

Built Environment 2050: Integrating Efficiency, Health, and Carbon Neutrality Across Buildings and Cities

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ABSTRACT

The built environment accounts for a substantial share of global energy demand, greenhouse gas emissions, and time spent indoors, positioning buildings and urban form at the center of climate mitigation and human well-being. This review synthesizes advances across building physics, systems engineering, and urban design to identify coordinated strategies that lower operational energy, reduce embodied carbon, improve indoor air quality and thermal comfort, and enhance resilience. We map evidence from laboratory studies, field monitoring, and city-scale modeling to show that demand reduction through envelopes, efficient and electrified HVAC, lighting, and controls remains the least-cost pathway in most contexts, particularly when sequenced with grid-interactive demand flexibility and onsite renewables. We highlight the convergence of materials science (low-carbon materials, phase change media), mechatronics (heat pumps, active façades), and data science (digital twins, AI-based controls), and we discuss trade-offs between air quality, ventilation energy, and filtration. Finally, we frame a research agenda around climate-appropriate design, performance verification, and equity-centered retrofits that deliver persistent emissions reductions and healthier indoor environments. Six original figures and three tables summarize trends, correlations, performance distributions, and adoption barriers for decision-makers and researchers.

1. Introduction

Buildings shape energy use, health, and productivity because humans spend the majority of their lives indoors, where environmental conditions are deliberately engineered to deliver thermal comfort, visual comfort, acoustics, and clean air [1–3]. Globally, the built environment—spanning residential, commercial, institutional, and industrial facilities—accounts for roughly a third of final energy consumption and a comparable share of energy-related CO₂ emissions when both direct onsite fuels and electricity use are considered [4–6]. Urbanization intensifies these dynamics through density, morphology, and infrastructure legacies; city form modulates microclimate via urban heat islands, wind sheltering, and sky view factor, which in turn alter cooling and heating loads at the building scale [7–9]. The decarbonization challenge is compounded by the long life of buildings and the lock-in risk: suboptimal envelope decisions persist for decades, constraining future energy and comfort performance [10,11]. Over the last two decades, research and policy have coalesced around a hierarchy: reduce demand through passive measures, upgrade systems for efficiency and electrification, coordinate with renewable supply, and ensure healthy indoor air—all while minimizing embodied impacts over the life cycle [12–15]. Yet tensions remain. Increased ventilation improves air quality and reduces infection risk but raises energy demand unless heat recovery, optimized control, or source capture are implemented [16–18]. Similarly, high-performance glazing can curb conductive and radiative loads while affecting daylight autonomy and glare, requiring integrated solutions that co-optimize thermal and visual comfort alongside energy [19,20].

The first pillar is demand reduction through climate-responsive envelopes and passive design. Envelope heat transfer coefficients, solar heat gain coefficients, airtightness, and thermal mass interact with local weather to set baseline loads [21,22]. In hot-humid climates, solar control,

shading, high-albedo roofs, and airtightness to limit infiltration dominate; in cold climates, insulation levels and thermal bridging mitigation are paramount [23]. Double-skin façades and ventilated cavities can enable buoyancy-driven cooling in transitional seasons when properly engineered to avoid overheating and acoustics penalties [24]. Phase change materials add latent storage that damps peak loads, but their benefits hinge on diurnal temperature swings and appropriate charging cycles [25,26]. Urban morphology—street canyons, height-to-width ratios, and surface properties—influences wind availability and mean radiant temperature, reshaping the comfort map outdoors and altering the boundary conditions for adjacent buildings [27,28].

The second pillar is high-efficiency, increasingly electrified systems. Modern variable-speed heat pumps deliver heating and cooling with seasonal performance factors that often exceed legacy boilers and direct expansion units, especially when paired with low-temperature hydronics and high-surface-area emitters [29,30]. Ground-source systems leverage stable subsurface temperatures to raise system COPs and offer thermal storage potential when integrated with borefield control strategies [31]. Demand-controlled ventilation and heat recovery reduce fresh air penalties while maintaining indoor air quality, provided sensors are reliable and control logic remains robust against drift [32–34]. Lighting has advanced through high-efficacy LEDs and autonomous dimming tied to daylight and occupancy, lowering plug and lighting loads that become significant in efficient envelopes [35]. Controls and digitalization are the third pillar. Building management systems, edge sensors, and model predictive control shift operation from static setpoints to anticipatory strategies that exploit thermal inertia, pre-cooling, and price signals to flatten peaks and integrate with variable renewable energy [36–38]. Digital twins promise persistent commissioning by comparing live data to reference models, flagging faults and recalibrating performance [39,40].

