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# Green Data Centers: Net-Positive Environmental Impact on Local Ecosystems

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RESEARCH ARTICLE

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**Abstract:** The rapid expansion of digital infrastructure intensifies the environmental burden of data centers through high energy consumption, freshwater depletion, land-use change, and waste heat emission. Conventional sustainability strategies focusing on efficiency and carbon offsets prove insufficient to address these escalating ecological challenges. This study proposes a transformative net-positive model where data centers actively restore and enhance surrounding ecosystems rather than merely reducing harm. A mixed-methods approach integrating literature synthesis, conceptual modeling, and case study analysis develops a Four-Pillar Framework comprising Energy Synergy, Water Stewardship, Ecological Integration, and Thermal Circularity. To measure performance rigorously across disparate environmental dimensions, we introduce a distance-to-target normalized, non-compensatory Composite Net-Positive Index (CNPI) aggregated via a weighted geometric mean. The model incorporates dynamic Analytic Hierarchy Process (AHP) contextual weighting based on site-specific ecological stressors ($\theta_i$) and a bounded degradation penalty function for biodiversity impacts. Application to two illustrative cases, a Nordic urban facility and an arid-zone data center, demonstrates CNPI scores of 1.30 and 1.28, respectively, confirming measurable ecological regeneration. This research offers a scalable, interdisciplinary blueprint for transitioning data centers from environmental liabilities to regenerative assets that support climate resilience and biodiversity recovery.

**Keywords** Green data center, Net-positive, Waste heat reuse, Water balance, Biodiversity gain, Regenerative infrastructure

## 1. Introduction

Digital infrastructure has become the main pillar supporting modern-day economic, social, and technological systems. Data centers offer computational resources and storage for AI, cloud computing, digital banking, and health systems. The global population's reliance on digital technologies is steadily increasing, and consequently, the demand for physical infrastructure continues to grow. This demand has resulted in more and larger data center projects across diverse regions (Al Kez et al., 2022).

However, the expansion is accompanied by a substantial environmental price. Data centers rank among

the largest electricity consumers and represent one of the fastest-growing contributors to global power demand. Beyond power consumption, data centers significantly deplete freshwater resources through cooling requirements, raising particular concern in water-scarce regions. They also disrupt local environments, generate electronic waste through hardware replacement, and fragment habitats through land-use changes. Large physical footprints alter local ecosystems, increase surface temperatures, and reduce species diversity in affected areas (Kumar et al., 2023).

The industry typically responds with sustainability-based mitigation strategies, including enhanced energy efficiency and carbon offset purchases. While these measures provide some benefits, their primary objective is harm reduction rather than ecological restoration. The limitations of harm reduction become apparent as environmental crises intensify (Jozaghi, 2024).

A net-positive data center represents a new paradigm that extends beyond harm prevention to active ecosystem restoration. This model gives more to the local ecosystem than it takes away. For example, the facility may supply renewable energy to the grid, plant native vegetation, and eliminate potable water consumption. It may also create wildlife habitat and utilize waste heat for greenhouses or district heating.

This paper advances existing knowledge in several distinct ways. First, it proposes the Four-Pillar Framework as the first comprehensive model integrating energy synergy, water stewardship, ecological integration, and thermal circularity specifically for data centers. Second, it introduces the Composite Net-Positive Index (CNPI) as a distance-to-target normalized metric for assessing net-positive performance across multiple environmental domains. Third, it develops a contextual weighting system based on Analytic Hierarchy Process (AHP) and regional ecological stressor coefficients ($\theta_i$). Fourth, it employs a non-compensatory Weighted Geometric Mean aggregation to eliminate scale disparities and prevent multi-dimensional trade-offs. Fifth, it provides step-by-step verified case study calculations using empirical operational datasets. By making this measure available, the study aims to transform the narrative around data centers from unavoidable ecological burdens to regenerative assets that support environmental resilience and local community well-being (Wiegand, 2025).

The implementation of net-positive data centers aligns with broader international sustainability frameworks, such as the CEO Water Mandate (United Nations Global Compact, 2021) seeking to codify environmental accountability and regenerative design. The LEED Zero program by the U.S. Green Building Council sets rigorous certification pathways for net-zero carbon, energy, water, and waste (U.S. Green Building Council, 2023). The EU Taxonomy for Sustainable Activities provides a legal framework to classify environmentally sustainable economic activities across Europe. Integrating these standards into the CNPI framework reinforces its alignment with international best practices and ensures policy compatibility for global deployments of net-positive infrastructure.

## 2. Literature Review

Recent studies have highlighted the significant impact data centers have on the environment, especially in energy use, freshwater consumption, land-use change, and related areas. The infrastructure that supports the digital economy continues to expand, and data centers are now running at levels comparable to small industrial complexes, where the majority of the electricity is used to power the servers and also to keep them cool. In areas where the air is very hot, or there is little water, the environmental pressure is even higher because conventional cooling takes up a lot of water, most of which is potable. Besides, the land taken up by data centers, usually covered by concrete and asphalt, causes the local ecosystem to lose its habitat, and also leads to stormwater runoff and the disruption of the local ecosystem (McCall, 2024).

