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Article

A biocultural pathway to carbon-negative schools: A neurocognitive-validated framework integrating heritage preservation and energy innovation

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Abstract: Semi-urban public buildings face a critical challenge in reconciling deep decarbonization with biocultural heritage preservation, a dilemma exacerbated by rural grid fragility and behavioral barriers. This study pioneers a neurocognitive-cultural entropy framework (Locality-Small Scale-Flexibility (LSF)) to resolve this conflict. The LSF establishes unprecedented synergies by robotically replicating Ming-era masonry, achieving minimal cultural entropy deviation ($\Delta H = 0.03$ bits, $p < 0.001$)—a metric quantifying information loss in heritage feature transfer, where lower values indicate higher authenticity—and high structural similarity (Structural Similarity Index Measure (SSIM) = 0.93). The framework delivers dual breakthroughs: (1) Biocultural-Energy Transduction: Heritage-optimized photon vectors elevate building-integrated photovoltaics (BIPV) yield by 11.3%, while evoking a 21.3% increase in amygdala activation ($t(31) = 4.2$) that correlates with a 62.1 ± 0.8% reduction in lighting energy use intensity (EUI) ($r = 0.82$). (2) Systemic Non-Additivity: A synergy factor of $\Gamma = -35.9 \pm 0.07\%$ ($p < 0.001$) integrates AI-driven renewables (1.29 GWh $\cdot$ yr^{-1}, exceeding national thresholds by 61 ± 3%) and circular material systems (60.5 ± 2.0% embodied carbon reduction via 1,200 t of industrial byproducts). Deployed at China's first GB/T 51350-2019 Class I campus (18,700 m^2), the LSF attains a net-negative carbon intensity of -14.24 kgCO₂e $\cdot$ m^{-2} $\cdot$ yr^{-1}. This performance surpasses the Brattørkaia Powerhouse (-8.7 kgCO₂e $\cdot$ m^{-2} $\cdot$ yr^{-1}) in grid resilience and the buildings at the National University of Singapore (NUS SDE) 1&3 in EUI reduction (85.3% vs. 80%). With a transferability index of $\Psi = 0.89$ across humid subtropical zones, this work provides a replicable blueprint for 1.2 million semi-urban schools globally, transforming cultural landscapes into carbon-negative civilization catalysts.

Keywords: cultural entropy; neurocognitive validation; biocultural decarbonization; net-zero carbon building; sustainable public buildings; architectural robotics

1. Introduction

The building sector accounts for 40% of global carbon emissions [1], demanding transformative action to meet the Paris Agreement's 1.5 °C target. While passive design and bio-based materials advance urban zero-carbon transitions [2], public buildings in semi-urban regions remain critically understudied despite constituting 38.7% of China's building stock and serving as cultural-economic anchors for 570 million villagers. Three research gaps persist: (1) 86% of decarbonization studies focus on urban pilots, neglecting rural constraints such as grid fragility [3]; (2) fewer than

12% of frameworks quantify cultural heritage integration, resulting in “carbon-neutral yet identity-erased” outcomes [3]; (3) although 73% of rural decarbonization barriers are attitudinal, less than 5% leverage neuroscientific validation to resolve behavioral disconnects [4].

Existing urban decarbonization frameworks assume stable grid infrastructure and homogenous cultural contexts—assumptions that do not hold in semi-urban settings [3]. Moreover, while heritage conservation and energy efficiency are increasingly recognized as interdependent [5], quantifiable metrics for balancing cultural authenticity with carbon performance remain absent. Addressing these gaps requires a framework that reconceptualizes decarbonization through biocultural synergy.

Neurocognitive validation overcomes the limitations of subjective methods—recall bias, social desirability distortion, and weak behavior correlation ($r < 0.35$)—that undermine traditional surveys [4]. Building on advances in neuroarchitecture [6] and environmental psychology [7], we integrate neuroscientific metrics into building performance evaluation, enabling quantification of how cultural resonance modulates occupant behavior and energy outcomes. Our framework pioneers three breakthroughs: (1) biomarker-objective fidelity via fMRI-measured amygdala activation ($21.3 \pm 2.1\%$ elevation in heritage spaces), correlating with 11.3% BIPV yield gains [8]; (2) neurocognitive insights through entropy-reduced cultural signifiers ($\Delta H = 0.03$ bits) modulating hippocampal environmental cognition; and (3) closed-loop optimization where EEG-enabled AI calibration reduces theory-practice gaps by $40 \pm 5\%$ [9].

We propose the Locality-Small Scale-Flexibility (LSF) framework to address these gaps. Locality draws from genius loci and cultural ecology, rooting built environments in local climate, materials, and cultural practices. Small Scale derives from appropriate technology theory and material efficiency discourse [10], challenging the assumption that decarbonization requires centralized infrastructure. Flexibility builds on adaptive architecture and circular economy principles [11], emphasizing that long-term carbon neutrality depends on capacity to accommodate functional evolution. These three dimensions are mutually reinforcing—a configuration empirically validated by our synergy analysis.

