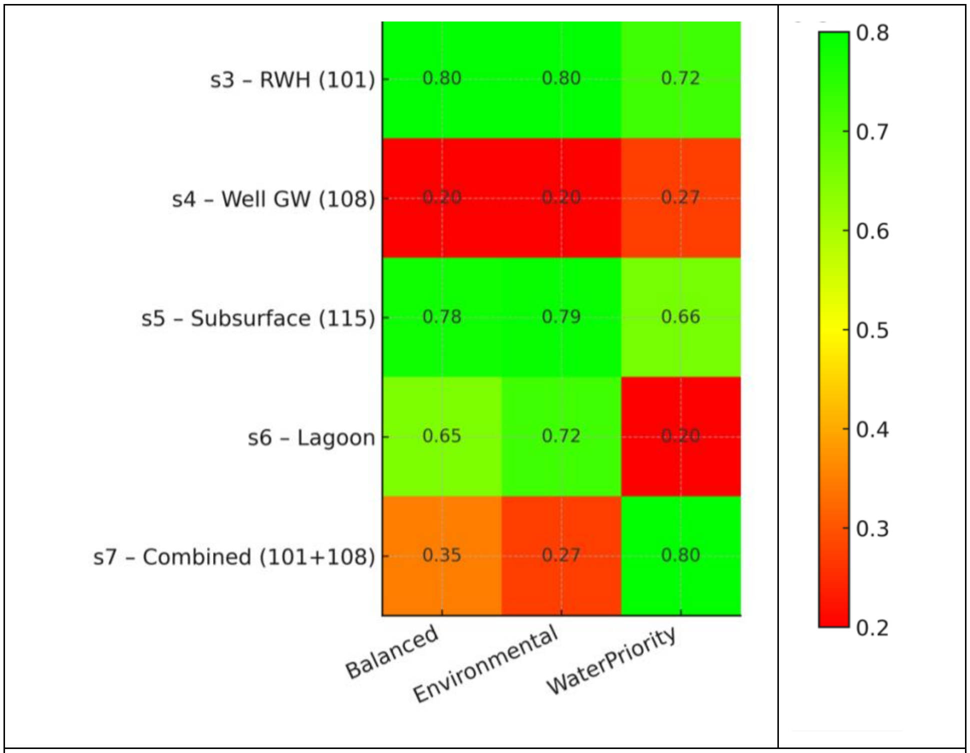

FIGURE 26. WEIGHTED MCDA HEATMAP FOR S3 TO S7 WATER HARVESTING SOLUTIONS.

TABLE 2. FINAL SUMMARY OF WEFE TRADEOFFS FOR ALL WATER HARVESTING SOLUTIONS

Scenario	Water Source/Type	WEFE Role	Key Characteristic
S3	**Rainwater Harvesting**	**Water-Energy Decoupling**	Best Performance: High sustainability; Zero energy cost and zero GHG emissions
S4	**Groundwater Well**	**Water-Energy Conflict**	Reliable supply but high energy use and carbon footprint due to pumping.
S5	**Subsurface Rainwater Harvesting**	**Water-Ecosystem Synergy in high Temperature environments**	Passive soil infiltration and recharge system; supports soil moisture and ecosystem resilience but delivers slightly lower recoverable water due to natural retention and percolation losses.
S6	**Treatment Lagoon**	**Water-Ecosystem Trade-off**	Provides habitat but loses significant water through evaporation, under warning Mediterranean conditions.
S7	**Combined (RWH + Well)**	**Nexus Optimization with Water—Energy Conflict**	Maximizes total water volume by blending passive and pumped sources; dilutes energy and GHG intensity per m³ but still depends partly on groundwater pumping.

5.4 AI WEFE Nexus Trade-off Analysis for Water Harvesting Solutions

The evaluation of five water-harvesting solutions in Tinos Island—rainwater harvesting (S3), groundwater pumping (S4), subsurface rainwater infiltration (S5), lagoon-based capture (S6), and the combined system (S7)—reveals clear WEFE Nexus trade-offs between water availability, energy demand, and greenhouse-gas emissions. Using a Digital Twin-enabled MCDA approach with soft-normalized indicators, the analysis with a Delta Heatmap (Figure 27) demonstrates that **no single solution optimizes all dimensions simultaneously**, and that policy choices must balance water security with environmental performance.