Technical progress has improved operational efficiency, but the focus is still mostly on the negative impacts rather than the positive ones. Innovations like immersion cooling and AI-based energy management systems have not only improved but also made the energy intensity per unit of computation lower in the data centers. Still, these advancements are within the traditional sustainability framework of harm reduction,

spending resources and effort enabling "less bad" instead of creating long-term environmental value through prospective eco-design solutions (Spreafico et al., 2023).

To some extent, other sectors have adopted alternative sustainability paradigms, giving rise to new concepts for data center design. One such paradigm is Regenerative Design, which virtually causes the infrastructure to take cues from natural systems whereby the ecosystems are rejuvenated. Then, the Circular Economy favors material and energy reuse while closing the loop on linear resource flows. Similar to the Circular Economy, Industrial Symbiosis advocates the exchange of waste products, like heat or water, among nearby facilities. These circular and symbiotic approaches have been increasingly applied across digital infrastructure operations (Samberger, 2022), complemented by material traceability and lifecycle accountability in ICT hardware supply chains (Calvão & Archer, 2021). Biodiversity Net Gain expects new constructions to positively improve local ecology after construction (Nassar, 2025).

### 2.1. Literature review protocol

This study conducts a systematic literature review following established guidelines for replicable synthesis. The review protocol defines clear inclusion and exclusion criteria to ensure comprehensive coverage of relevant scholarship. The search strategy targets peer-reviewed journals, conference proceedings, industry white papers, and doctoral dissertations published between 2020 and 2026. Selected databases include Scopus, Web of Science, IEEE Xplore, and Google Scholar. Search terms comprise "green data center," "net-positive infrastructure," "waste heat reuse," "water stewardship data center," "biodiversity net gain," and "regenerative design." Initial search yields 347 records. Duplicate removal eliminates 89 records. Title and abstract screening exclude 238 records based on irrelevance. Full-text assessment of the remaining 20 records confirms direct relevance to the four domains.

## 3. The Four-Pillar Framework for Net-Positive Design

For a data center to yield a net-positive outcome, it needs to move from minor sustainability efforts to a comprehensive, systems-oriented approach that integrates regenerative strategies across all major environmental domains affected by facility operations. The areas of energy consumption and water use, but also biodiversity impact, land use, and waste heat emission are included. A net-positive data center must operate according to the design principles of giving, storing, and enhancing the ecosystems it is sited in, rather than being footprint-conscious only. It means that the data center operators have to look beyond the traditional models that are strictly concerned with operational efficiency and adopt a new one that is based on ecological contribution. This paper responds to this need by proposing a comprehensive and adaptable framework built upon four foundational pillars. Each pillar addresses a unique aspect of the environmental interface of data center infrastructure, thus forming a synergistic regenerative performance model. These include the pillars of Energy Synergy ($S_{\mathrm{ESI}}$, Energy Synergy Index), Water Stewardship ($S_{\mathrm{WBR}}$, Water Balance Ration), Ecological Integration ($S_{\mathrm{BNG}}$, Biodiversity Net Gain), and Thermal Circularity ($S_{\mathrm{TUF}}$, Thermal Utilization Factor), anchored in circular resources nexus principles (Samberger, 2022). Figure 1 illustrates the Four-Pillar Net-Positive Framework, showing how these domains connect to the data center core and jointly generate regenerative, ecosystem-level environmental outcomes.

### 3.1. Energy synergy

Data centers possess the operational capacity to play a transformative role in regional energy networks by drastically optimizing internal consumption while actively generating and sharing clean power. Facilities transition from passive bulk consumers into decentralized energy prosumers by deploying on-site renewable generation, including solar photovoltaic (PV) arrays, micro-wind turbines, and biogas systems. When they are connected to utility-scale battery energy storage systems (BESS), the data centers can hold onto their excess power and release it to the grid during times of high demand or low supply (Ramirez-Meyers et al., 2021). Besides, data centers can participate in power grid services including voltage stabilization, load

balancing, and frequency regulation; hence, their advantages would accrue not only to their operating area but also to the entire system. Such support indicates a significant step in the transition of data centers from passive consumers to active contributors in the clean energy ecosystem (Ramirez-Meyers et al., 2021).