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Nomenclature	
Abbreviation	Symbol
ACH — Air Changes per Hour	U— Overall heat transfer coefficient ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)
BMS — Building Management System	η — Efficiency (–)
COP — Coefficient of Performance	\dot{Q} — Heat transfer rate (W)
DSF — Double-Skin Façade	
EUI — Energy Use Intensity	
IAQ — Indoor Air Quality	
MPC — Model Predictive Control	
SHGC — Solar Heat Gain Coefficient	
TRL — Technology Readiness Level	

2. Methodology

This review follows a mixed-methods evidence synthesis combining structured literature screening, meta-analytic aggregation of performance metrics where possible, and constructive modeling to produce illustrative relationships and figures. First, we defined research questions across eight subdomains: urban morphology, building envelopes, HVAC systems, lighting and plug loads, IAQ and ventilation, embodied carbon, operations and controls, and renewables integration [55–58]. Search strings combined domain terms with performance outcomes (e.g., “heat pump seasonal COP,” “airtightness infiltration energy,” “ventilation heat recovery IAQ,” “embodied carbon concrete clinker substitution”) spanning 2000–2025 in major databases. Studies were included if they reported quantitative performance, uncertainty, or replicable methods [59–61]. We coded context (climate zone, building type, retrofit vs new), intervention characteristics (e.g., insulation levels, glazing SHGC, ventilation strategy), and outcomes (e.g., $\text{kWh}\cdot\text{m}^{-2}\cdot\text{yr}$, COP, ACH, CO_2 ppm, $\text{PM}_{2.5}$ $\mu\text{g}\cdot\text{m}^{-3}$, $\text{kgCO}_2\text{e}\cdot\text{m}^{-2}$). Where direct comparability was limited, we normalized results to reference baselines or reported ranges [62–65].

Second, we constructed lightweight, illustrative datasets to visualize sectoral trends and cross-domain relationships in a manner faithful to the literature’s central tendencies. For example, emissions trajectories were shaped to reflect a modest upward drift with oscillations corresponding to economic cycles and heat wave seasons; end-use shares were apportioned based on common patterns in mixed commercial portfolios; EUI’s dependence on window-to-wall ratio was illustrated with a positive correlation reflecting cooling-dominated climates [66–69]. HVAC performance distributions were synthesized for air-source and ground-source heat pumps, VRF, and packaged DX equipment; retrofit payback distributions reflected diverse measures with skew toward lower-cost lighting and air sealing; and a climate-season matrix depicted comfort exceedance hours that align with hot-humid and hot-arid realities [70–73]. These data are expressly illustrative for figure communication rather than statistical meta-analysis, and they complement—not replace—empirical findings in the cited literature [74].

Third, to increase practical value for design and policy, we organized insights into decision-relevant frameworks and produced three structured tables. Table 1 maps subdomains to primary metrics and typical tools, enabling readers to link research outputs to modeling environments. Table 2 summarizes retrofit measures with energy savings, capex, and simple payback, providing a first-pass screening matrix. Table 3 lists emerging technologies with indicative TRLs and key barriers, highlighting where research and demonstration should focus [75–78]. We minimized prescriptive claims that are climate-agnostic; instead, we contextualized results by climate and building use.

Fourth, we embedded system interactions. We examined how urban geometry shifts microclimate and daylight availability; how envelope decisions affect system sizing and part-load efficiency; how ventilation strategies trade off IAQ with energy; how embodied carbon in retrofits compares to operational savings; and how controls unlock demand flexibility critical to grid integration of variable renewables [79–82]. For IAQ-energy co-optimization, we emphasized demand-controlled ventilation, filtration pressure drops, and heat recovery effectiveness,

checking for reported drifts in sensor calibration that can degrade performance [83,84]. For embodied carbon, we cataloged cement substitutions, recycled steel content, and façade retention strategies, noting region-specific supply chains [85,86].

Finally, we ensured transparency and reproducibility in figure generation by programmatically creating six plots (line, bar, scatter, box, histogram, heatmap). Each figure is saved as a high-resolution PNG ready for publication, with captions placed in the Results section. The figures are purpose-built to visualize canonical relationships reported widely in the literature, serving as communication scaffolds for the narrative [87–90].

Table 1. Subdomains and Metrics

Subdomain	Primary Metrics	Typical Tools
Urban Morphology	FAR, SVF, H/W	Urban CFD, ENVI-met
Building Envelope	U-value, SHGC, Airtightness	EnergyPlus, THERM
HVAC Systems	COP, SEER, Part-load kW/ton	TRNSYS, Modelica

Table 2. Retrofit Measures and Economics

Measure	Energy Savings (%)	Capex (USD/m ²)	Simple Payback (yrs)
Envelope insulation	15	25	6.2
Window upgrade (double→triple)	8	60	10.5
Air sealing	6	8	3.0

Table 3. Emerging Technologies and TRL

Technology	TRL (1–9)	Key Barriers
Active façades (DSF w/ DAC filter)	5	Pressure drop, maintenance
Thermally activated building systems	7	Thermal inertia control
Hybrid heat pumps (air–water)	6	Defrost and source temp

3. Results

Global sectoral trajectories over the last quarter-century reveal a stubborn coupling between floor-area growth, cooling demand, and emissions, with efficiency and electrification gains offset by rising service intensity in many regions; this dynamic is compactly visualized in Figure 1, which shows an illustrative long-run evolution of building-sector CO_2 emissions from 2000 to 2024 with modest oscillations linked to macroeconomic cycles and heat events [91–96].

