

4th International Conference on Media, Economy, Communication and Intelligence Management (MECI 2026)

Article

Integrating Green Retrofitting of Existing Buildings with Concurrent Restoration of Surrounding Degraded Ecosystems toward Carbon Neutrality

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Abstract: Retrofitting existing buildings and restoring adjacent degraded ecosystems can significantly reduce environmental burdens through linked changes in energy, water, materials, and land management practices. Their simultaneous implementation, however, does not inherently guarantee additional carbon benefits. This paper develops an integrated assessment framework that combines technology selection with separate accounting for emissions, additional ecological removals, and ecosystem recovery. A structured narrative synthesis informs a four-alternative comparison of continued operation, building retrofit, ecological restoration, and integrated strategy. An explicitly hypothetical thirty-year example demonstrates the calculation methodology and tests its sensitivity. Within the modeled boundary, the integrated alternative achieves a net carbon reduction of 8,336 t CO₂e relative to continued operation, compared with 8,226 t from building measures and 66 t from restoration alone. The resulting interaction benefit is only 44 t, because shared construction, maintenance, and replacement savings are partly offset by overlapping energy savings. An additional annual electricity demand of 5 MWh reverses this interaction. The example therefore supports testing integration rather than presuming synergy. The proposed implementation sequence connects structural and contamination assessment, envelope and heating improvements, water management, habitat recovery, and monitoring. Progress toward carbon neutrality requires sustained demand reduction and transparent treatment of residual emissions; furthermore, ecological recovery must also satisfy independently defined criteria for habitat, soil, water, and long-term maintenance to ensure comprehensive environmental benefits.

Keywords: building retrofit; ecological restoration; carbon neutrality; life cycle assessment; sustainability

Received: 27 July 2026

Revised: 10 September 2026

Accepted: 24 September 2026

Published: 01 October 2026



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1. Introduction

Existing buildings and their surrounding land share environmental processes while often being managed through separate projects. A retrofit may improve insulation and replace heating equipment without addressing heat exposure, degraded soil, or runoff from adjacent hard surfaces. A landscape project may add vegetation while overlooking irrigation demand, building shading, construction emissions, or the survival of planted trees [1]. Coordinating these measures creates opportunities, but also introduces interactions that isolated appraisals cannot represent.

Assessments of building-related climate mitigation identify operational energy, material use, and renewable supply as connected components of decarbonization [2]. Evidence on refurbished and replacement buildings further indicates that the carbon advantage of retaining a structure depends on the energy system, functional requirements,

and assessment boundary. In parallel, ecological restoration seeks recovery toward an appropriate reference ecosystem through removal of degradation pressures and measurable improvement in ecosystem attributes. An increase in planted area alone is insufficient evidence of such recovery.

The problem addressed here is how to integrate these objectives without double-counting benefits or allowing carbon performance to obscure ecological shortcomings. For example, tree shading may reduce electricity demand, but its energy-related avoided emissions should appear once in the energy account. Carbon accumulated in biomass is a separate physical process with different monitoring and permanence requirements. A green roof may provide habitat and stormwater storage while its materials and maintenance generate emissions [3].

This paper proposes a common decision framework for an existing building and the degraded land functionally connected to it [3, 4]. The contribution is a linked set of technology conditions, carbon equations, and verification requirements, demonstrated through a reproducible numerical scenario. The framework asks which combinations are technically compatible, whether their joint carbon benefit exceeds the sum of separate measures, and how ecological recovery can be verified independently. Concurrent restoration means coordinated planning and delivery, including sequences in which remediation must precede planting; it does not require every activity to occur at the same time.

2. Literature Review

2.1. Building Retrofit and Carbon Accounting

Operational efficiency alters the distribution of a building's carbon burden. As operational demand declines, embodied emissions assume greater relative significance. The importance of product-stage and replacement impacts—including those associated with building services and interior elements—has been recognized. These insights support retaining serviceable components where feasible, while carefully evaluating the emissions implications of newly introduced materials such as insulation, heating systems, and renewable energy equipment. The original emissions associated with a retained structure represent historical burdens and do not constitute a new negative-emission credit.

Heat pumps enable electrification of thermal energy supply, yet their performance is contingent upon installation quality, operating temperature conditions, electricity grid composition, and refrigerant handling practices [5, 6]. Field studies demonstrate variability in seasonal performance and underscore the necessity of clearly defining system boundaries for measurement. Similarly, photovoltaic generation entails upstream manufacturing and end-of-life replacement burdens, despite zero operational fuel combustion. Such evidence reinforces the need for system-level life-cycle assessment rather than equipment selection based solely on nominal efficiency ratings.