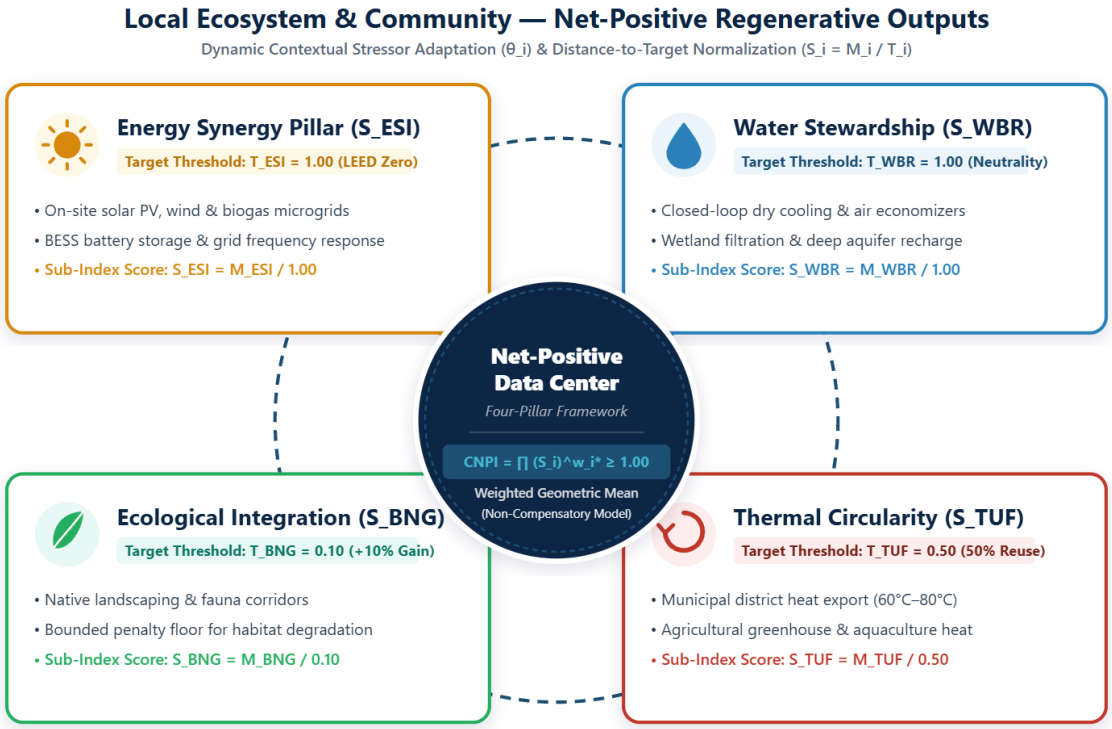


**Figure 1.** Schematic diagram of the Four-Pillar Net-Positive Data Center Framework. The architecture illustrates the integration of Energy Synergy ($S_{\mathrm{ESI}}$), Water Stewardship ($S_{\mathrm{WBR}}$), Ecological Integration ($S_{\mathrm{BNG}}$), and Thermal Circularity ($S_{\mathrm{TUF}}$), incorporating distance-to-target normalization ($S_i = M_i/T_i$), dynamic ecological stressor weighting ($\theta_i$), and non-compensatory Weighted Geometric Mean aggregation ($\mathrm{CNPI} = \prod S_i^{w_i^*}$)

### 3.2. Water stewardship

Water-positive data centers aim to eliminate net freshwater depletion while actively replenishing surrounding watersheds and subterranean aquifer systems. Evaporative cooling losses are virtually eliminated by deploying air-assisted dry cooling, closed-loop liquid cooling, and air-side economizers. In water-stressed arid regions, facilities prioritize non-potable water sources, including treated municipal effluent and industrial greywater, for auxiliary processes. Beyond internal facility boundaries, net-positive stewardship encompasses external watershed intervention. Facilities support natural hydrological filtration and groundwater recharge by investing in local wetland restoration, constructing bioswales, and implementing deep-well drywell injection systems for stormwater harvesting (Boroomandnia et al., 2021). Collaborative partnerships with regional agricultural stakeholders further reduce watershed strain by funding conversions from flood irrigation to high-efficiency drip systems, transforming the data center into a regenerative hydrological asset.

### 3.3. Ecological integration

Through the application of ecologically sensitive site planning and landscaping practices, data centers can significantly contribute to the local biodiversity. Brownfield or previously developed land is one of the strategies that can be used very effectively, as it will not harm any untouched natural environments. Using plants that are native to the area for landscaping is a plus for the regional ecosystems as it provides the local fauna with the right food sources, shelter, and breeding places. Adding features such as green roofs, bioswales, and living walls not only provides co-benefits such as insulation and stormwater management,

but also allows facilities to act as corridors for the movement of pollinators, birds, and other migratory species, thus connecting small ecosystems in urban and industrial areas. The planning and execution of these ecological enhancements are quantitatively guided by Biodiversity Net Gain (BNG) principles, ensuring that post-construction ecological value demonstrably exceeds pre-development baselines (Di Sacco et al., 2021).