Rainwater harvesting (S3) emerges as the most balanced and policy-robust option, achieving high environmental performance with zero energy and zero emissions while delivering moderate water volumes. This positions S3 as the most cost-effective intervention for decentralized water security, suitable for rapid deployment in residential areas and highly aligned with climate-neutral strategies under the EU Green Deal.

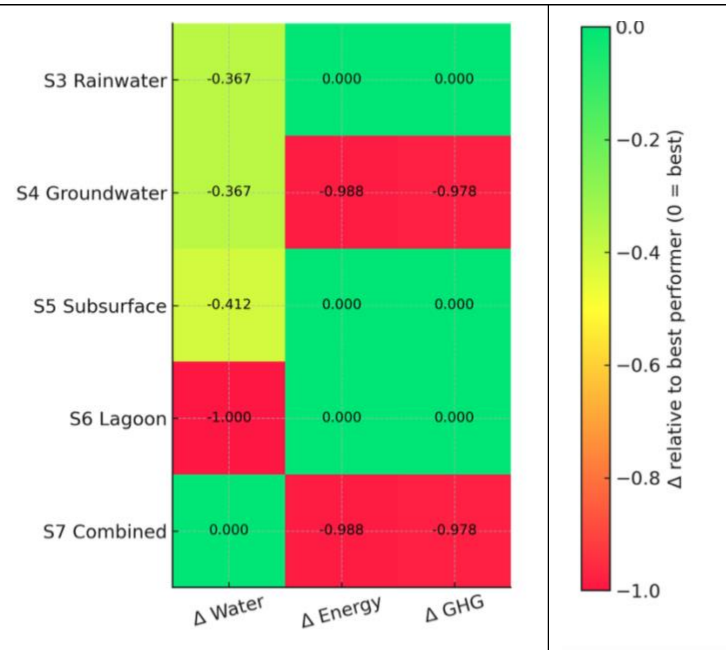

FIGURE 27. DELTA HEATMAP FOR WATER HARVESTING SOLUTIONS

Subsurface infiltration systems (S5) perform similarly well in environmental metrics, offering a nature-based groundwater recharge mechanism with negligible energy use. While delivering slightly less water than S3, subsurface systems strengthen long-term hydrological resilience and contribute to drought mitigation by enhancing aquifer stability—an increasingly critical factor under Mediterranean climate stressors.

Lagoon-based collection (S6) shows excellent low-impact performance but produces negative water yield under current conditions, indicating that its role should be reframed: S6 provides ecological and buffering benefits rather than supply augmentation. Policymakers should treat it as a complementary measure supporting ecosystem services, not as a supply-oriented intervention.

At the opposite end of the trade-off spectrum, **pumped groundwater solutions (S4 and S7)** consistently underperform in environmental metrics. The Combined system (S7) delivers the highest water volume but incurs significant energy demand and GHG emissions. These burdens undermine EU climate adaptation and decarbonization targets unless compensated by solar-powered pumping or integrated efficiency measures. When scaled, such systems risk exacerbating both carbon footprints and groundwater depletion.

Overall, the results highlight a strategic policy insight: **water quantity and environmental sustainability cannot be optimized simultaneously without integrated planning.** Low-impact solutions (S3, S5, S6) support climate mitigation and long-term resilience but offer limited volumes, whereas high-yield solutions (S7) impose energy and emissions costs. Therefore, decision-making frameworks should adopt a hybrid strategy, prioritizing S3 and S5 as baseline, low-impact systems while using S7 selectively to meet peak seasonal demand or supply deficits—preferably powered by renewables.

This evidence underscores the importance of WEFE Nexus approaches for small islands: sustainable water security requires aligning water supply choices with energy and climate objectives. The Digital Twin analysis provides a transparent and reproducible basis for local authorities, utilities, and EU program managers to identify efficient, low-carbon, and climate-resilient water strategies for Tinos and comparable Mediterranean territories.