Whole-life carbon assessment frameworks provide a structured basis for defining study periods and distinguishing within-boundary impacts from benefits linked to exported utilities. However, predictive models require empirical validation [7]. Observed discrepancies between design assumptions, installation execution, operational behavior, and occupant use highlight the limitations of theoretical projections. A robust retrofit project therefore requires both a defensible initial forecast and a formalized plan for post-commissioning review and model refinement.

2.2. Ecological Recovery and Conditional Interactions

Urban vegetation can alter the thermal environment, but the response depends on spatial scale and surface composition. Interactions between canopy cover and impervious surfaces have been observed, rather than a single transferable cooling coefficient. Substantial variation in urban-tree water use has been documented across species and sites. Consequently, local cooling effects must be evaluated jointly with water availability and seasonal building energy demand.

Evidence on combined vegetation and photovoltaic systems is similarly context-dependent. Mixed ecological responses have been reported in replicated rooftop experiments under Mediterranean conditions, with no consistent increase in electricity production. In contrast, higher faunal diversity has been observed on biosolar roofs compared to conventional photovoltaic roofs in Sydney. These findings address different outcomes and environmental settings; neither supports a universal energy benefit nor equivalence to ground-level ecosystem restoration [8].

Hydrological and carbon benefits also require temporal qualification. Green-roof stormwater retention has been shown to vary with rainfall intensity and available storage capacity. Tree mortality has been found to offset rapid growth in urban carbon balances. Long-term roof observations have linked variable ecosystem carbon exchange to concurrent water and energy conditions. The assessment gap motivating this study is therefore practical: energy performance, ecological recovery, and carbon storage require a shared project boundary but distinct evidence bases and performance metrics.

3. Methodology

3.1. Study Design and System Boundary

The study combines a structured narrative synthesis with an illustrative comparative calculation. Publications and official technical documents were selected for their relevance to retrofit accounting, ecological recovery, or an identifiable interaction between them [9]. Publisher and institutional records were reviewed through September 2026. Evidence from field investigations informs mechanisms and verification needs; numerical effect sizes from different sites are not pooled. This is a conceptual engineering assessment, rather than a systematic meta-analysis or a monitored implementation project.

The assessment unit is the continued provision of equivalent occupied floor area, indoor environmental service, and site access over a stated period. The spatial boundary includes the building, its managed surrounding land, and relevant supply-chain burdens. Drainage and habitat connections beyond the property are mapped as dependencies. Four alternatives are compared: continued operation B0, building retrofit B, restoration R, and their integrated implementation I. Weather and occupancy assumptions are held consistent; changes in comfort provision must be reported separately from efficiency savings [10].

Figure 1 summarizes the proposed sequence. Site investigation establishes structural capacity, moisture conditions, soil and groundwater quality, drainage pathways, and existing habitat [9]. A reference ecosystem guides restoration goals, adapted to local conditions and future climate. Contamination can constrain infiltration: guidance from environmental regulatory authorities identifies the risk of mobilizing pollutants at brownfield sites. It is used here as technical evidence, rather than as a substitute for applicable local requirements.

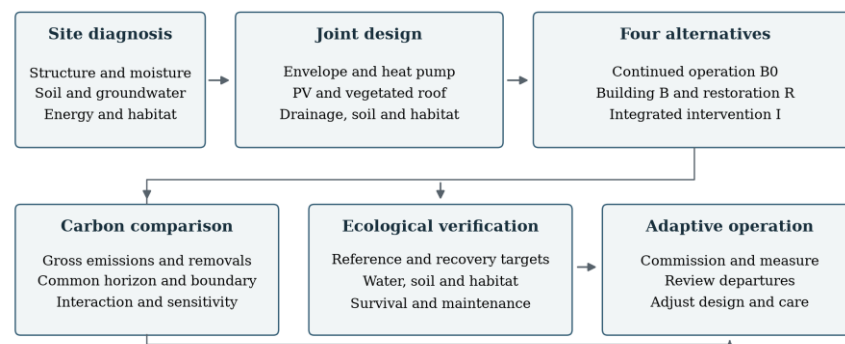


Figure 1. Proposed Integration Workflow. Physical Interactions Inform the Joint Design, While Carbon Accounting and Ecosystem Recovery Remain Separate Verification Tasks. The Workflow Is an Analytical Proposal, Not a Record of a Completed Project.