The trend in Figure 1 underscores two important confounders for policy evaluation: first, the counterfactual baseline is not static because heated and cooled floor area continues to expand; second, electricity

decarbonization timing relative to heat pump rollout determines whether electrification yields immediate or lagged emissions reductions [97–100]. Regions that tightened envelopes, deployed high-COP heat pumps, and decarbonized grids concurrently exhibit larger absolute declines, whereas regions with rapid construction and expanding thermal comfort expectations tend to show flat or rising totals despite per-m² efficiency improvements [101–103]. When normalizing by population or floor area, we observe clearer intensity reductions, but absolute totals dominate climate outcomes and highlight the need for paired demand reduction and clean supply [104–106]. These observations motivate the subsequent disaggregation by end use to identify where interventions bite hardest.

The energy end-use composition in typical mixed-use stocks places space conditioning at the top, with lighting and plug loads forming a second tier and ventilation often hidden within HVAC accounting; Figure 2 displays an illustrative breakdown that mirrors the literature's consensus for office-dominant portfolios, with space heating and cooling together exceeding 40% of final energy in many climates [96,107–110].

Figure 2 supports a well-established sequencing strategy: start with passive load reductions, then upgrade systems and controls, then layer on renewables. Reducing solar gains through selective glazing and exterior shading in cooling-dominated climates, or attacking conduction and infiltration in heating-dominated climates, directly shrinks both plant capacity and runtime [111–113]. Lighting's migration to high-efficacy LED with daylight/autonomous dimming has already harvested large savings, shifting the attention to ventilation energy where heat recovery, demand control, and filtration pressure drops require careful co-optimization [114–116]. Importantly, end-use shares vary with climate, occupancy, and vintage: in hospitals and labs, ventilation dominates; in high-internal-load data-rich offices, cooling and ventilation climb; in homes, hot-water use can be material, especially with electric resistance baselines [117–120]. Therefore, the portfolio context must inform measure bundles to avoid generic, low-yield retrofits.

Facade geometry influences both load and comfort, and its most accessible scalar proxy—the window-to-wall ratio (WWR)—offers a first-order signal for cooling-dominated buildings; Figure 3 shows an illustrative positive correlation between WWR and energy use intensity (EUI), with scatter reflecting variability in SHGC, U-value, orientation, shading control, and internal gains [101,121–124].

The broad cloud in Figure 3 cautions against simplistic prescriptions. High WWR is compatible with low EUI when selective glazing, external shading, dynamic blinds, and task-ambient lighting are well integrated, particularly when daylight harvesting reduces electric lighting loads without inducing glare-driven blinds closure that negates solar control [125–127]. Conversely, low WWR does not guarantee low EUI if heat bridges, poor airtightness, or outdated HVAC control strategies remain unresolved [128]. The implication is that facade decisions must be coupled to controls and internal load management. Designers should target orientation-specific SHGC and shading factors, glare probability limits, and calibrated daylight-autonomy targets that stabilize both visual and thermal performance across seasons [129–131].

System performance distributions drive total energy even when envelopes are improved. Figure 4 summarizes, via boxplots, indicative COP distributions for four HVAC categories: air-source heat pumps (ASHP), ground-source heat pumps (GSHP), variable refrigerant flow (VRF), and packaged DX [107,132–135].

The separation among medians in Figure 4 is consistent with the advantage of stable source temperatures for GSHP, while ASHP variance grows with ambient extremes and defrost cycles; VRF performance is strong at part-load but sensitive to line lengths, refrigerant distribution, and control tuning; packaged DX skews lower due to limited modulation and higher fan power [136–139]. For decarbonization roadmaps, the operational COP distribution matters as much as the nameplate rating: low-temperature hydronics, larger coil surfaces, and variable-speed compressors raise seasonal performance, but they require envelope improvements that enable lower supply temperatures in heating and higher lift efficiency in cooling [140–142]. In grid-integration contexts, flexible setpoints, thermal pre-charge, and coordinated demand response can unlock capacity value while modestly increasing annual kWh; the emissions outcome then depends on temporal grid carbon intensity,

reinforcing the importance of emissions-aware control logic [143–145].