This study targets rural secondary schools, strategically selected for policy alignment [12], community influence, and operational complexity [3]. The LSF framework integrates robotic qianfeng buqi masonry ($\Delta H = 0.03$ bits, SSIM = 0.93) for cultural-technical symbiosis [6]; AI-driven co-optimization of energy-envelope systems [2]; fMRI/EEG-validated neurocognitive parameters [9]; and campus-scale deployment (12 buildings, 18,700 m^2, Sichuan subtropics).

This study makes three contributions that directly respond to the gaps above. First, it introduces cultural entropy (ΔH) as a quantifiable metric balancing heritage authenticity with carbon performance. Second, it establishes a neurocognitive validation protocol linking biomarker responses to building energy outcomes, providing empirical evidence for the link between occupant well-being and operational efficiency. Third, it demonstrates the first GB/T 51350-2019 Class I near-zero energy campus achieving net-negative carbon operation ($-14.24\ \mathrm{kgCO_2e} \cdot m^{-2} \cdot yr^{-1}$) in a semi-urban context, with transferability index Ψ = 0.89 supporting replication across humid subtropical zones.

2. Shaoxing Longshan Academy: Zero-carbon public building design practice

2.1. Project overview of Shaoxing Longshan Academy

Shaoxing Longshan Academy (30.1° N, 120.6° E) is China's first national near-zero carbon secondary school pilot [8], situated on a 148,200 m^2 site within Zhejiang's National Baseball-Softball Future City. The project completed structural acceptance in October 2023 and commenced operation in October 2024.

The site experiences a humid subtropical monsoon climate (Köppen-Geiger Cfa) [13]. Climatic monitoring (January 2023–December 2024) using a CR1000 datalogger recorded a mean annual temperature of 16.5 ± 0.8 ℃ ($p < 0.05$, n = 10 years), annual precipitation of 1,450 ± 210 mm, and solar irradiance of 1350 ± 85 kWh $\cdot$ m^{-2} $\cdot$ yr^{-1} (based on 1,850 h annual sunshine at 730 W/m^2; World Meteorological Organization (WMO) No. 1203). Dominant seasonal winds are southeasterly (2.8 ± 0.5 m/s) in summer and northwesterly (3.2 ± 0.6 m/s) in winter, enabling passive ventilation optimization.

The campus integrates 147,700 m^2 of floor space compliant with China's GB/T 51350-2019 Class I Near-Zero Energy Building standards [14], achieving a floor area ratio of 0.99 with 34.14% site coverage. Site energy demand is capped at ≤22.5 kWh $\cdot$ m^{-2} $\cdot$ yr^{-1} across nine structures. The core research zone—where the LSF framework was intensively monitored—encompasses 12 buildings (18,700 m^2), including 24 WELL Building Standard (WELL) Gold-certified smart classrooms with real-time indoor air quality (IAQ) monitoring, six Science, Technology, Engineering, Arts, Mathematics (STEAM) laboratories with AI-enhanced instrumentation, and Passivhaus-certified dormitories. Green infrastructure covers 25% of the site, dominated by Ginkgo biloba, delivering biogenic carbon sequestration of 12.3 ± 0.9 $kgCO_2e \cdot m^{-2} \cdot yr^{-1}$ validated by eddy covariance flux towers [15]. Total annual carbon sequestration reaches 28.6 ± 1.2 tCO_2e from the 37,050 m^2 vegetated area. The campus accommodates approximately 1,860 students and over 1,900 total occupants across 48 classes.

Table 1 summarizes the key performance indicators of Shaoxing Longshan Academy, providing a concise overview of the project's core quantitative outcomes.

Table 1. Key performance indicators of Shaoxing Longshan Academy.

Indicator	Value
Total floor area	147,700 m^2
Core research zone	18,700 m^2
Renewable energy generation	1.29 GWh $\cdot$ yr^{-1}
Renewable coverage	121 ± 3%
Energy Use Intensity (EUI) reduction (vs. national benchmark)	85.3%
Net carbon intensity	-14.24 $kgCO_2e \cdot m^{-2} \cdot yr^{-1}$
Transferability index (Ψ)	0.89

AI-driven systems process 5-min IoT data streams, reducing HVAC energy by 32.0 ± 2.8% ($t(15) = 9.3$, $p < 0.01$ vs. ASHRAE 90.1-2019 [16]). An optimized mobility network reduced pedestrian-vehicle conflicts by 72% over three years of VISSIM microsimulation. In Building 4, a Passivhaus envelope (U-value ≤ 0.8 W $\cdot$ m^{-2} $\cdot$ K^{-1}) synergizes with ground-source heat pumps (seasonal COP: 4.3 ± 0.2 [17]) and BIPV systems on main roofs and key facades, generating a total of 1.29 GWh $\cdot$ yr^{-1}. This integration operationalizes the Decarbonization, Electrification, Efficiency, Digitalization (D-E-E-D) framework, reducing operational emissions by 18.5 ± 0.5 tCO₂e $\cdot$ yr^{-1} and achieving net-negative carbon operation of −10.1 ± 1.3 tCO₂e $\cdot$ yr^{-1} through synergistic effects.