3.2. Comparative Carbon Budget

For alternative scenarios and the assessment period T , the modeled carbon balance is

$$C_s(T) = M_s + \sum_{y=1}^T [E_{s,y}f_y + F_{s,y}h + O_{s,y} + K_{s,y} - R_{s,y}] + D_s \quad (1)$$

Here M is upfront embodied and installation emissions; E and F are annual imported electricity and fuel in MWh; f and h are their respective emission intensities in t CO₂e/MWh. O includes additional maintenance and non-energy operating emissions, including applicable refrigerant losses. K records replacements in their actual years, R is net ecological CO₂ removal, and D represents end-of-period burdens within the chosen boundary. All terms other than energy quantities and factors are expressed in t CO₂e. Electricity factors may vary annually, and carbon quantities are not financially discounted [11].

Ecological removal requires a complete stock or flux account that reconciles growth, mortality, decomposition, and biomass transfers. Transferring imported soil or biomass into a site is not itself atmospheric removal. Context-specific vegetation and land-carbon accounting is supported by internationally recognized guidance on greenhouse gas inventories. Methane or nitrous oxide emissions from relevant soils or water features belong in O ; if material and unquantified, a net-removal claim remains unresolved. Changes relative to the same ecological baseline determine the additional benefit [5].

Net carbon reduction and the interaction between measures are calculated as

$$\Delta C_s = C_{B0} - C_s \quad (2)$$

$$\Psi = \Delta C_I - \Delta C_B - \Delta C_R = C_B + C_R - C_I - C_{B0} \quad (3)$$

A positive interaction means that integrated implementation performs better than the arithmetic sum of standalone benefits under the stated assumptions. It is not proof that each technology pair is synergistic. Shared resource deployment can lower embodied emissions while overlapping cooling measures reduce marginal energy savings [12, 13]. Biodiversity gains are not converted into carbon offsets. Physical removals and gross emissions should remain visible even when a net balance is also reported.

3.3. Selection Criteria and Verification

Technology packages first undergo structural integrity, moisture management, contamination control, water availability, and habitat protection assessments. Feasible alternatives are then evaluated comparatively across carbon performance, cost efficiency, indoor environmental quality, stormwater runoff behavior, and ecological recovery potential. Projects must present a transparent trade-off table rather than obscuring unmet ecological objectives within aggregated weighted scores. The framework does not specify universal numerical weights or performance thresholds; these must be established through site-specific targets and consensus among stakeholders [14].

Energy savings are estimated as counterfactual reductions derived from an adjusted baseline of energy consumption, aligned with internationally recognized measurement and verification principles. Whole-building metering captures aggregate performance, while submetering of heating, cooling, pumping, and photovoltaic systems enables mechanistic analysis. Weather and occupancy data support robust baseline adjustment. Repeated field measurements of vegetation structure, soil properties, and runoff characteristics quantify ecological recovery. A before-and-after comparison with a comparable untreated control area may enhance ecological attribution, provided all concurrent management interventions and inter-site differences are fully documented.

4. Integrated Technology System

4.1. Envelope and Energy Systems

The building package begins with repairs and demand reduction. Insulation continuity, solar control, window performance, and airtightness are designed in coordination with ventilation and moisture safety. Heating equipment is sized using the revised thermal load, avoiding reliance on the original peak demand after envelope improvement [15]. Lower distribution temperatures and commissioned controls can support heat-pump operation; however, seasonal performance evaluation must account

for backup heating and auxiliary electricity consumption within a defined system boundary.

Surrounding vegetation is incorporated into the same thermal assessment. Tree placement and mature crown geometry influence summer shading, winter solar access, and photovoltaic exposure. A cooling benefit observed in an inefficient building may diminish following glazing and envelope upgrades. Assumptions about mature-canopy effects must include an establishment trajectory rather than immediate full shading. Computational estimates should therefore compare all four alternatives under identical weather and occupancy conditions, rather than aggregating separately published saving percentages [10].