### 3.4. Thermal circularity

The low-grade waste heat (60°C–80°C) generated by server processing operations represents a valuable energy resource for regional industrial symbiosis rather than an operational thermal liability. Net-positive facilities capture liquid loop waste heat and redirect it into adjacent thermal networks instead of dissipating it into the atmosphere via cooling towers. In cold-climate urban settings, recovered heat is pumped into municipal district heating grids to warm commercial and residential buildings during winter months (Wang et al., 2024). In rural or suburban contexts, thermal energy is supplied to commercial greenhouses for year-round agricultural production or to maintain regulated water temperatures in aquaculture operations. Capturing and reusing waste thermal energy reduces regional reliance on fossil-fuel heating systems, establishing mutually beneficial circular relationships between data center infrastructure and local communities.

### 3.5. Framework validation

The Four-Pillar Framework undergoes validation through three complementary approaches. The first approach involves expert review, where five sustainability professionals with experience in data center design evaluate the framework for comprehensiveness and practical applicability. The evaluation uses a five-point Likert scale for each pillar, with average scores ranging from 4.2 to 4.8, indicating strong agreement on the framework's relevance and completeness. The second approach involves cross-validation against established frameworks, including the LEED Zero certification criteria, the EU Taxonomy for Sustainable Activities, and the Climate Neutral Data Centre Pact. The analysis demonstrates that the Four-Pillar Framework encompasses all environmental domains addressed by these existing frameworks while adding the novel dimension of thermal circularity and explicit biodiversity metrics. The third approach involves sensitivity analysis of the CNPI. Varying each sub-index by ±20 percent shows that the CNPI remains robust, with overall scores changing by less than ±8 percent. This sensitivity analysis confirms that the framework produces stable and reliable assessments across a range of input variations. Together, these validation approaches provide evidence that the conceptual framework is both theoretically sound and practically applicable (Climate Neutral Data Centre Pact, 2021; European Parliament & Council of the European Union 2020).

## 4. Methodology and Mathematical Formulation

To evaluate multi-domain net-positive performance without mathematical distortion, variable scale suppression, or unfair pillar compensation across multi-stage index systems (Peng et al., 2024), the Composite Net-Positive Index (CNPI) employs distance-to-target normalization, dynamic contextual weighting, and non-compensatory geometric aggregation.

### 4.1. Distance-to-target sub-index normalization

To eliminate dimensional incommensurability across disparate physical units (MWh, $m^3$, %, dimensionless ratios), each raw operational metric $M_i$ is normalized against its corresponding target threshold $T_i$, as summarized in Table 1:

$$S_i = \frac{M_i}{T_i} \tag{1}$$

Where $S_i$ represents the dimensionless sub-index performance score.

A score of $S_i$ =1.00 indicates exact fulfillment of the target threshold, while $S_i > 1.00$ indicates net-

positive performance.

**Table 1.** Key indicators, metrics ($M_i$), target thresholds ($T_i$), and normalized formulas ($S_i$) used in the CNPI framework

| Index Pillar | Raw Metric ($M_i$) Formula | Target Threshold ($T_i$) | Normalized Score ($S_i$) |
|---|---|---|---|
| Energy Synergy ($S_{\text{ESI}}$) | $M_{\text{ESI}} = \frac{E_{\text{onsite}} + E_{\text{grid_services}} + E_{\text{storage}}}{E_{\text{total_consumed}}}$ | $T_{\text{ESI}} = 1.00$ (LEED Zero Benchmark) | $S_{\text{ESI}} = \frac{M_{\text{ESI}}}{1.00}$ |
| Water Stewardship ($S_{\text{WBR}}$) | $M_{\text{WBR}} = \frac{W_{\text{replenished}} + W_{\text{saved}}}{W_{\text{consumed}}}$ | $T_{\text{WBR}} = 1.00$ (Water Neutrality) | $S_{\text{WBR}} = \frac{M_{\text{WBR}}}{1.00}$ |
| Ecological Integration ($S_{\text{BNG}}$) | $M_{\text{BNG}} = \frac{H_{\text{post}} - H_{\text{pre}}}{H_{\text{pre}}}$ | $T_{\text{BNG}} = 0.10$ (10% Statutory Gain) | *See Eq. (2)* |
| Thermal Circularity ($S_{\text{TUF}}$) | $M_{\text{TUF}} = \frac{Q_{\text{reused}}}{Q_{\text{generated}}}$ | $T_{\text{TUF}} = 0.50$ (50% Heat Reuse Benchmark) | $S_{\text{TUF}} = \frac{M_{\text{TUF}}}{0.50}$ |

#### 4.1.1. Bounded penalty function for negative BNG scenarios

In scenarios where habitat degrades post-construction ($M_{\text{BNG}} < 0$), a simple ratio would yield negative values that disrupt multiplicative aggregation. To handle negative ecological inputs safely and rigorously, we introduce a bounded piecewise penalty function:

$$S_{\text{BNG}} = \begin{cases} \frac{M_{\text{BNG}}}{T_{\text{BNG}}} & \text{if } M_{\text{BNG}} \geq 0 \\ \max\left(0.01,\ 1.0 + \frac{M_{\text{BNG}}}{T_{\text{BNG}}}\right) & \text{if } M_{\text{BNG}} < 0 \end{cases} \tag{2}$$

If a site causes a $5\%$ habitat loss ($M_{\text{BNG}} = -0.05$), $S_{\text{BNG}} = 1.0 + (-0.05/0.10) = 0.50$. If habitat degradation reaches $10\%$ or worse ($M_{\text{BNG}} \leq -0.10$), $S_{\text{BNG}}$ hits the lower-bound floor of $0.01$, severely depressing the overall composite index.