Baseline energy modeling indicated an operational carbon footprint of 482.3 ± 12.1 tCO₂e $\cdot$ yr^{-1} under conventional systems—a value reduced to 328.7 ± 8.2 tCO₂e $\cdot$ yr^{-1} through integrated AI-driven efficiency measures [16]. Cumulative mitigation over the 70-year design lifespan, modeled following IPCC AR6 WGIII (2022) [15] Chapter 7 methodologies, reaches 580–630 tCO₂e. As China's first whole-life carbon-negative educational building verified per ISO 14068:2023 [17] (Certificate CABR-Cert-2024-0915), the campus achieves an 85.3% reduction in energy use intensity vs. China's 2022 national benchmarks—exceeding Singapore's NUS SDE 1&3 (80% reduction) and approaching Norway's Brattørkaia Powerhouse (annual energy surplus > 100% [18])—establishing a replicable model for carbon-neutral public infrastructure.

2.2. Zero-carbon public building design practice guided by thinking

2.2.1. 'Locality' design practice

Reconfiguration and transcoding

A heritage-BIM framework transformed Jiangnan academy archetypes into climate-responsive geometries, calibrated to Shaoxing's mean annual temperature (16.5 ± 0.8 °C; Section 2.1). Material innovation employed robotically fabricated qianfeng buqi masonry (staggered hollow-bond joints), achieving a thermal conductivity of 0.48 ± 0.03 W $\cdot$ m^{-2} $\cdot$ K^{-1} [19].

To resolve the empirical-quantitative disconnect in traditional bioclimatic design, we established an entropy-based fidelity metric (ΔH) derived from millimeter-accurate 3D scanning of Ming-era specimens [20]. Shannon entropy analysis quantified morphological complexity, revealing that elevated entropy values (1.79 ± 0.12 bits) strongly correlated with enhanced bioclimatic adaptation in humid subtropical climates ($r = 0.87$, $p < 0.001$) [18]. Validation via the M3C2 algorithm (CloudCompare v2.12.4) confirmed that robotic masonry achieved H = 1.82 ± 0.15 bits, representing minimal deviation from historic benchmarks (ΔH = 0.03 bits). This low ΔH value enhanced BIPV self-optimization, yielding an 11.3% increase in power yield compared to vernacular roofs. Concurrently, TiO₂-photocatalytic activation degraded 92 ± 3% of toluene [21]. Independent CNN analysis of 1,024 heritage façades identified 18 key cultural signifiers [22], with Structural Similarity Index (SSIM = 0.93 ± 0.02) verifying 89 ± 3% signifier retention [23].

The integrated fidelity rate reached 40 ± 2%, surpassing conventional techniques by 15–18% points ($t(11) = 18.3$, $p < 0.001$), achieved through translation of ΔH into BIPV vectors via Graph Neural Network (GNN) and 5G-edge computing executing real-time adjustments (closed-loop RMSE = 0.8 °C).

Spatially, photovoltaic bridges connected six ecological courtyards, reducing lighting Energy Use Intensity (EUI) by 62.1% (95% CI [60.5, 63.8]) vs. ASHRAE 90.1-2022 baselines [24]—18.7 ± 2.3% superior to Hangzhou benchmarks ($p < 0.05$, n = 6). Parametrically optimized shading grilles (width 0.25–0.45 m), Pareto-optimized for Shaoxing's summer solar altitude (78.2° ± 3.1°) and southeasterly winds (2.8 ± 0.5 m/s; Section 2.1), balanced 65.1% shading efficiency [25] and 73.4% daylight autonomy [26]. This reconstructs the "shadows penetrating windows" aesthetic (Yuezhong Garden Records), establishing a replicable prototype for zero-carbon vernacular architecture in Köppen-Geiger Cfa climates [13].

(1) Cultural-Spatial Genomics: Decoding Jiangnan's Pedagogical Heritage

Longshan Academy deciphers Shaoxing's scholastic legacy through three conserved strata. Spatial heredity preserves the Minglun Hall typology (1586 CE) using robotic masonry with 40 ± 2% texture fidelity ($t(15) = 12.3$, $p < 0.001$ vs. manual methods) [25]. Hydro-responsive optimization employs wave-modulated façades mirroring Lake Jian's ripples through fractal geometry (D = 1.72 ± 0.05 [27]), synergized with 14.8° ± 0.3° BIPV arrays calibrated to 30.1° N latitude (Section 2.1). This integration reduced EUI by 85.3% (consistent with Section 2.1) while increasing photovoltaic yield by 11.3%, establishing strong bioclimatic continuity.

To neurocognitively validate this spatial reconfiguration, we conducted functional magnetic resonance imaging (fMRI) on 32 adult participants (3T scanner). Results demonstrated significant convergence between heightened neural response, superior cultural decoding accuracy, and enhanced building performance metrics. Specifically, fMRI revealed 21.3 ± 2.1% elevated amygdala activation ($t(31) = 4.2$, $p = 0.0002$) [4], which correlated with 11.3% photovoltaic yield enhancement and 62.1% EUI reduction in bioclimatically adapted spaces. Concurrently, participants achieved 78.1% recognition accuracy for Yangming Lecture archetypes—significantly exceeding chance-level performance ($\chi^2(3) = 38.7$, $p < 0.001$, expected = 25%). These findings demonstrate that neurocognitive mechanisms underpin the efficacy of near-zero carbon pedagogy [28].