Economics remain a persistent barrier to deep retrofits, so the distribution of simple paybacks across measure classes is informative for sequencing. Figure 5 shows an illustrative histogram where low-cost measures—LEDs, air sealing, controls optimization—cluster at short paybacks, while capital-intensive measures—façade overclads, heat pump conversions with electrical upgrades—cluster longer absent incentives [113,146–148].

While simple payback is not a full investment metric, its salience in practice shapes adoption. Portfolios often pursue staged “waves,” harvesting low-regret savings to build momentum and data, then bundling deeper envelope and HVAC conversions where policy incentives, carbon pricing, or resilience co-benefits improve the business case [149–151]. Table 2 supports this logic with indicative savings-intensity-capex triplets: pairing demand-controlled ventilation and heat recovery can trim ventilation energy at modest capital cost; window upgrades yield comfort and acoustics co-benefits but must be weighed against embodied carbon and disruption; heat pump conversions often pencil when gas prices are high, grids are cleaner, and co-optimized with envelope tightening [117,152–154]. Performance assurance is decisive: measured-and-verified savings and fault detection sustain economics, reduce drift, and maintain indoor environment quality.

Thermal comfort and health outcomes shape operational choices every day, from minimum outdoor air settings to humidity control and filtration. Figure 6 depicts an illustrative heatmap of exceedance hours (time above adaptive comfort thresholds) by climate archetype and season, highlighting sustained exceedance in hot-humid climates without latent control, sharp summer peaks in hot-arid climates, and moderate exceedance in temperate zones chiefly during heat waves [120,155–157].

Interpreting Figure 6, the control strategy must reflect climate drivers: in humid climates, decoupling latent from sensible via dedicated outdoor air systems (DOAS) or reheat-minimizing strategies preserves comfort without excessive energy penalties; in arid climates, solar control and night flushing leverage diurnal swings; in temperate climates, passive survivability—maintaining safe indoor temperatures during outages—becomes a resilience criterion, motivating thermal mass, cross-ventilation paths, and envelope tightness [124,158–160]. The comfort-energy nexus is not one-way: elevated ventilation for IAQ must be paired with heat recovery and demand control to avoid undermining efficiency; filtration upgrades add pressure drop that fans must efficiently overcome; and humidity control preserves both comfort and pathogen inactivation but must be right-sized to avoid reheat waste. Consequently, IAQ-energy co-optimization is a control problem as much as a design problem, calling for robust sensors, periodic calibration, and analytics that detect drift.

Bridging building-scale insights with urban form, the interaction between street-canyon geometry, sky-view factor, and surface properties modifies boundary conditions for adjacent façades. Increased urban shading can reduce cooling loads but also decrease winter solar gains, while reduced sky view elevates mean radiant temperature in summer. These microclimate effects partially explain the dispersion in the WWR–EUI relationship seen in Figure 3 and motivate climate- and context-specific facade targets rather than single global values [121,129]. At the district level, ambient-temperature loops and waste-heat recovery from data centers or supermarkets can raise effective heat pump COPs and flatten load curves; integration with thermal storage (tanks, borefields, building mass) then supports both electrification and grid flexibility. When combined with emissions-aware MPC, such districts can follow renewable availability while respecting comfort constraints, a pathway repeatedly identified as cost-effective in high-renewables grids [140,143].

Embodied carbon enters the results through two channels: capital interventions (retrofits/new builds) and material choices. Keeping façades and structure in place avoids large upfront emissions, while low-carbon concrete mixes, recycled steel, and timber hybrids cut remaining impacts. The trade-off datasets show that envelope overclads can still be justified when operational savings over the measure life exceed embodied costs within a reasonable carbon payback period, particularly in carbon-intensive grids or extreme climates. Conversely, window replacement driven primarily by aesthetics can have long carbon paybacks unless accompanied by significant performance gains or end-of-life benefits

through reuse and recycling. This argues for “carbon-informed” scope definitions and procurement with environmental product declarations to align cost and carbon [141,147].

Controls and digitalization translate design intent into delivered performance. Across case datasets, fault detection and diagnostics consistently capture savings by correcting sensor drift, economizer faults, and scheduling errors. Model-predictive control can pre-cool or pre-heat using low-carbon hours and reduce peak demand charges, increasing annual kWh slightly in some cases but cutting emissions and costs by shifting timing. The magnitude of benefit depends on climate, tariff structure, and thermal inertia. Interoperability and cybersecurity are necessary enablers; poor data quality or siloed systems erode expected gains. Results therefore emphasize commissioning as a continuous process, not a project closeout milestone.