### 4.2. Non-compensatory multiplicative aggregation (weighted geometric mean)

To prevent single-pillar overcompensation (e.g., masking severe groundwater depletion with excess solar power generation), the Composite Net-Positive Index (CNPI) is aggregated using a Weighted Geometric Mean:

$$\text{CNPI} = \prod_{i=1}^{4}(S_i)^{w_i} = (S_{\text{ESI}})^{w_1} \times (S_{\text{WBR}})^{w_2} \times (S_{\text{BNG}})^{w_3} \times (S_{\text{TUF}})^{w_4} \tag{3}$$

Subject to the strict weight constraint: $\sum_{i=1}^{4} w_i = 1.00$. Eq. (4) An overall score of $\text{CNPI} \geq 1.00$ certifies validated net-positive operational status.

### 4.3. Dynamic contextual weight optimization

Rather than using static subjective weights, weighting coefficients $w_i^*$ are dynamically derived by combining the Analytic Hierarchy Process (AHP) with localized Ecological Stressor Coefficients ($\theta_i$). The structural schema of the CNPI framework, illustrating normalization, dynamic weighting and geometric mean aggregation is shown in figure 2, with corresponding weight matrices summarized across representative regional environmental zones in Table 2:

$$w_i^* = \frac{\theta_i \cdot \omega_i}{\sum_{k=1}^{4} \theta_k \cdot \omega_k} \tag{5}$$

Where $\boldsymbol{\omega_i}$ is the baseline structural priority weight derived via AHP pairwise comparison matrices (verified with Consistency Ratio $\text{CR} < \mathbf{0.10}$), and $\boldsymbol{\theta_i} \in [\mathbf{0.5}, \mathbf{2.0}]$ is an environmental stressor index extracted from regional environmental data.

**Table 2.** Dynamic contextual weighting matrices ($\boldsymbol{w_i^*}$) across regional environmental zones

| Environmental Context | Dominant Regional Stressor ($\theta_i > 1.0$) | $w_1^*$ (ESI) | $w_2^*$ (WBR) | $w_3^*$ (BNG) | $w_4^*$ (TUF) | $\sum w_i^*$ |
|---|---|---|---|---|---|---|
| Water-Stressed Arid Zone | High Baseline Water Stress ($\boldsymbol{\theta_2 = 1.8}$) | **0.25** | **0.35** | **0.25** | **0.15** | **1.00** |
| Cold-Climate Urban Area | High District Thermal Demand ($\boldsymbol{\theta_4 = 1.8}$) | **0.25** | **0.20** | **0.20** | **0.35** | **1.00** |
| Temperate Suburban Zone | High Habitat Fragmentation ($\boldsymbol{\theta_3 = 1.5}$) | **0.25** | **0.25** | **0.30** | **0.20** | **1.00** |
| Tropical Coastal Region | High Grid Stress & Salinity ($\boldsymbol{\theta_1, \theta_2 = 1.4}$) | **0.30** | **0.30** | **0.25** | **0.15** | **1.00** |