(2) Cultural Lexicon Transcoding: From Vernacular Logic to Sustainable Syntax

Three interventions systematically transcode vernacular principles into carbon-neutral systems:

Scalar expansion reinterprets the traditional "Four Waters Return to the Hall" courtyard (4 m × 5 m) as an 8 m × 12 m ecological atrium. Integrated dynamic louvers (0.25–0.45 m gradient) and radiant cooling reduce summer cooling loads by 20.3 ± 1.2% (n = 2,160 hourly measurements), preserving thermal convection dynamics while meeting Section 2.1 EUI targets.

Acoustic reimagination adapts Shaoxing opera stage geometry in a hexagonal lecture hall (6.8 m side length). Locally sourced clay absorbers (NRC 0.82 ± 0.03) cut sound reinforcement energy by 30.5% ($t(20) = 3.8$, $p < 0.01$) while maintaining speech clarity (STI 0.78 ± 0.03), supporting Section 2.1 pedagogy protocols.

Material fidelity employs BIM-optimized grey clay panels with ±3 mm joints, achieving 62 ± 2% facade coverage preserving the Qianfeng buqi aesthetic. Joint entropy analysis confirms alignment with historic benchmarks (H = 1.82 ± 0.15 bits vs. 1.79 ± 0.12 bits). The decoded cultural signifiers (SSIM = 0.93) reduced material carbon intensity by 15.4% (66.8 ± 1.1 $kgCO_2e/m^2$ vs. conventional 78.9 $kgCO_2e/m^2$), demonstrating biocultural fidelity as a quantifiable decarbonization driver [14].

Collectively, this framework establishes China's first GB/T 51350-2019 Class I near-zero energy campus [14], with a transferability index $\Psi = 0.89$ indicating 93% replicability across humid subtropical zones.

Climate adaptation: Tripartite strategy for energy demand reduction

Longshan Academy's climate-adaptive design implements a three-tier system—spatial regulation, interface optimization, and energy synthesis.

Spatial regulation centers on an 8-m-high atrium (BIM-optimized ratio 1:1.25), where AI-driven skylights generate a $0.8 \pm 0.1\ m \cdot s^{-1}$ stack effect and 47.3 ± 2.1% natural ventilation coverage during transitional seasons, enhanced by 17.3 ± 2.1% under southeasterly winds (2.8 ± 0.5 m/s; Section 2.1). Winter Low-E glazing ($U = 1.2 \pm 0.1\ W \cdot m^{-2} \cdot K^{-1}$) reduces heat loss by 32.0 ± 1.8% vs. ASHRAE 90.1-2022 [29]. East–west façades employ robotic clay curtain walls (35% porosity) with 22% operable glazing, achieving a passive ventilation rate of 5.2 ACH. Deep vestibules (4.5 m) reduce unintended airflow by 68% [30].

Interface optimization integrates native vertical species (Ficus pumila, Hedera helix) with radiative misting, lowering surface temperatures by 9.2 ± 0.5 ℃, while a 3.2-m cantilevered eave (22° ± 0.5°) blocks 91.0 ± 1.2% of direct summer irradiance. Southern photovoltaic-responsive louvers (35% porosity) adjust tilt angles seasonally to 75° ± 2° in summer (blocking 88.0 ± 1.5% direct irradiance) and 15° ± 1° in winter (maintaining 65.2 ± 2.1% visible transmittance), generating $12.0 \pm 0.3\ MWh \cdot yr^{-1}$. Eastern and western façades deploy robotic clay tubes with Ficus pumila greening, reducing surface temperatures by 10.5 ± 0.3 ℃—14.1% superior to green walls ($t(20) = 3.1$, $p = 0.006$). Northern dual-silver Low-E glazing ($U = 0.80 \pm 0.05\ W \cdot m^{-2} \cdot K^{-1}$) completes the adaptive envelope, achieving 37.2 ± 0.9% solar heat gain reduction.

Energy synthesis employs Lake Jian underground pipes (2.3 km) for air precooling, coupled with PV-geothermal heat pumps (COP 4.3 ± 0.2; Section 2.1). This reduces HVAC energy by 41.2 ± 1.5% vs. GB 50189-2015 [30], with an associated operational carbon reduction of $18.5 \pm 0.5\ tCO_2e \cdot yr^{-1}$. Neurocognitive validation confirmed 18.7 ± 2.3% higher comfort perception ($r = 0.82$, $p = 0.004$) through fMRI amygdala activation (Section 2.2.1(1)). The system achieves a transferability index $\Psi = 0.89$ across subtropical zones (Köppen Cfa) [13].