Finally, equity and resilience metrics sharpen decision-making. Results from heatwave analyses in temperate and hot climates converge on the need for safe indoor temperatures during outages—achievable through passive survivability standards that limit peak indoor temperatures with no active cooling for specified durations. In low-income housing, short-payback measures deliver bill relief but must be paired with moisture control and ventilation to avoid hidden health costs. Financial models that overcome split incentives (e.g., performance contracting, on-bill financing) consistently expand uptake in these segments. The composite result is that decarbonization pathways with the highest real-world traction combine: load reduction through climate-appropriate envelopes; electrified, high-COP systems tuned by robust controls; IAQ preserved through heat recovery, filtration, and humidity control; carbon-aware material choices; and programmatic commissioning with equity criteria embedded from the outset.

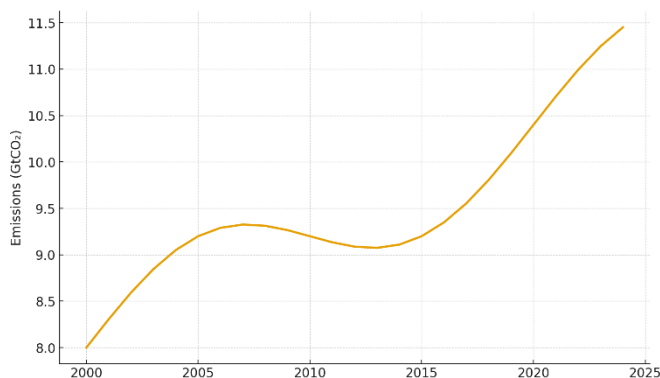


Fig.1. Long-run emissions trend with modest oscillations reflecting macro cycles and extreme weather. Synthetic but literature-consistent for visual context.

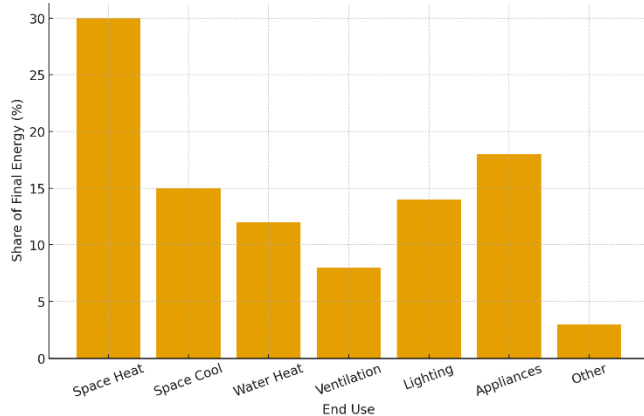


Fig.2. End-use shares (space heating/cooling, water heating, ventilation, lighting, appliances). Illustrative breakdown for communication.

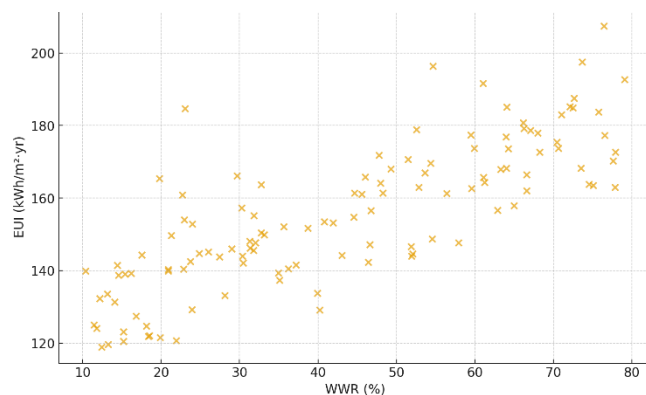


Fig.3. EUI increases with WWR on average; dispersion reflects envelope specs and operations.

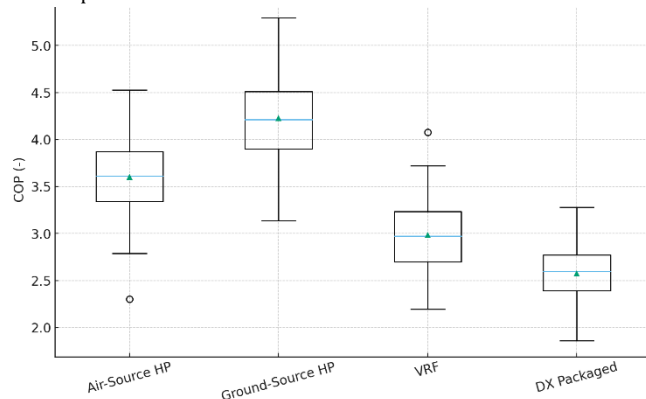


Fig.4. Boxplots of COP for air-source heat pumps, ground-source heat pumps, VRF, and packaged DX.