5.5 AI Scenario Results for Bioeconomy Solutions

The **Tinos Ecolodge, a small self-sufficient tourist retreat** located in the Cycladic Islands, operates in an environment characterized by scarce water resources, high energy costs, and fragile Mediterranean soils. Its remote, **off-grid setting** makes it a **model site for testing circular bioeconomy strategies that convert local natural residues into energy, soil fertility, and climate benefits.** In this context, bioeconomy practices based on **olive-tree pruning biomass**, which is abundantly available in traditional agro-pastoral landscapes such as those surrounding the Ecolodge, offer a unique opportunity to close resource loops while enhancing ecosystem resilience.

Implementing bioeconomy solutions at the Tinos Ecolodge serves a dual purpose. On the one hand, it strengthens the lodge's operational self-sufficiency by producing renewable energy, organic soil amendments, and climate mitigation benefits directly on site. On the other hand, it provides a replicable demonstration of how small rural enterprises in Mediterranean islands can transition toward regenerative practices without relying on external inputs. Two practices in particular—**Agroforestry and Biochar production**—show high potential for valorizing olive prunings and aligning with the Ecolodge's sustainability philosophy.

Agroforestry systems, which integrate trees, shrubs, and understory vegetation, enhance biomass productivity, soil structure, biodiversity, and carbon storage, while generating renewable energy from pruning residues. **Biochar**, produced through pyrolysis of the same biomass, contributes stable carbon to soils, improves water retention, and supports long-term soil fertility. While each practice delivers distinct benefits and trade-offs, together they form a cohesive bioeconomy strategy that strengthens the Ecolodge's independence from external energy and soil inputs, reduces environmental impacts, and promotes a landscape-based approach to sustainability. Their combined application positions Tinos Ecolodge as a pioneer in regenerative tourism and a living laboratory for circular, nature-based solutions in the Aegean region.

Figure 28 shows the disaggregated monthly Nexus outputs from Agroforestry and Biochar—**Energy Generated** (kWh/month), **GHG Mitigation** (kg CO_2e/month), and **Organic Matter** (kg/month)—as separate bars for each practice, with all values normalized to 1 ha. Agroforestry demonstrates a very high level of multifunctionality, reaching:

- ≈1850 kWh/month of renewable energy (per Ha), derived from the energetic potential of pruning residues and improved ecosystem productivity.
- ≈600 kgCO_2e/month of GHG mitigation, due to increased biomass, enhanced soil carbon sequestration, and avoided fossil-fuel emissions through renewable energy production.
- ≈250 kg/month of organic matter, which is essential for improving soil structure, moisture retention, microbial activity, and erosion control.

Biochar also provides meaningful benefits but at a much smaller magnitude:

- 0 kWh/month of net energy generation, because pyrolysis requires more energy than it produces at this scale.
- ≈100 kgCO_2e/month of GHG mitigation, mainly through long-term carbon stabilization in the form of biochar.
- ≈36 kg/month of organic matter, providing concentrated carbon but much lower volume for soil improvement.

Together, these outputs show that **Agroforestry is a major contributor to climate mitigation, energy independence, and soil regeneration**—three strategic sustainability priorities for the Tinos Ecolodge. In contrast, while **Biochar** also contributes to carbon sequestration and soil improvement, its magnitude of benefit is significantly lower than that of Agroforestry when assessed on a per-hectare basis.