The integrated spatial-climatic system reduces HVAC energy by 42.0 ± 1.8% vs. GB 50189-2015 [31], contributing 22.6% to campus-wide HVAC savings (32.0 ± 2.8%; Section 2.1). Detailed methodology for calculating this localized energy contribution is provided in **Supplementary material 1**. Fenestration achieves 132.2% equivalent energy savings ($F(2,15) = 8.2$, $p = 0.004$). East façade (WWR = 0.25) integrates robotic terracotta tubes (Ø = 200 mm) with Low-E glazing (SC = 0.40 ± 0.02), achieving a 41.3% reduction in solar heat gain. West façade BIPV curtain walls generate 14,000 ± 350 kWh · yr^{-1} while blocking 83.5% of peak irradiance. South façade (WWR = 0.45) employs electrochromic triple-silver Low-E glazing (U = 0.90 ± 0.05), eliciting a 12.3 ± 1.1% higher visual cortex BOLD signal than static glazing ($t(29) = 3.8$, $p = 0.007$). North façade (WWR = 0.50) uses high-transmission Low-E glass (VLT = 0.60 ± 0.02), achieving 92.0 ± 1.8% daylight compliance [32]—17.3% points above local benchmarks.

This configuration reduces local cooling and heating loads by 18.6 ± 0.9% ($p < 0.01$). Synergy analysis confirms non-additive effects: with independently simulated subsystem savings summing to 43.5 ± 1.8% (spatial: 15.0 ± 1.2%; ventilation: 10.5 ± 0.9%; envelope: 18.0 ± 1.5%) and campus-wide HVAC reduction of 32.0 ± 2.8%, the synergy factor $\Gamma = -35.9 \pm 0.07\%$ ($p < 0.001$). The transferability index $\Psi = 0.91$ ($R^2 = 0.93$) supports replication. Comparative monitoring against Shaoxing Library demonstrates 23.7% heating/cooling load reduction ($p < 0.01$) and 22.9% HVAC energy decrease.

Resource endowment: Zero-carbon energy supply system

Shaoxing Longshan Academy leverages its solar endowment (1,350 ± 120 kWh · m^{-2} · yr^{-1}; Section 2.1) through an integrated BIPV and BAPV deployment. Roof-mounted CdTe photovoltaic tiles generate 192,000 ± 4,800 kWh · yr^{-1}, while U-glass PV curtain walls on the south façade (VLT 50.0 ± 2.0% [33]) yield 31,000 ± 775 kWh · yr^{-1}. Combined with west façade flexible PV (14,000 ± 350 kWh · yr^{-1}) and additional roof-mounted arrays (963,000 ± 24,075 kWh · yr^{-1}), total BIPV output reaches 1,200,000 ± 30,000 kWh · yr^{-1} (1.29 GWh). A BAPV carport contributes an additional 89,000 ± 2,225 kWh · yr^{-1}.

An adaptive energy management protocol prioritizes diurnal photovoltaic generation, storing surplus in a 400-kWh LFP battery (DoD 80%, $\eta \geq 92\%$ [34]), with nocturnal operation combining storage discharge and grid supplementation when load factor exceeds 0.65. Total renewable generation (BIPV + BAPV) reaches 1,289,000 ± 32,225 kWh · yr^{-1}, covering 121 ± 3% of campus energy demand. Synergized with ground-source heat pumps (COP 4.3 ± 0.2) and a rainwater recycling system (65 ± 3% non-potable coverage), the lifecycle carbon intensity achieves −14.24 $kgCO_2e \cdot m^{-2} \cdot yr^{-1}$ [35]—38.7% lower than Shanghai benchmarks [36]—establishing China's first fMRI-validated neuroclimate-optimized campus (Section 2.2.1(1)).

2.2.2. Small-scale design practice

The "small-scale" design approach translates theoretical spatial principles (Section 2.2.1) into strategies focused on dematerialization, structural efficiency, and circular economy.

Dematerialization-driven spatial optimization

Longshan Academy reinterprets Jiangnan academic archetypes as vertically integrated courtyard clusters, where three enclosed units interconnected via photovoltaic bridges reduce functionally redundant floor areas by 28.0 ± 1.2% (χ^2 test, $p < 0.001$). Vertical compression to 3.6-m floor heights synergizes with exposed steel frames and BIM-optimized MEP, curtailing material use by 15.3 ± 0.7% vs. GB 50009-2012 [37] (*t*-test, $p < 0.001$). Standardized 15° mono-pitch trusses embed CdTe photovoltaic tiles, achieving spatial efficiency FAR = 0.99—14.2% above regional benchmarks—while satisfying GB/T 51350-2019 Class I thresholds [14].

Structural lightweighting with carbon synergy

BIM-optimized steel frames reduce consumption by 18.2 ± 0.9% and structural mass by 60.5 ± 1.8% vs. conventional concrete ($p < 0.001$), attaining 42 kg/m^2 material intensity. Prefabricated autoclaved lightweight concrete (ALC) panels ($\lambda = 0.13 \pm 5\%$ $W \cdot m^{-1} \cdot K^{-1}$) cut on-site carbon by 35.3 ± 1.5% [38]. Topology-optimized trusses integrating photovoltaic tiles reduce embodied carbon by 22.7 ± 0.8% [39]. CABR verification (Cert. 2024-021 [40]) confirms 40.2 ± 2.1% less construction waste and 31.5% exceeding GB/T 50378-2019 Three-Star [41] (χ^2 test, $p < 0.001$).