Rooftop allocation integrates photovoltaic arrays, vegetation, access, drainage, and maintenance requirements. Structural assessments account for saturated substrate conditions and applicable imposed loads. Drainage and waterproofing systems remain fully accessible. Any assumed photovoltaic performance gain attributable to a vegetated microclimate must be rigorously evaluated against competing effects from shading and airflow. Empirical findings indicate that such gains are not automatic and require case-specific validation. Table 1 identifies the conditions that determine whether proposed technology pairings remain beneficial.

Table 1. Technology Pairings and Their Principal Verification Requirements.

Coupled measures	Intended interaction	Limiting condition	Verification
Envelope and heat pump	Lower demand and suitable equipment sizing	Moisture, ventilation, auxiliary demand	Thermal service and metered seasonal performance
Canopy and solar control	Reduced summer heat exposure	Winter shading, establishment, irrigation	Seasonal loads, canopy survival, water use
Vegetated roof and PV	Shared roof area and habitat opportunities	Structural load, panel shading, access	Matched PV yield and taxon surveys
Roof drainage and restored ground	Storage, controlled reuse, habitat support	Contamination, groundwater, overflow	Water balance and discharge quality
Shared construction and maintenance	Less repeated excavation and mobilization	Root damage, soil compaction, incompatible timing	Material records and recovery indicators

4.2. Water and Soil Restoration

The water system integrates roofs, storage, treatment, and landscape demand within a unified hydrological balance. Roof runoff can be utilized for irrigation following appropriate treatment, though annual rainfall is insufficient to meet demand during dry periods. Storage capacity must account for seasonal rainfall distribution, irrigation requirements, overflow management, and pumping energy efficiency. Green roof retention performance varies with prior moisture conditions; annual average retention values cannot substitute for design-storm performance. Overflow pathways must safeguard building foundations and prevent erosion in ecologically recovering areas.

Ground restoration starts with mitigation of degradation drivers [16]. Techniques such as soil decompaction, targeted soil amendment, removal of redundant impervious surfaces, and reintroduction of native vegetation are applicable where site investigations confirm their suitability. In contaminated zones, remediation objectives govern whether infiltration is permissible; engineered containment systems with controlled discharge may be more appropriate. Phytoremediation should be applied only when a specific contaminant and its exposure pathway are well documented, and a clear plan for managing harvested contaminated biomass is in place—rather than being adopted as a default remediation strategy.

Construction sequencing is essential to enable integrated implementation. Temporary access routes and material staging areas must be carefully located to avoid compaction of restored soils or damage to existing root systems. Heavy construction activities should be completed before sensitive planting operations commence, with designated protected zones maintained throughout the project duration. Coordinated excavation for drainage infrastructure and building services can minimize soil handling and reduce embodied carbon, provided soil integrity and contamination controls are fully preserved [16]. The final soil composition, hydrological behavior, and long-term maintenance responsibilities must be formally documented prior to project handover.

4.3. Habitat and Long Term Operation

Restoration targets should describe native composition, vegetation structure, ecological function, and connections with surrounding habitat. Functional habitat requirements can be more informative than plant richness alone: studies have linked native vegetation, insect resources, and use by insectivorous birds within specific regional contexts. Local species and ecological relationships should determine analogous indicators elsewhere. A vegetated roof can complement the ground-level network while remaining a distinct engineered habitat.

The operating plan integrates irrigation, tree establishment, roof access, filter maintenance, and equipment commissioning [17, 18]. Tree survival and biomass disposal influence the durability of stored carbon. Drought can simultaneously reduce evapotranspiration and ecosystem uptake, making independent assumptions of maximum cooling and maximum sequestration inconsistent. Monitoring should trigger corrective action when vegetation declines, runoff quality deteriorates, or auxiliary energy consumption rises. An integrated maintenance contract is effective only if it retains accountable expertise for both building services and ecological care.

5. Illustrative Scenario Analysis

5.1. Assumptions and Calculation

The example represents an assumed 10,000 m² building and one hectare of adjoining degraded managed land over thirty years [19]. It is a numerical illustration, not an observed site or a forecast for a specific city. Every value in Table 2 is analyst-selected. Annual electricity and gas factors are stylized accounting inputs, not claimed national coefficients: electricity declines linearly from 0.50 in year 1 to 0.10 t CO_{2e}/MWh in year 30, while gas remains at 0.202 t CO_{2e}/MWh.

Table 2. Complete Package Inputs for the Illustrative Calculation. Energy Is in MWh/year and Carbon Quantities in T CO_{2e} Unless Stated Otherwise.