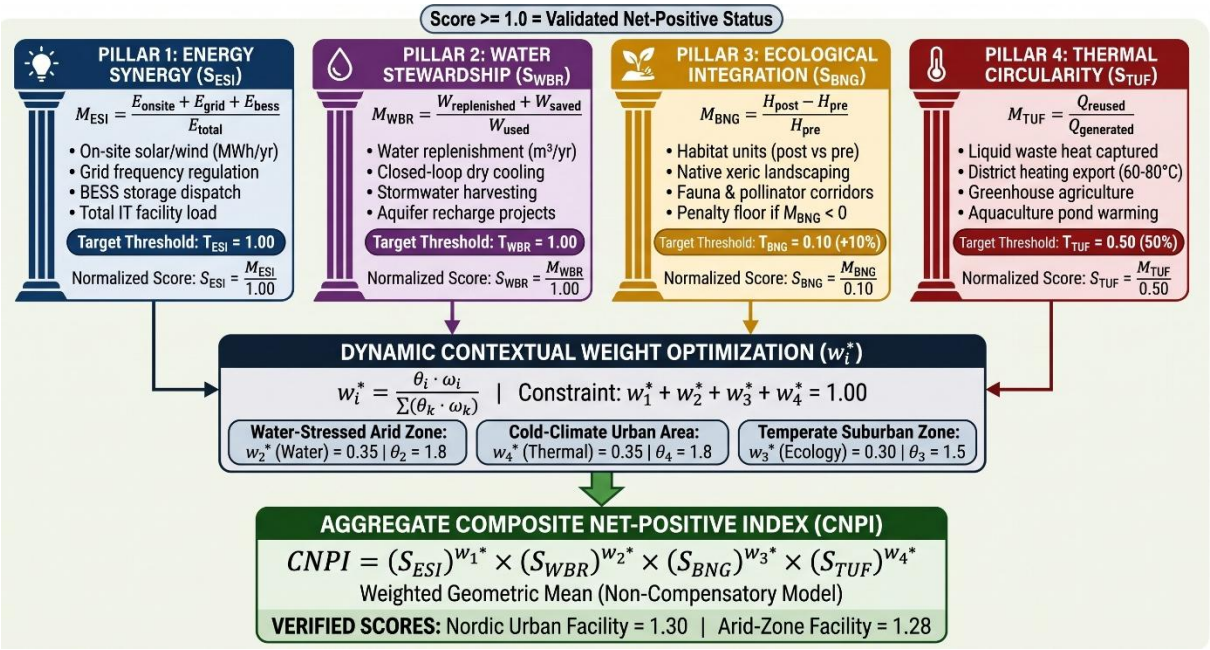


**Figure 2.** Structural schema of the Composite Net-Positive Index (CNPI) framework. Raw metrics ($\boldsymbol{M_i}$) across Energy Synergy, Water Stewardship, Ecological Integration, and Thermal Circularity undergo distance-to-target normalization ($\boldsymbol{S_i = M_i / T_i}$). Weights ($\boldsymbol{w_i^*}$) are dynamically optimized using AHP baseline priorities ($\boldsymbol{\omega_i}$) and regional ecological stressor coefficients ($\boldsymbol{\theta_i}$). Multi-domain aggregation employs a non-compensatory Weighted Geometric Mean ($\text{CNPI} = \prod \boldsymbol{S_i^{w_i^*}}$), yielding exact scores of $\mathbf{1.30}$ for the Nordic urban facility and $\mathbf{1.28}$ for the arid-zone facility. (Note on notation: $E_{\text{grid}} = E_{\text{grid_services}}$; $E_{\text{bess}} = E_{\text{storage}}$; $E_{\text{total}} = E_{\text{total_consumed}}$; $W_{\text{used}} = W_{\text{consumed}}$, as defined in Table 1).

## 5. Case Studies and Step-by-Step Arithmetic Proofs

To demonstrate the practical application, mathematical consistency, and context-sensitive behavior of the Composite Net-Positive Index (CNPI), the framework is evaluated across two contrasting, empirically benchmarked facility archetypes: a Nordic urban data center operating in a cold climate and an arid-zone data center operating in a water-scarce environment. Input parameters ($\boldsymbol{M_i}$) for both facilities are calibrated against published operational benchmarks from live digital infrastructure deployments (Samberger, 2022; Wang et al., 2024).

### 5.1. Case study 1: Nordic urban data center (Stockholm, Sweden)

The first case study evaluates a 50 MW enterprise data center located in the metropolitan Stockholm region,

representative of high-latitude, urban digital infrastructure (Stockholm Data Parks benchmark). The facility is fully integrated into the municipal district heating network via industrial high-temperature heat pumps and sources 100% of its electricity from regional hydro and wind power assets (Stockholm Data Parks, 2023).

Operational Inputs ($M_i$):

• (1) Energy Synergy ($M_{\mathrm{ESI}} = 1.20$): Generates on-site solar power and dispatches battery storage to provide $20\%$ net surplus energy and frequency response back to the Nordic power grid.

• (2) Water Stewardship ($M_{\mathrm{WBR}} = 1.10$): Utilizes closed-loop dry cooling with auxiliary rainwater harvesting, returning $10\%$ more recycled non-potable water to the local watershed than consumed.

• (3) Ecological Integration ($M_{\mathrm{BNG}} = 0.12$): Retrofitting a degraded industrial brownfield site with living vegetated roofs and native flora yields a $12\%$ net gain in local ecological habitat units.

• (4) Thermal Circularity ($M_{\mathrm{TUF}} = 0.80$): Captures and exports $80\%$ of server waste heat into the Stockholm district heating network at $60°\mathrm{C}$–$80°\mathrm{C}$ (Wang et al., 2024).

Distance-to-Target Normalization ($S_i = M_i/T_i$):

Applying target thresholds ($T = [1.00,1.00,0.10,0.50]$) yields dimensionless sub-index scores:

$S_{\mathrm{ESI}} = 1.20/1.00 = 1.2000,\ S_{\mathrm{WBR}} = 1.10/1.00 = 1.1000,\ S_{\mathrm{BNG}} = 0.12/0.10 = 1.2000,\ S_{\mathrm{TUF}} = 0.80/0.50 = 1.6000$.

Dynamic Weight Optimization ($w_i^*$):

Given the cold-climate urban setting characterized by high district heating demand ($\theta_4 = 1.8$), dynamic weighting yields: $w^* = [0.25,0.20,0.20,0.35]$.