Material circulation and lifecycle optimization

Structural circularity utilizes 92% recycled steel, reducing embodied carbon by 23.0 ± 1.2% [38]. Localized envelopes incorporate 62% indigenous ceramic tiles via low-temperature sintering (40% energy reduction), achieving ≥4.0 MPa strength and ≥45 dB sound attenuation. Waste-valorized components incorporating 1,200 t of industrial byproducts enable 60.5 ± 2.0% embodied carbon reduction [39]. These interventions achieve material carbon intensity of 66.8 ± 1.1 kgCO$_2$e/m^2—58.3% below GB/T 51350-2019 thresholds [14] (χ^2 test, $p < 0.001$)—while maintaining cultural fidelity (89 ± 3% signifier retention; Section 2.2.1).

2.2.3. Flexibility-oriented longevity design

Structural longevity via decoupled topology

(1) 12 m × 12 m column-free cores with motorized partitions enable rapid conversion between classrooms and lecture halls; (2) prefabricated 8 m × 8 m units feature demountable ALC walls (<4 h disassembly [42]); (3) MEP integration in 200-mm technical strata eliminates structural penetrations. Achieving 60 ± 3% faster reconfiguration (*t*-test, $p < 0.001$) and 5.4 ± 0.3 kgCO$_2$e $\cdot$ m^{-2} $\cdot$ yr^{-1} carbon reduction. Design lifespan ≥ 70 years [43].

Computational carbon-driven design

(1) Topology optimization reduced steel consumption by 15.4% (362 vs. 428 t); (2) climate-responsive envelope tuning optimized east window-to-wall ratio to 0.28, curtailing cooling load by 23.0 ± 1.2% [38]; (3) HVAC replacement with ground-source heat pumps (COP 4.3 ± 0.2) yielded 31.0% carbon emission reduction.

After 17 cycles, HVAC operational carbon reached 82.3 tCO$_2$e $\cdot$ yr^{-1} (39.8% reduction), contributing 35.1% to campus-wide HVAC savings (32.0 ± 2.8%; Section 2.1), with carbon intensity ≤ 12.1 kgCO$_2$e $\cdot$ m^{-2} $\cdot$ yr^{-1}—32.3% below GB/T 51350-2019 Class I benchmarks [14].

Smart electrification and carbon sequestration

A PV-Storage-DC-Flexibility system integrates AI lighting (32,000 kWh $\cdot$ yr^{-1} saved), heat recovery with ground-source precooling (42.0 ± 1.5% HVAC reduction), and grid-responsive storage, achieving site energy 14.7 kWh $\cdot$ m^{-2} $\cdot$ a^{-1}—53% below regional benchmarks (2024 monitoring).

Carbon sequestration integrates vertical greening (2.3 ± 0.1 tCO$_2$e · yr^{-1}), rooftop vegetation (40.0 ± 1.8% efficiency gain), and bamboo composites, achieving 42% green coverage and contributing to Section 2.1's 28.6 ± 1.2 tCO$_2$e · yr^{-1} total, offsetting 15.0 ± 0.5% of operational carbon.

2.2.4. Other design practices

Longshan Academy's BIM-integrated platform (12 teams) enabled real-time energy-carbon co-simulation, bi-weekly parameter optimization, and carbon-tagged components for digital twins, reducing design changes by 42% and construction carbon by 18% [35].

2.3. Lifecycle carbon-negative validation

Shaoxing Longshan Academy achieves net-negative carbon operation at -10.1 ± 1.3 tCO$_2$e · yr^{-1} through synergistic integration of renewable generation, efficiency measures, and biogenic sequestration. The annual carbon balance is derived as:

$$(271.5 + 18.5 + 28.6) - 328.7 = -10.1\ \text{tCO}_2\text{e} \cdot \text{yr}^{-1}$$

$$(271.5 + 18.5 + 28.6) - 328.7 = -10.1\ \text{tCO}_2\text{e} \cdot \text{yr}^{-1}$$

where avoided grid emissions from on-site renewables total (based on China's 2023 grid emission factor of 0.2107 kgCO$_2$e · kWh^{-1} applied to renewable generation), ground-source heat pumps contribute 18.5 ± 0.5 tCO$_2$e · yr^{-1} savings over conventional HVAC, biogenic sequestration captures 28.6 ± 1.2 tCO$_2$e · yr^{-1} [24], and direct operational emissions total 328.7 ± 8.2 tCO$_2$e · yr^{-1}.

Projected over the 70-year design lifespan with 0.8% annual efficiency decay [15], cumulative carbon mitigation reaches 580–630 tCO$_2$e, verified by the China Academy of Building Research (Certificate CABR-Cert-2024-0915). This establishes China's first whole-life carbon-negative campus with fMRI-validated neurocognitive optimization (Section 2.2.1(1)).

2.4. Tripartite strategy efficacy

The integrated locality-small scale-flexibility framework establishes the Yangtze River Delta's first GB/T 51350-2019-certified educational building operating at net-negative carbon [14] (Cert. ZJ-2024-0421), codifying a replicable paradigm for carbon-neutral urbanization.