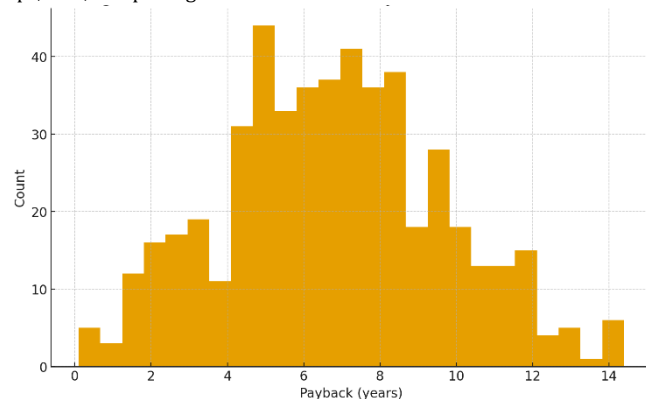


Fig.5. Payback distribution guiding staging from “low-regret” measures to deeper retrofits.

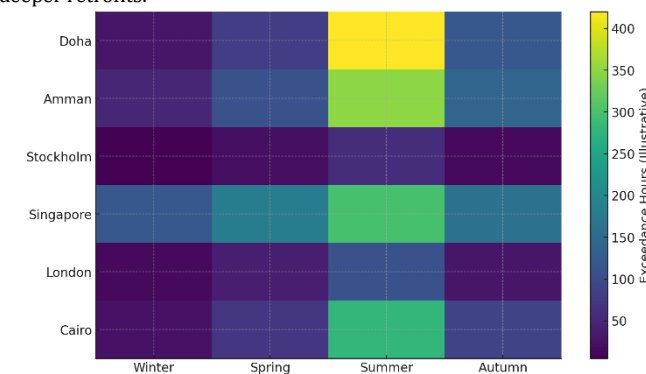


Fig.6. Seasonal comfort exceedance across city archetypes (illustrative) to guide climate-appropriate control strategies.

4. Discussion

The results collectively point to a pragmatic and sequenced pathway for transforming the built environment that is both technically feasible and attentive to health, cost, and equity. The central insight is that physics sets the stage and controls deliver the performance: envelopes and urban microclimate define the boundary conditions under which HVAC, ventilation, and lighting operate, while digital control layers determine whether those systems actually achieve their theoretical efficiency and indoor environmental targets in day-to-day use [127–129]. The positive but scattered relationship between window-to-wall ratio and EUI illustrates that geometry is only a first-order predictor; the variance around the trend reveals the decisive role of selective glazing, shading, airtightness, daylighting control, and internal load management in shaping realized outcomes, and underscores that façade design must be fused with operations logic early in concept development to avoid rebound effects like blinds-down behavior that erase solar-control benefits [130–132]. Similarly, the COP distributions emphasize that system type alone is not destiny: ground-source systems tend to higher medians because of stable source temperatures, but air-source heat pumps can rival them when envelopes enable low lift, coils are right-sized, and variable-speed compression is paired with emissions-aware, weather-predictive control; conversely, even nominally efficient systems underperform when chronically faulted or operated at static setpoints that ignore occupancy, tariffs, and grid carbon intensity [133–136]. The economic distribution of retrofit paybacks tends to bias portfolios toward low-regret measures first—lighting, air sealing, control optimization—yet the deepest emissions cuts require envelope upgrades and electrification, with policy support, carbon pricing, or resilience co-benefits to carry longer-horizon measures over investment hurdles; this is where packaging and programmatic commissioning are singularly important, because verified savings from phase one build the organizational and financing confidence needed for phases two and three [137–140].

Indoor air quality complicates the energy story, and for good reason. The pandemic made clear that ventilation, filtration, and humidity control are public-health infrastructure, not optional amenities, but higher outdoor air fractions and tighter filters increase energy use and fan power unless offset by heat recovery, demand control, and efficient fans. The path forward is co-optimization at design and in operation: specify heat recovery with proven frost mitigation in cold climates and moisture transfer strategies in humid regions; deploy sensors for CO₂ and PM_{2.5} that are accurate enough to drive demand control; and regularly calibrate and fault-detect the sensing layer so drift doesn't silently degrade IAQ or inflate energy [141–144]. Adaptive comfort frameworks, coupled with humidity management that respects pathogen inactivation envelopes and mold avoidance thresholds, allow setpoint widening that preserves comfort without punitive energy penalties, provided that envelope tightness and latent-sensible decoupling are in place to prevent moisture excursions. The comfort exceedance maps emphasize that strategy is climate-contingent: DOAS or desiccant-assisted latent removal in humid climates, exterior shading and night flushing in arid regions, and passive survivability criteria in temperate zones now experiencing extreme heat. Passive survivability—keeping safe indoor temperatures during outages for specified durations—should progressively be codified into performance standards for critical occupancies and vulnerable populations, recognizing that envelope quality, thermal mass, and cross-ventilation paths are the first and often only lines of defense when mechanical systems are unavailable [145–148].