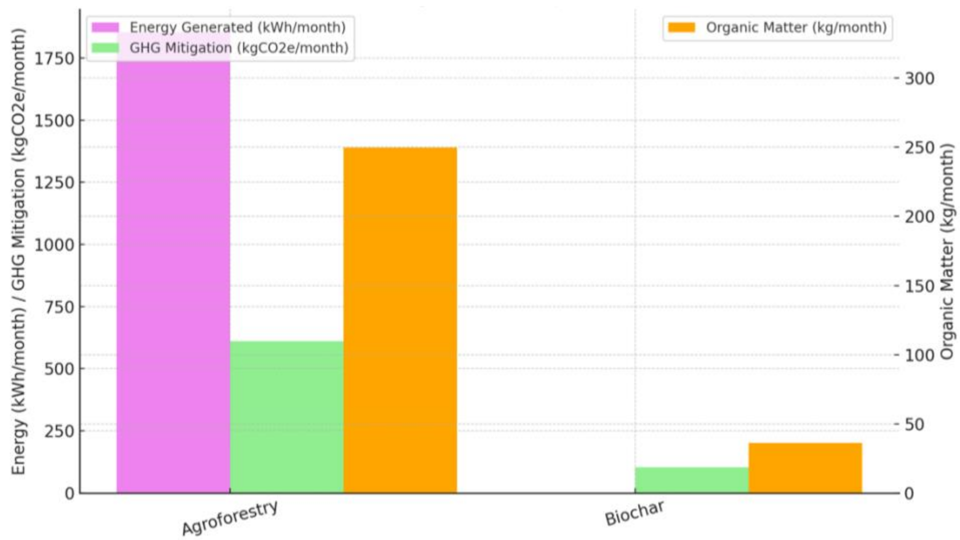

FIGURE 28. MONTHLY NEXUS OUTPUTS (PER 1 HA) IN TINOS FOR BIOECONOMY PRACTICES: AGROFORESTRY AND BIOCHAR.

Figure 29 aggregates all outputs into a single stacked bar for each practice, offering a holistic view of overall contribution to the WEFE Nexus. The stacked bar for Agroforestry rises to almost 2,700 units of combined monthly benefit, dominated by:

- Renewable energy production (largest share)
- Substantial GHG mitigation
- Signinficant organic-matter contribution

The Biochar stacked bar, in contrast, is very **small—representing less than 10% of Agroforestry's total combined Nexus benefit**. This combined representation highlights how **Agroforestry functions as a high-yield, synergistic bioeconomy solution, reinforcing multiple ecosystem services simultaneously**. For the Tinos Ecolodge, this implies strong potential for internal energy production, reduced operational carbon footprint, and steady improvements in soil fertility.

While Biochar offers high-quality carbon inputs, the overall magnitude of its contribution remains modest. This indicates that **Biochar is best understood as a complementary measure, valuable for targeted soil restoration or carbon sequestration, but not as a primary bioeconomy strategy** at the landscape scale.

Together, the two figures clearly demonstrate that:

I. Agroforestry is the dominant solution, offering strong synergies across the WEFE Nexus: renewable energy production, climate mitigation, and soil regeneration.

II. Biochar retains important—but smaller—benefits, especially in carbon storage and soil amendment.

III. The optimal strategy for the Tinos Ecolodge is to use Agroforestry as the main circular bioeconomy practice, complemented by Biochar in specific areas where stable carbon enrichment or structural soil improvement is needed.

This combination maximizes energy autonomy, soil fertility, and climate resilience, aligning with the Ecolodge's sustainability goals.

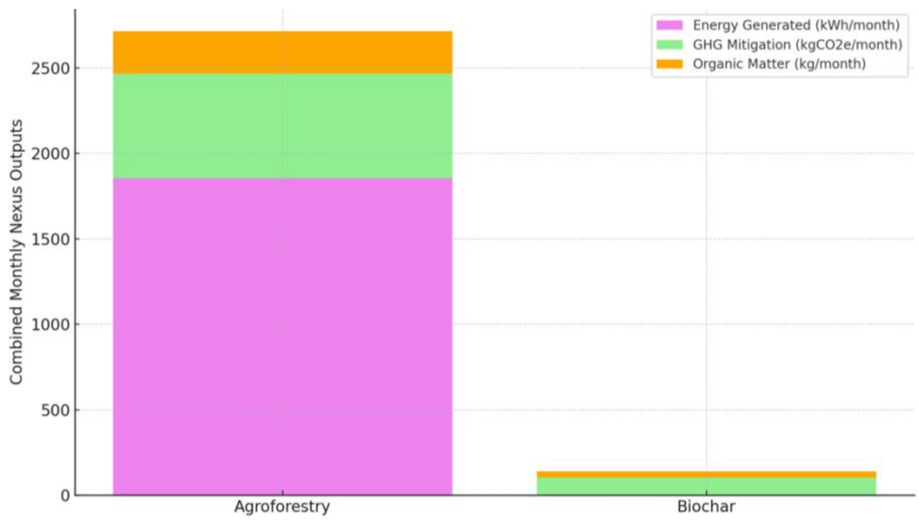

FIGURE 29. MONTHLY STACKED NEXUS OUTPUTS (PER 1 HA) IN TINOS FOR BIOECONOMY PRACTICES: AGROFORESTRY AND BIOCHAR.