3. Discussion

This study validates three neurocognitive-AI synergies proposed in the introduction. First, fMRI-measured amygdala activation showed 21.3 ± 2.1% elevation in heritage-embedded spaces [4], directly correlating with 11.3% BIPV yield gain—providing empirical evidence that cultural resonance catalyzes tangible energy performance. Second, entropy-reduced cultural signifiers ($\Delta H = 0.03$ bits) preserved Ming-era architectural identity while enhancing participant recognition accuracy (78.1%, $\chi^2(3) = 38.7$, $p < 0.001$) [18]. Third, closed-loop optimization integrating EEG-derived neural feedback with AI reduced the theory-practice gap by 40 ± 5%

through 17 iterative co-simulation cycles. Collectively, these synergies demonstrate that LSF efficacy stems not merely from technical integration but from measurable biocultural-energy transduction pathways.

The LSF framework achieves an 85.3% EUI reduction and net-negative carbon intensity of -14.24 $kgCO_2e \cdot m^{-2} \cdot yr^{-1}$, outperforming the Brattørkaia Powerhouse (90% EUI reduction, -8.7 $kgCO_2e \cdot m^{-2} \cdot yr^{-1}$) and NUS SDE 1&3 (80% EUI reduction). Three core innovations underpin this performance:

Grid resilience. Unlike Brattørkaia, which relies on Norway's subsidized grid and hydropower baseload [28], our integrated BIPV-geothermal-microgrid system achieves 121% renewable autonomy in grid-constrained settings via industrial byproduct-valorized storage ($\eta \geq 92\%$, DoD 80%) and AI-assisted load shedding.

Cultural-technical synergy. In contrast to Brattørkaia's climate-agnostic design [28], our biocultural coding strategy ($\Delta H = 0.03$ bits, SSIM = 0.93) boosts BIPV yield by 11.3% and promotes fMRI-validated stewardship behavior, reflected by 21.3% amygdala activation correlating with 62.1% lighting EUI reduction ($r = 0.82$).

Scalability. While Brattørkaia's thermal mass concrete (380 $kgCO_2e/m^2$) limits rural applicability [28], our lightweight steel system (42 kg/m^2 material intensity; 120 $kgCO_2e/m^2$ embodied carbon) enables campus-wide deployment with transferability index $\Psi = 0.89$. Cross-climate adaptations include Mediterranean (Csa) solar chimney-cortile courtyards (38 ± 4% HVAC reduction, $\Delta H \leq 0.05$ bits) and Andean (BSk) radiative cooling-BIPV hybrids compensating for 30% irradiance loss at 3,500 m.

Cross-climate invariants sustaining performance include entropy threshold $\Delta H \leq 0.05$ bits, non-additive synergy $\Gamma < -30\%$ via BIM-AI co-simulation, and material costs $\leq$ €120/m^2. Limitations include fMRI scalability (mitigated by EEG proxies with $R^2 > 0.85$), 24-month monitoring duration, and geothermal dependency (offset by sand-based thermal storage at €12/kWh in arid regions).

3.1. Policy and regulatory innovation

The entropy-based cultural fidelity metric ($\Delta H \leq 0.03$ bits, $p < 0.001$) and Structural Similarity Index (SSIM = 0.93 ± 0.02) establish quantifiable parameters for harmonizing heritage conservation with decarbonization mandates. We recommend incorporating ΔH thresholds (e.g., $\Delta H \leq 0.05$ bits) into China's GB/T 51350-2019 as mandatory criteria for near-zero energy public buildings in culturally significant regions. Industrial symbiosis policies—particularly tax incentives under frameworks like MOF Cai Shui [2023] No. 12—should mandate ≥30% recycled content in public construction to replicate the project's 60.5 ± 2.0% embodied carbon reduction achieved through 1,200 t of valorized industrial byproducts. Furthermore, neuroergonomic standards should be integrated into building codes (e.g., GB 50736-2012), leveraging fMRI-validated enhancements in environmental cognition (21.3 ± 2.1% elevated amygdala activation, $t(31) = 4.2$) to synchronize occupant well-being with energy efficiency. For policymakers, we additionally recommend incorporating entropy-based heritage metrics ($\Delta H \leq 0.05$ bits) into green building standards and mandating ≥ 30% recycled content in public construction through tax incentives.

3.2. Scalable technical frameworks and real-world applications

The LSF framework demonstrates high transferability (Ψ = 0.89) across humid subtropical (Köppen Cfa) zones, offering a replicable blueprint for 1.2 million schools in semi-urban regions globally. Core scalable elements include vertically integrated courtyard clusters reducing redundant floor areas by 28.0 ± 1.2%, BIM-optimized lightweight steel structures achieving 42 kg/m^2 material intensity, and AI-managed BIPV and BAPV systems generating 1.29 $GWh \cdot yr^{-1}$—exceeding GB/T 51350-2019 renewable thresholds by 61 ± 3% points. For architects and engineers, the non-additive synergy factor (Γ = −35.9%) confirms that integrated subsystem optimization outperforms isolated interventions—advocating for early-stage cross-disciplinary co-design. For campus operators, the demonstrated 121% renewable coverage and 85.3% EUI reduction validate that AI-driven IoT systems can achieve net-negative operation without compromising cultural authenticity.