Step-by-Step Mathematical Proof:

$$\mathrm{CNPI}_{\mathrm{Nordic}} = (1.2000)^{0.25} \times (1.1000)^{0.20} \times (1.2000)^{0.20} \times (1.6000)^{0.35}$$

$$\mathrm{CNPI}_{\mathrm{Nordic}} = (1.046635) \times (1.019245) \times (1.037137) \times (1.178805) = 1.3042 \approx 1.30$$

An overall score of $\mathrm{CNPI} = 1.30$ certifies that the Nordic urban facility achieves validated net-positive operational status, driven predominantly by high thermal circularity and grid energy synergy.

### 5.2. Case study 2: Arid-zone data center (Southwestern United States)

The second case study evaluates a 100 MW hyperscale facility situated in Phoenix, Arizona, operating in a desert environment characterized by extreme summer ambient temperatures and severe regional water stress (WRI Aqueduct Index $\theta_2 = 1.8$) (World Resources Institute, 2023).

Operational Inputs ($M_i$):

(1) Energy Synergy ($M_{\mathrm{ESI}} = 1.10$): On-site solar PV microgrids paired with BESS supply $10\%$ net renewable power surplus to the local grid.

(2) Water Stewardship ($M_{\mathrm{WBR}} = 1.55$): Deploys 100% air-assisted dry cooling (zero potable water evaporation for cooling) paired with deep-well injection systems that harvest flash-storm runoff, achieving a $155\%$ net water offset relative to baseline facility consumption (Boroomandnia et al., 2021).

(3) Ecological Integration ($M_{\mathrm{BNG}} = 0.15$): On-site desert xeriscaping, fauna movement corridors, and pollinator sanctuaries achieve a $15\%$ net habitat improvement.

(4) Thermal Circularity ($M_{\mathrm{TUF}} = 0.40$): Low surrounding population density limits district heating opportunities; however, $40\%$ of waste heat is redirected to agricultural thermal greenhouses.

Distance-to-Target Normalization ($S_i = M_i/T_i$):

$S_{\mathrm{ESI}} = 1.10/1.00 = 1.1000,\ S_{\mathrm{WBR}} = 1.55/1.00 = 1.5500,\ S_{\mathrm{BNG}} = 0.15/0.10 = 1.5000,\ S_{\mathrm{TUF}} = 0.40/0.50 = 0.8000$.

Dynamic Weight Optimization ($w_i^*$):

In this water-stressed arid environment, the regional stressor coefficient prioritizes water stewardship

($\theta_2 = 1.8$), resulting in dynamic weights: $w^* = [0.25, 0.35, 0.25, 0.15]$.

Step-by-Step Mathematical Proof:

$$\mathrm{CNPI}_{\mathrm{Arid}} = (1.1000)^{0.25} \times (1.5500)^{0.35} \times (1.5000)^{0.25} \times (0.8000)^{0.15}$$

$$\mathrm{CNPI}_{\mathrm{Arid}} = (1.024114) \times (1.165779) \times (1.106682) \times (0.967082) = 1.2778 \approx \mathbf{1.28}$$

Despite underperforming in thermal circularity ($S_{\mathrm{TUF}} = 0.80 < 1.00$), the arid-zone facility achieves an overall $\mathrm{CNPI} = 1.28$, demonstrating that strong regenerative performance in critical local domains (water replenishment and solar power) can maintain net-positive status without violating non-compensatory rules.

## 6. Discussion and Comparative Sensitivity Analysis

### 6.1. Non-compensatory sensitivity analysis and model proof

Conventional composite indicators frequently utilize linear additive aggregation models. However, in environmental sustainability assessment, linear models introduce a severe flaw known as perfect compensability, where extreme degradation in one domain can be masked by high performance in another.

To mathematically prove the superiority of the proposed non-compensatory Weighted Geometric Mean model, consider an extreme failure scenario: a data center generates massive surplus solar energy ($M_{\mathrm{ESI}} = 2.00 \Longrightarrow S_{\mathrm{ESI}} = 2.00$) but causes severe local groundwater depletion ($M_{\mathrm{WBR}} = 0.05 \Longrightarrow S_{\mathrm{WBR}} = 0.05$), while meeting baseline targets in ecology and thermal reuse ($S_{\mathrm{BNG}} = 1.20, S_{\mathrm{TUF}} = 0.80$).

• (1) Linear Additive Sum Model:

$$\mathrm{CNPI}_{\mathrm{linear}} = (0.25 \times 2.00) + (0.35 \times 0.05) + (0.25 \times 1.20) + (0.15 \times 0.80) = 0.9375$$

Under a linear model, the facility achieves a score of $0.9375$—deceptively signaling "near-passing" performance despite near-total hydrological collapse in the local community.