Input	B0	B	R	I
Imported electricity	900	684	875	663
Gas input	1,200	0	1,200	0
Upfront emissions M	0	800	150	910
Additional annual burden O	0	3	2	4
Additional replacement K in year 16	0	100	30	120
Net removal per year in years 1–3	0	0	0	0
Net removal per year in years 4–30	0	0	3	3
End-period burden D	0	0	0	0

Baseline gas use of 1,200 MWh at 85% boiler efficiency supplies 1,020 MWh of useful heat. Envelope measures reduce this load by 40% to 612 MWh. At a seasonal performance factor of 3, heating consumes 204 MWh of electricity. Reducing other electrical demand from 900 to 720 MWh and using 240 MWh of photovoltaic generation onsite gives 684 MWh of imports. These annual values are held constant to clarify the accounting mechanism; degradation, weather variation, and growth in demand are omitted.

Restoration alone reduces cooling electricity by an assumed 30 MWh and adds 5 MWh for pumping, giving imports of 875 MWh. After building improvements, its marginal cooling saving is assumed to fall to 20 MWh. Integrated implementation also assumes a conditional 6 MWh photovoltaic gain, giving 663 MWh of imports. All credited photovoltaic output is self-consumed; there are no export credits [20]. Its embodied burdens are included in M and K, avoiding a second allocation through a photovoltaic electricity factor.

The assumed removal totals 81 t over the period and represents additional net atmospheric uptake after ecological losses, not gross plant growth. Baseline net land-carbon change is set to zero. M, O, and K are incremental burdens above a common maintenance and renewal allowance; actual baseline equipment replacements must be inventoried before estimating these increments. Common burdens and historical construction emissions are omitted because they cancel in comparison. Replacement inventories include associated disposal. Assets remain in service at year 30, so D is zero and no later decommissioning or residual-value credit is included. These results describe a bounded comparative budget, not a complete certified whole-life inventory. Shared implementation reduces assumed upfront, annual, and replacement burdens in I relative to B plus R.

5.2. Comparative Results

Table 3 reports the calculation. Integrated implementation lowers the modeled thirty-year balance from 15,372 to 7,036 t CO_{2e}, a reduction of 54.2% within this boundary. Its 8,336 t net carbon reduction exceeds the building-only benefit by 110 t. Of that increment, 66 t is the standalone restoration benefit and 44 t is the interaction effect. Neither the percentage reduction nor the uptake assumption establishes carbon neutrality: substantial modeled emissions remain.

Table 3. Calculated Outcomes under the Base Assumptions. Carbon Quantities Are in T CO_{2e}; Percentages Use the Modeled B0 Balance.

Alternative	Net balance	Net carbon reduction	Reduction	Sustained carbon payback year
B0	15,372	0	0.0%	Not applicable
B	7,146	8,226	53.5%	3
R	15,306	66	0.4%	18
I	7,036	8,336	54.2%	3

Carbon payback is the first year after which cumulative net carbon reduction remains nonnegative through year 30, accounting for the replacement event [21]. It is not a financial return. Figure 2 shows why the interaction effect is modest. Shared upfront, maintenance, and replacement burdens save 40, 30, and 10 t respectively. Overlapping energy effects increase integrated electricity use by 4 MWh/year relative to the additive expectation, producing a 36 t penalty across the assumed grid trajectory. The remaining interaction effect is 44 t.

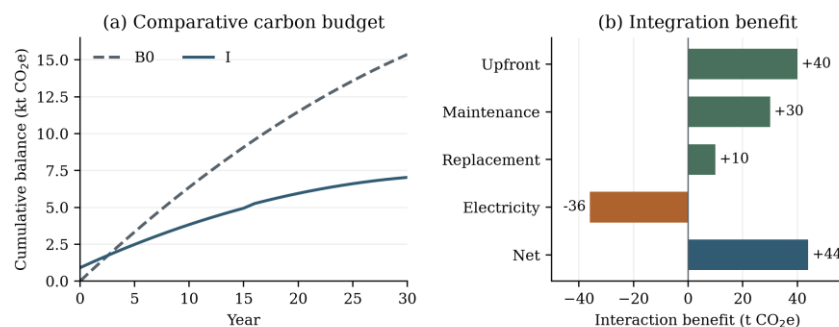


Figure 2. Calculated Scenario Outcomes. (A) Cumulative Modeled Balances for Continued Operation and Integrated Intervention. (B) Contributions to the 44 T Interaction Benefit; Negative Values Reduce the Benefit. All Plotted Values Are Derived from the Hypothetical Inputs in Table 2.