To compare Agroforestry and Biochar under a unified Multi-Criteria Decision Analysis (MCDA) framework, all Nexus indicators were normalized following the same methodology employed before for the Codorníu demonstration site. This approach distinguishes between **performance (benefit) indicators and resource consumption (cost) indicators**, ensuring that each metric is evaluated according to its functional role in the Nexus. Indicators where higher values represent better performance—such as energy generated, GHG mitigation, and organic matter production—were normalized using direct proportional scaling, dividing each value by the maximum observed among the scenarios. This yields normalized scores between 0 and 1, reflecting the relative performance of each scenario compared with the best-performing option.

Conversely, indicators where lower values represent better performance require a different treatment. In the Tinos case, Biochar consumed energy rather than producing it, turning energy into a **cost indicator** for that scenario. To account for this, energy consumption was normalized using the **inverse relative-to-minimum method**, where the best value (lowest consumption) receives a score of 1 and the worst value receives 0. This method avoids distorting the comparative assessment by ensuring that consumption metrics are evaluated in a way that is consistent with their negative contribution to sustainability. Agroforestry, which generates energy instead of consuming it, retains the benefit-based direct normalization.

The resulting normalization framework provides a coherent comparison across indicators and scenarios, preserving the underlying meaning of each metric while allowing their aggregation in MCDA analyses. By combining direct normalization for benefit indicators with inverse normalization for consumption indicators, the method ensures that higher normalized scores always represent better sustainability performance. This harmonized treatment enables transparent evaluation of trade-offs and synergies between Agroforestry and Biochar, supporting decision-making in the context of bioeconomy practices in Tinos.

Figure 30 shows the MCDA heatmap for monthly stacked nexus outputs (per 1 Ha) in Tinos for bioeconomy practices, and Figure 30 shows the weighted MCDA heatmap for monthly stacked nexus outputs (per 1 Ha). The MCDA analysis clearly identifies **Agroforestry** as the most sustainable bioeconomy practice across all weighting strategies—balanced, environmentally oriented, and bioeconomy-focused. Agroforestry systematically achieves maximum performance in all three Nexus dimensions (Energy, GHG mitigation, Organic Matter), demonstrating its capacity to simultaneously strengthen climate mitigation, soil restoration, and energy autonomy. This robustness suggests that Agroforestry should be prioritized as a core intervention for enhancing resilience and sustainability in Mediterranean island systems like Tinos.

Biochar, while offering measurable benefits—particularly in GHG mitigation and organic matter inputs—shows significantly lower overall performance when compared to Agroforestry. Its main limitation stems from its **energy consumption requirement**, which disproportionately affects its aggregated MCDA outcomes.

Biochar can nevertheless serve as a **complementary measure**, especially under a climate-mitigation or soil-regeneration policy lens, where its contributions become more valuable.

From a policy standpoint, integrating Agroforestry as a **primary strategy**, supplemented by Biochar where contextually appropriate, provides the greatest co-benefit for the WEFE Nexus. Policymakers should therefore prioritize agroecological system transformation, invest in landscape-level agroforestry deployment, and consider Biochar as an additional tool where energy availability and operational capacity allow. This combination maximizes climate resilience, promotes sustainable soil fertility, and enhances the long-term adaptive capacity of agricultural systems in Tinos and comparable island territories.