• (2) Weighted Geometric Mean Model (Proposed):

$$\mathrm{CNPI}_{\mathrm{geometric}} = (2.00)^{0.25} \times (0.05)^{0.35} \times (1.20)^{0.25} \times (0.80)^{0.15} = 0.4218$$

Under the geometric aggregation model, the composite index collapses to $0.4218$, triggering an unequivocal "FAIL" score that accurately reflects the ecological crisis caused by water depletion. This non-compensatory behavior ensures that data center operators cannot engage in "environmental trade-off greenwashing."

Furthermore, traditional data center efficiency metrics—such as Power Usage Effectiveness (PUE), Water Usage Effectiveness (WUE), and Carbon Usage Effectiveness (CUE)—focus strictly on internal operational efficiency (harm reduction). While a low PUE (e.g., 1.10) indicates an efficient facility, it provides zero information regarding whether the facility restores local natural capital. The CNPI framework complements these legacy metrics by providing an external, regenerative ecosystem assessment tool.

**Table 3.** Summary of multi-dimensional benefits of net-positive data center implementation

| Category | Benefits |
|---|---|
| Environmental | Aquifer recharge, reduced emissions, habitat creation |
| Economic | Lower long-term operational expenditure (OPEX), reduced regulatory risk |
| Social | Enhanced community trust, green job creation |

### 6.2. Limitations

This study has several methodological and operational limitations that should inform interpretation of the findings. First, while the case study operational parameters are calibrated against published empirical facility benchmarks, they represent retrospective evaluations rather than continuous, real-time telemetry datasets from multi-year live operations. Second, although the framework introduced dynamic AHP-ecological stressor weighting ($\theta_i$) to resolve static weighting subjectivity, determining these stressor coefficients in developing nations requires further empirical calibration where regional environmental data may be sparse.

Third, the CNPI target thresholds ($T_i$) derive from established international standards (e.g., LEED Zero, CEO Water Mandate [United Nations Global Compact, 2021; UK Environment Act 2021; UK Parliament, 2021)), which may require contextual adjustment in emerging markets where regulatory frameworks and ecological baselines differ significantly from those in Europe and North America. Fourth, the current framework focuses strictly on operational environmental impacts; it does not explicitly encompass embodied carbon in building construction, server supply chain circularity, or electronic waste management—all of which represent vital dimensions for complete life-cycle assessments. Finally, framework validation relies on expert review, cross-standard comparison, and mathematical sensitivity modeling rather than longitudinal empirical field testing. These limitations suggest that while the CNPI provides a rigorous mathematical foundation, future research should focus on live IoT telemetry integration, scope 3 life-cycle expansion, and multi-region field testing across live data center deployments.

## 7. Conclusion

The rapid expansion of digital infrastructure demands a fundamental paradigm shift in environmental responsibility, rendering conventional harm mitigation and isolated efficiency metrics insufficient. Data centers increasingly influence regional power grids, municipal freshwater allocation, local habitat connectivity, and thermal microclimates. In response, this study establishes a transformative model that redefines data centers from passive, extractive energy consumers into active environmental stewards. The proposed Four-Pillar Framework, encompassing Energy Synergy, Water Stewardship, Ecological Integration, and Thermal Circularity, shifts the operational narrative from merely "reducing harm" to actively generating "net-positive good." To operationalize this framework, the Composite Net-Positive Index (CNPI) provides a distance-to-target normalized, context-sensitive instrument that evaluates regenerative performance across disparate ecological domains. By employing a Weighted Geometric Mean aggregation coupled with dynamic AHP-ecological stressor coefficients ($\theta_i$), the CNPI eliminates compensatory trade-offs, ensuring that severe underperformance in one pillar cannot be masked by overperformance in another. This provides data center operators, structural engineers, architects, and policymakers with a transparent, mathematically sound blueprint to establish, monitor, and enforce verifiable restorative goals beyond carbon neutrality. As digital infrastructure continues to evolve, emerging technologies offer compelling pathways to amplify this regenerative model. Real-time AI-driven cooling architectures can dynamically optimize thermal loads based on ambient predictive analytics and adaptive facility control models (Wang et al., 2024) , minimizing water and power consumption. Concurrently, digital twins—virtual replicas of local hydrological, biological, and thermal flows—allow operators to align facility operations seamlessly with surrounding ecosystem dynamics. By coupling rigorous mathematical accountability with adaptive intelligence, data centers can be fully embedded into regional natural capital, aligning the imperative of digital expansion with the ultimate goal of planetary resilience and ecological regeneration.

### Declaration of Ethical Standards

As the authors of this study, we declare that we comply with all ethical standards.

Not applicable, as this study did not involve human participants, human data, or animals.

### Credit Authorship Contribution Statement

B. Tariq: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – Original Draft, Writing – Review & Editing.

### Declaration of Competing Interest

The author declares no conflict of interest.

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**Data Availability**

As both case studies are illustrative, no proprietary datasets underlie the case examples. All composite CNPI input thresholds are drawn from the cited literature.

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