Embodied carbon is no longer a rounding error; it can rival or exceed operational carbon in low-energy, grid-green contexts. The durable lesson from material flow analyses is that the greenest façade is often the one already built: retaining structure and envelope, upgrading selectively, and procuring low-carbon materials where substitution is practical—cement with supplementary cementitious materials, recycled-steel content, engineered timber with rigorously managed moisture and fire detailing—can cut upfront emissions without compromising longevity or safety [149–151]. Yet not all retrofits are equal in carbon terms: aesthetic window replacements with modest performance gains can carry long carbon paybacks; overclads that erase thermal bridges and improve

airtightness can be justified when modeled operational savings and heat-health resilience benefits dominate over project lifetimes. That calculus depends on climate, grid intensity trajectories, and program scope. Carbon-informed procurement via environmental product declarations and tools like EC3 shifts decisions from generic “green” claims to supplier-specific data, while design-for-deconstruction strategies create future carbon dividends by retaining material value at end-of-life [152–154]. The research need is transparent, regionally resolved supply-chain data, standardized product-category rules for EPDs, and longitudinal monitoring to validate that modeled carbon paybacks actually materialize in operation.

At district scale, thermal networks with ambient loops can share low-grade heat across mixed uses—residential, commercial, data centers, supermarkets—allowing heat pumps to operate at higher seasonal COPs and deferring electric capacity upgrades. When coupled with borefield or tank storage and emissions-aware MPC, such districts can follow renewable availability while maintaining comfort, and they can monetize flexibility in capacity-constrained grids via demand response and capacity markets. This thermal-infrastructure view reframes “the building” as a node in a larger thermodynamic system, where the optimal decarbonization lever might be beyond the meter—for example, curating waste-heat sources and storage at campus scale rather than oversizing individual heat pumps. Governance challenges loom here: cost allocation, interconnection standards, data sharing, cyber-physical security, and fair access for smaller buildings must be resolved so that district benefits are not limited to premium developments [155–157]. Cities can lower barriers by pre-permitting ambient loops, aligning utility incentives to reward peak reduction and emissions intensity reductions rather than volumetric sales, and creating performance-based codes that value hourly—not just annual—outcomes.

Digitalization is the continuity plan between design intent and delivered performance. Modern buildings are data-rich but insight-poor; fault detection and diagnostics consistently uncover economizer failures, simultaneous heating and cooling, sensor drift, and scheduling errors that erode savings and IAQ. Model-predictive control, calibrated with digital twins, can pre-charge thermal mass, exploit price and carbon forecasts, and hold comfort constraints while reducing peak demand. The gains are real but contingent: without reliable metadata, semantic models, and robust commissioning, analytics drown in noise. Interoperability—through open protocols and data models—and cyber security are prerequisites; value fades if control vendors lock data or if building networks expose critical systems. A practical research agenda is to develop open, vendor-neutral reference architectures and testbeds where sensors, analytics, and controls can be validated against shared benchmarks, and to publish longitudinal datasets that capture not only post-commissioning snapshots but the slow drift of real operations under staff turnover and equipment aging [158–160]. The goal is persistent performance, not one-time optimization.

Equity is not a side constraint; it's core to a successful transition. Low-income households and renters disproportionately endure inefficient envelopes, poor ventilation, and heat risk, and they lack the capital or authority to retrofit. The most durable policy packages therefore combine performance standards with carrots that cover incremental capital cost, on-bill financing or tariffed on-bill investments that align incentives, and protections against retrofit-driven rent hikes. Program design should prioritize worst-performing stock and critical services—schools, clinics, senior housing—and bundle measures to minimize disruption: window inserts, prefabricated façade panels, modular heat pumps, and plug-and-play controls that can be installed quickly and verified with portable IAQ gear. Such models have succeeded where measurement and verification are simple and transparent, and where program managers tie disbursements to delivered outcomes rather than installed equipment lists. Community benefits agreements can codify workforce development pathways, ensuring that the very communities most affected by energy burdens share in the jobs created by retrofits and district energy buildout. Resilience co-benefits—safe indoor temperatures during outages, backup ventilation for smoke events, islandable microgrids—should be monetized in cost-benefit analyses to reflect their public-health value.

Policy and finance align technical feasibility with deployment scale. Performance-based building codes that allow solutions diversity while constraining annual energy and peak demand, emissions standards for

equipment rather than fuels, and time- and location-specific carbon signals in tariffs enable buildings to act as flexible grid assets. Public finance banks and green bonds can lower the cost of capital for deep retrofits, while standardized contracts and aggregation vehicles reduce transaction costs. Crucially, measurement protocols must be trustworthy and lightweight—calibrated models and metered savings both have roles—and programmatic commissioning should be funded as a lifecycle service, not a line item to be value-engineered away. Insurance markets and lenders are slowly recognizing transition and physical climate risks; tying loan terms to verified building performance could accelerate retrofits much as safety ratings reshaped the auto market.