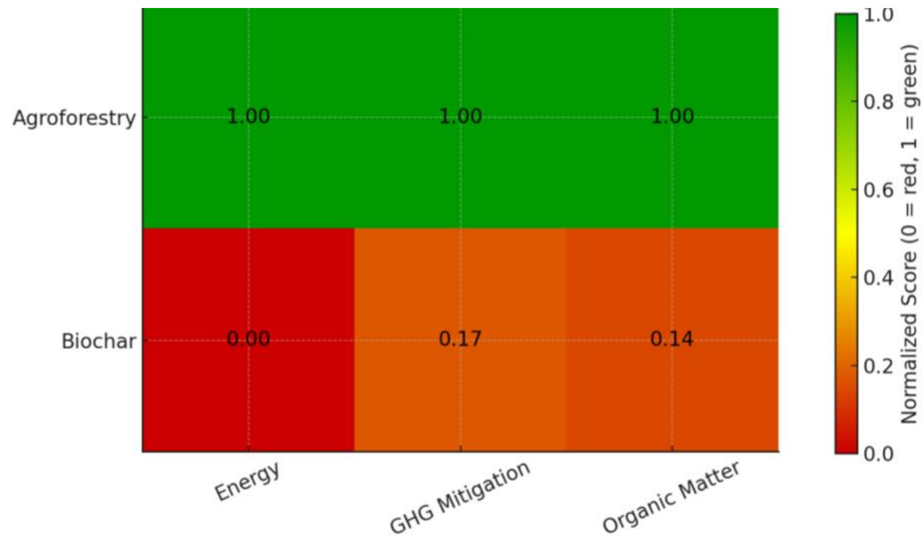

FIGURE 30. MCDA HEATMAP FOR BIOECONOMY PRACTICES: AGROFORESTRY AND BIOCHAR IN TINOS.

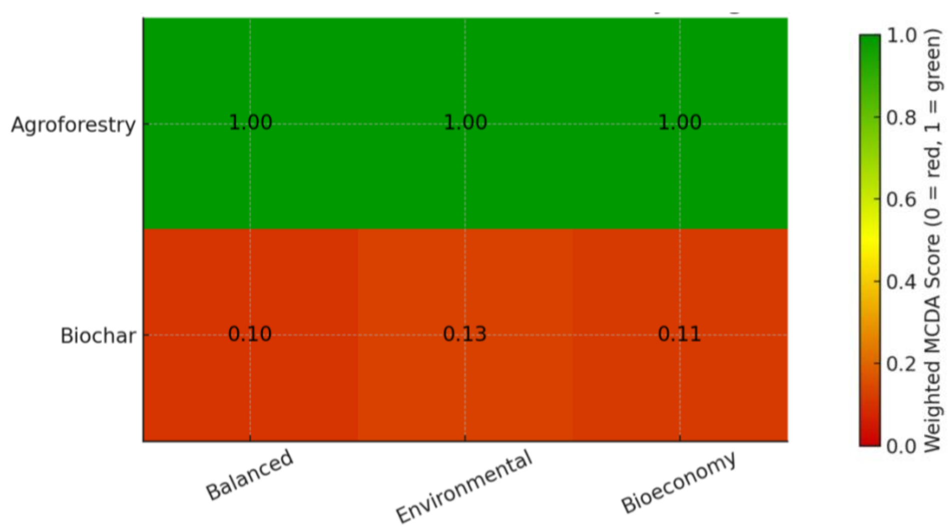

FIGURE 31. WEIGHTED MCDA HEATMAP (BALANCED, ENVIRONMENTAL AND BIOECONOMY) IN TINOS FOR BIOECONOMY PRACTICES: AGROFORESTRY AND BIOCHAR.

5.6 AI WEFE Nexus Trade-off Analysis for Bioeconomy Practices

The trade-off assessment between Agroforestry and Biochar was conducted using the Delta-Heatmap approach (, which quantifies the differential performance of each practice across harmonized WEFE Nexus indicators. All metrics were normalized using the Codorníu methodology (X/Xmax), enabling a transparent comparison on a 0–1 scale. The resulting differential values represent the relative advantage of Agroforestry over Biochar for each Nexus dimension. The heatmap reveals a consistent dominance of Agroforestry, demonstrating that this practice delivers substantially higher integrated benefits without generating trade-offs or negative externalities across the assessed ecosystem services.