Application pathways across climates include direct adoption in humid subtropical zones (Cfa) with localized material sourcing (Ψ = 0.89 validated); in Mediterranean climates (Csa), solar chimney-cortile courtyards adapted from the atrium design achieve 38 ± 4% HVAC reduction while preserving heritage fidelity ($\Delta H \leq 0.05$ bits for stone lattices); in arid regions (BWh), sand-based thermal storage (€12/kWh) substitutes for geothermal systems, with badgir windcatchers integrated with radiative cooling maintaining net-negative performance; in continental climates (Dwa), topology-optimized thermal mass with phase-change materials achieves 35 ± 3% heating load reduction; and in resource-constrained settings, cost-optimized EEG wearables (target < \$50/unit) can substitute fMRI validation, maintaining correlation strength ($R^2 > 0.85$) while reducing validation costs by > 90%.

Crucially, the non-additive synergy factor ($\Gamma = -35.9 \pm 0.07\%$, $p < 0.001$) confirms that integrated subsystem optimization yields greater decarbonization than isolated interventions—a principle applicable across all climate zones.

3.3. Cross-sector collaboration and industry transformation

Four cross-sector collaborations can accelerate adoption. First, with the construction industry, partnerships with precast concrete manufacturers can scale the 92% recycled steel and 62% indigenous ceramic tile supply chains, reducing embodied carbon by 60.5% while creating new markets for industrial byproducts. Prefabricated demountable structures (60 ± 3% faster reconfigurations) offer new product categories for modular construction. Second, with the technology sector, collaboration with AI and IoT platform developers can commercialize the BIM-carbon co-simulation framework (17 optimization cycles reducing HVAC carbon by 39.8%) as a standard design tool. Digital twins processing 5-min IoT data streams (32.0 ± 2.8% HVAC reduction) should become mandatory for public infrastructure. Third, with public health and education sectors, the fMRI-validated neurocognitive metrics (21.3% amygdala activation correlating with 62.1% lighting EUI reduction, r = 0.82) provide evidence for integrating well-being metrics into green building certifications (e.g., WELL, LEED), opening pathways for cross-sector funding mechanisms (health + education + environment co-financing). Fourth, with the economic sector, the project's lifecycle net-negative carbon intensity (-14.24 kgCO₂e · m^{-2} · yr^{-1}) redefines economic models for sustainable construction. High-return elements include BIPV curtain walls delivering 11.3% yield increases through cultural entropy transduction, prefabricated structures enabling 60 ± 3% faster reconfigurations, and industrial byproduct valorization cutting material costs by 22.5 ± 1.1%. For Global South deployment, cost-optimized EEG wearables offer scalable neurovalidation.

3.4. Knowledge advancement and future directions

This research bridges critical gaps between bioclimatic design and empirical neuroscience, demonstrating that cultural resonance physically enhances environmental performance. The 21.3 ± 2.1% elevation in amygdala activation correlates directly with 11.3% photovoltaic yield gains—establishing a measurable link between spatial heritage and resource efficiency.

Future work must prioritize four pathways: cross-climate validation in arid zones via Persian windcatcher adaptations; digital twin deployment for 50-year cyber-physical monitoring; open-source repositories for entropy-based heritage templates ($\Delta H \leq 0.05$ bits) to lower adoption barriers; and expansion of neurovalidation to arid zones using EEG proxies, ensuring the LSF framework evolves as a universal protocol for carbon-negative urbanization. Longitudinal validation beyond the 24-month monitoring period remains essential, particularly for PV-geothermal synergy dependent on site-specific resources like Lake Jian's 14.5 ± 0.3 °C geothermal potential. As villages worldwide confront climate urgency, this project illuminates a replicable future: one where zero-carbon transitions amplify, rather than erase, the cultural landscapes they inhabit.

4. Conclusion

This research establishes the Locality-Small Scale-Flexibility (LSF) framework as a transformative paradigm for zero-carbon public buildings in semi-urban regions. Deployed at Shaoxing Longshan Academy, the framework achieves three radical shifts: (1) quantifiable cultural-climate integration via entropy-based fidelity metrics ($\Delta H = 0.03$ bits, SSIM = 0.93), resolving the false dichotomy between heritage conservation and decarbonization; (2) neurocognitive validation linking cultural resonance to a 62.1 ± 0.8% lighting EUI reduction (amygdala activation: 21.3 ± 2.1%, $t(31) = 4.2$); and (3) systemic non-additivity ($\Gamma = -35.9 \pm 0.07\%$, $p < 0.001$) integrating AI-driven renewables and circular material systems. The LSF attains a net-negative carbon intensity of -14.24 kgCO₂e · m^{-2} · yr^{-1}, surpassing the Brattørkaia Powerhouse in grid resilience while achieving China's strictest GB/T 51350-2019 Class I certification. With a transferability index $\Psi = 0.89$ across humid subtropical zones, this work provides a replicable blueprint for 1.2 million semi-urban schools globally, transforming cultural landscapes into carbon-negative civilization catalysts.

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Informed consent statement: Written informed consent was obtained from all individual participants prior to their involvement in the study.

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