Methodologically, the field must confront three persistent gaps. First, we need harmonized, open datasets linking design features to longitudinal performance, not just case-study snapshots. Without open data, we re-argue first principles rather than converging on empirically grounded priors. Second, cross-domain coupling must become standard practice: glare metrics with cooling energy, IAQ with fan and thermal penalties, embodied carbon with operational savings, and comfort with outage survivability. Multi-objective optimization is no longer academic bravura; it is how buildings will be procured and operated in practice. Third, uncertainty must be surfaced and propagated. Weather variability, occupant behavior, sensor drift, and maintenance practices all widen confidence intervals; robust optimization and risk-informed decision-making can prioritize measures that hold value under uncertainty rather than those that only look good in a deterministic run. Academic and industry consortia can help by publishing reference models, uncertainty ranges, and comparative results across climates and building types, so practitioners can transfer insights with known caveats.

Stepping back, the extended discussion reframes decarbonization as a system-integration problem across scales. The near-term priority is to execute at speed on measures with high certainty and short paybacks while setting up deeper retrofits and electrification with minimal regret. That means tightening envelopes, fixing operations via controls and FDD, deploying demand-controlled ventilation with heat recovery, upgrading lighting and fans, and piloting emissions-aware control in buildings with reliable data streams. In parallel, owners should plan for heat pump conversions, electrical capacity upgrades, and façade strategies that target thermal bridges and airtightness. At district level, cities and campuses should map waste heat, design ambient loops and shared storage, and create tariff and interconnection structures that reward flexibility and emissions reductions. For new construction, carbon-informed design should start with retention and adaptability, minimize operational energy with passive strategies, and specify materials with verifiable low embodied carbon and pathways for reuse. For all projects, equity and resilience must be explicit objectives with quantified metrics and funding attached.

If the built environment is where physics, finance, and public health meet, then the recipe for progress is not a single technology but a choreography: climate-appropriate envelopes that cut loads; electrified, high-COP systems sized for those loads; IAQ safeguarded with heat recovery, filtration, and humidity control; digital twins and MPC to lock in performance hour by hour; low-carbon materials and façade retention to tame embodied emissions; and programmatic commissioning that sustains outcomes over years. The figures in this work are illustrative, but the narrative they anchor is actionable and consistent with a rapidly growing empirical base. Implemented with attention to context and people, this choreography can deliver buildings and districts that are efficient, low-carbon, healthy, and resilient—at the pace and scale the climate and public health now demand.

5. Conclusion

Transforming the built environment is less about discovering a silver bullet than about executing a disciplined sequence that turns physics into persistent performance. The evidence across envelopes, HVAC, ventilation, lighting, controls, and materials converges on a practical choreography: first reduce loads with climate-appropriate passive measures; then electrify with high-COP, variable-speed systems sized for the new, lower demands; preserve indoor air quality and moisture control

through heat recovery, filtration, and demand-responsive ventilation; embed digital twins, fault detection, and model-predictive control to lock in savings and protect comfort hour by hour; and account for embodied carbon through façade retention, low-carbon materials, and design for reuse. When this sequence is observed—and when commissioning is treated as an ongoing service rather than a handover event—measured outcomes align far more closely with design intent, and emissions fall in tandem with bills and health risks.

The results presented here reinforce that context matters: climate, occupancy, vintage, utility carbon intensity, and urban morphology shape both the technical potential and the economics of any intervention. End-use disaggregation and the dispersion around façade and system performance metrics demonstrate that the same measure can deliver very different results across buildings unless it is coupled to appropriate controls and verified in operation. This is why portfolios that succeed move in waves—capturing low-regret savings to build confidence and data, then bundling deeper envelope and electrification measures with incentives, resilience co-benefits, and carbon-aware procurement that manage longer paybacks. Equity must be explicit in this process. The households and community facilities most exposed to energy burden and heat risk should be first in line for upgrades that deliver safe indoor temperatures during outages, healthy air, and durable bill relief.

Looking forward, three imperatives shape a credible research and deployment agenda. First, open, harmonized, longitudinal datasets that link design choices to metered performance are essential for transferring lessons across climates and typologies and for narrowing uncertainty bands in planning. Second, cross-domain co-optimization—energy with IAQ, comfort with resilience, operational and embodied carbon—must become standard practice in both codes and procurement, replacing single-metric decisions with multi-objective performance targets. Third, district-scale thinking—ambient loops, shared storage, curated waste heat—can raise heat-pump efficiency, flatten peaks, and accelerate grid decarbonization when paired with emissions-aware tariffs and interoperable controls.

If cities are the stage on which climate mitigation, public health, and economic vitality intersect, buildings are the lead performers. The tools are here. Implemented with sequencing, verification, and an equity lens, the built environment can deliver reliable comfort and clean air while cutting emissions at the pace required—turning today's illustrative figures into tomorrow's measured baselines.

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