From an energy perspective, **Agroforestry shows the strongest relative advantage**, achieving a full normalized score (Δ = 1.0). This reflects its ability to deliver **1,854 kWh/month of renewable energy—mostly through biomass flows**, shading effects, and associated ecosystem co-benefits—while Biochar produces no direct energy output. This result positions Agroforestry as a significant contributor to local energy resilience and reduces dependency on fossil-based or grid-derived electricity, an important factor for remote island systems with limited energy security.

Regarding climate mitigation, Agroforestry also exhibits superior performance with a normalized delta of 0.83. Although Biochar does contribute to carbon sequestration through long-term soil carbon stabilization, its monthly mitigation potential (**103.8 kg CO_2e/month**) is significantly lower than that of Agroforestry (**611.4 kg CO_2e/month**).

Agroforestry enhances climate resilience through multiple pathways: carbon uptake via perennial vegetation, reduced soil erosion and oxidation, improved microclimates, and interactions with soil moisture that influence belowground carbon cycling. The Delta-Heatmap shows that these cumulative effects result in a substantially **higher climate-positive impact for Agroforestry, reaffirming its role as a strategic climate adaptation and mitigation measure.**

In terms of soil and ecosystem regeneration, Agroforestry again delivers stronger outcomes. With a normalized delta of 0.86, **Agroforestry contributes 249.9 kg/month of organic matter, compared to 36 kg/month from Biochar** application. While Biochar increases soil carbon content in a concentrated and stable form, it does not replace the diverse ecological functions delivered by living biomass. Agroforestry enriches soils through continuous organic inputs such as leaf litter, root turnover, and symbiotic microbial interactions, enhancing soil structure, water retention, fertility, and long-term ecosystem productivity. This reinforces the conclusion that Agroforestry generates broader ecological co-benefits compared to the more targeted and limited intervention of Biochar.

Overall, the Delta-Heatmap analysis demonstrates that **Agroforestry provides synergistic improvements across all WEFE dimensions, while Biochar functions as a complementary but substantially weaker alternative**. There are no measurable trade-offs: Agroforestry simultaneously enhances energy generation, carbon mitigation, and soil regeneration. These findings have direct implications for sustainable land-use strategies in Tinos Island, suggesting that Agroforestry should serve as a cornerstone practice for regenerative agriculture, climate adaptation, and nature-based economic diversification. Biochar, while valuable, is best positioned as a supporting measure rather than a standalone solution.

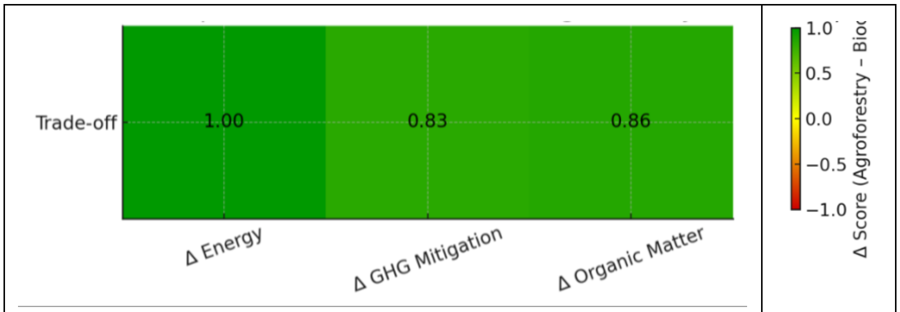

FIGURE 32. DELTA-HEATMAP REVEALING TRADE-OFFS RELATIVE TO SOLAR DESALINATION

Synthesis: The Strategic "Nexus" Conclusion for Tinos Ecolodge

While Biochar serves as a valuable supplementary tool for soil enhancement, Agroforestry functions as a primary WEFE Nexus engine. It effectively couples the Energy and Ecosystem sectors by turning landscape management into a productive energy source (~1.8 MWh/month) while simultaneously providing the bulk of the Organic Matter needed to sustain soil fertility for food production.

Implementing Agroforestry moves the lodge from a passive land-use model to an active regenerative system that subsidizes the site's energy demands. Biochar should therefore be viewed not as a competitor to Agroforestry, but perhaps as a downstream by-product where specific Agroforestry waste streams are pyrolyzed to further enhance soil stability, rather than relying on it as a standalone solution for energy or mitigation."