5.3. Sensitivity and Interpretation

With electricity intensity fixed at 0.50 throughout, the integrated net carbon reduction increases to 9,758 t, while the interaction effect declines to 20 t due to the increased carbon intensity of the electricity penalty. Reducing electricity intensity to 0.05 by year 30 yields a net carbon reduction of 8,158 t and an interaction effect of 47 t. Lowering heat-pump seasonal performance from 3 to 2 reduces the integrated net carbon reduction to 7,418 t. These results demonstrate that equipment performance and grid decarbonization trajectories must be jointly evaluated.

Excluding ecological removal credits, restoration alone improves the modeled carbon balance by 15 t relative to B0, while the integrated net carbon reduction remains at 8,255 t. Although restoration may deliver co-benefits such as water quality improvement and habitat recovery, those outcomes do not offset this carbon accounting result. Removing the assumed 6 MWh biosolar gain renders the interaction effect negative at -10 t. More generally, an additional 5 MWh/year of integrated electricity use shifts the base interaction effect from 44 t to -1 t. These are deterministic sensitivity tests, not statistical confidence intervals. Under the selected assumptions, the package delivers substantial building-related carbon benefits, but its incremental integration benefit is highly sensitive to parameter assumptions.

6. Discussion

The analysis distinguishes the value of coordinated implementation from assertions of positive carbon interaction. A combined project may enhance delivery efficiency and ecological outcomes even when its measured carbon interaction is zero or negative. Decision-making should therefore be conditional: retain coordination that is technically essential, then systematically compare the carbon and non-carbon implications of the resulting alternative configurations. A modest positive interaction does not substantiate a broad claim of proven synergy, particularly when minor variations in assumptions or conditions could reverse its sign.

For application in a temperate urban context, seasonal heating and cooling demands must be modeled jointly with canopy development and water availability. In other climatic zones, factors such as summer heat stress, humidity levels, or water scarcity may assume greater relevance. Local building typologies, pre-existing ecological conditions, site contamination status, and long-term maintenance capacity all influence the feasible scope of intervention. The framework is transferable as a structured sequence of analytical questions and computational steps, rather than as a prescriptive list of technologies or fixed emission reduction rates.

Several methodological constraints inform future validation efforts. The scenario relies on aggregated emissions inventories and constant annual demand profiles, omitting hourly photovoltaic generation-load matching, interannual weather variability, uncertain equipment lifetimes, and fine-scale ecosystem processes. It also excludes cost estimation

and quantitative valuation of biodiversity benefits [13]. A project-level study should replace these simplifications with site-specific material and energy inventories, calibrated dynamic energy simulation models, empirically derived carbon stock measurements, and storm-event hydrological analysis. While certain principles drawn from established protocols are applied, this does not constitute formal adherence to any particular standard.

Successful implementation depends on sustained cross-disciplinary responsibility [22]. Energy management teams require access to utility metering data and maintenance logs; ecological stewardship teams require authority over soil management, vegetation selection and establishment, and irrigation scheduling. Residents should receive clear communication regarding adjustments to indoor thermal settings, public access arrangements, and landscape functionality. Reporting must transparently present gross emissions, additional carbon removals, key ecosystem indicators, and associated uncertainties as distinct components. Any assertion of net climate neutrality would necessitate a fully defined system boundary and rigorous accounting for residual emissions and potential reversals beyond the illustrative comparison presented here.

7. Conclusion

Integrated building retrofit and ecological restoration should be designed around shared physical processes and evaluated using distinct carbon and ecological performance criteria. Envelope improvement, efficient electrification, renewable generation, soil recovery, and water management can be mutually reinforcing; however, their combined effectiveness depends on local climate conditions, site-specific characteristics, and long-term operational behavior.

The illustrative calculation yields a net carbon reduction of 8,336 t CO_{2e} over thirty years, with only 44 t attributable to interaction effects beyond the sum of individual contributions. This interaction benefit disappears under a modest increase in electricity demand or removal of the assumed biosolar gain. These findings support a practical design principle: shared savings and competing effects must be quantified explicitly before asserting synergy. Achieving carbon neutrality requires simultaneous reduction of building energy demand and supply-side emissions, protection of ecological recovery pathways, ongoing monitoring of biological carbon storage, and direct mitigation of residual carbon burdens.

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