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Integrated Pathways to Net-Zero: Bridging Sustainable Construction, Renewable Energy, and Urban Design

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***Abstract*— Cities are the primary arena for decarbonization because most energy demand, building stock turnover, and infrastructure investment are concentrated in urban regions. This paper reviews integrated pathways that link (i) low-embodied-carbon construction, (ii) building- and district-scale renewable energy incorporation, and (iii) urban design strategies that reduce demand and enable clean energy at scale. It emphasizes how renewables, solar PV/BIPV, solar thermal, wind (where viable), geothermal/heat pumps, biomass (selective), and energy storage, are designed into buildings, districts, and city systems, alongside compact urban form, transit accessibility, and green infrastructure. A multi-scale framework is proposed to align lifecycle carbon (materials + construction), operational carbon (energy), and citywide emissions (buildings + mobility) to support net-zero delivery.**

***Keywords*— Net-Zero Buildings, Embodied Carbon, Renewable Energy Integration, Urban Design, Life Cycle Assessment (LCA)**

I. INTRODUCTION

A. Why integration matters

Increasingly, embodied emissions dominate the whole-life carbon of a building as the operational efficiency of buildings increases. This shifts "net zero" from a single technology decision, i.e., how energy is generated to a combination of materials + energy + urban systems. The master planning phase of a building (e.g., block orientation, heights, canyon ratios and solar access) can either enhance or permanently limit the yield of renewable energy generated (particularly PV/BIPV) and passive performance (Li et al., 2024; Dsilva et al., 2023).

B. This review focuses on:

- What building-material and structural choices most reduce embodied carbon (and by how much)? (Dsilva et al., 2023)
- How are renewable systems incorporated at building, district, and city scales to approach net-zero? (Kim et al., 2021; Lou & Hsieh, 2024)
- Which urban design strategies most strongly enable both low demand and high renewable penetration? (Li et al., 2024)

II. METHODS AND EVIDENCE BASE

Using a structured process to conduct this narrative review, first preference is given to those sources that see (a) net zero strategies and the renewable design requirements as being clearly defined, and/or (b) provide quantitative life cycle assessment results for materials designed specifically to reduce embodied carbon via various required interventions. The quantitative case study for embodied carbon from Heliyon currently available from PMC serves as the reference point for the research. The data tables used and the scenario comparisons presented, are fully verifiable (Lou & Hsieh, 2024; Kim et al., 2021; Dsilva et al., 2023).

III. EMBODIED CARBON: WHAT WORKS IN PRACTICE

A. LCA boundaries and decision timing Text

Life Cycle Assessment (LCA) for buildings commonly follows EN 15804 modules (A1–A3 product stage; A4–A5 construction; B use stage; C end of life; D benefits beyond system boundary). The key practical insight is that LCA is most effective when used early (concept/schematic design) because major carbon drivers, structure, façade, concrete binder choice, reinforcement quantities, are still adjustable (Dsilva et al., 2023).

B. Case Study: 26% reduction through early LCA

Dsilva et al. (2023) report an LCA-based comparison where early design decisions reduce embodied carbon intensity from 680 to 500 $kgCO_2e/m^2$ (a 26% reduction) for a 5,943 m² building case study. This result is explicitly stated in the accessible PMC version and is therefore cross-verifiable (Dsilva et al., 2023).

TABLE I
EMBODIED CARBON CHANGE (CASE STUDY)

Indicator	Baseline	Optimized	Change
Embodied carbon intensity ($kgCO_2e/m^2$)	680	500	−26%

Source: Heliyon case study reported by Dsilva et al. (2023).

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C. High-leverage material levers

The same study shows that concrete and reinforcement steel are major contributors and that binder substitution (e.g., SCMs) and recycled content strategies can materially reduce emissions without changing building use. Circular-economy framing (material selection, resource efficiency, end-of-life recovery) is used in the paper to structure decision levers across the building life cycle (Dsilva et al., 2023).

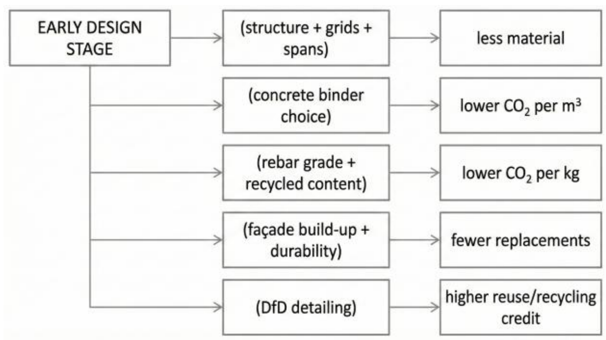

FIGURE II EMBODIED CARBON LEVERS (FLOW DIAGRAM)

This reflects the case study's emphasis on early-stage LCA and material decisions as primary reduction mechanisms (Dsilva et al., 2023).

IV. RENEWABLE ENERGY INCORPORATION (BUILDING → DISTRICT → CITY)

A. Net-zero energy/carbon strategy stack

Net-zero building pathways generally combine demand reduction, electrification, renewables, storage/flexibility, and monitoring/controls. Climate change can alter renewable sizing requirements (especially as cooling loads increase), meaning resilience is partly addressed through passive cooling, shading, and urban heat mitigation that keep renewable demand manageable (Junk et al., 2025; Kim et al., 2021; Lou & Hsieh, 2024).

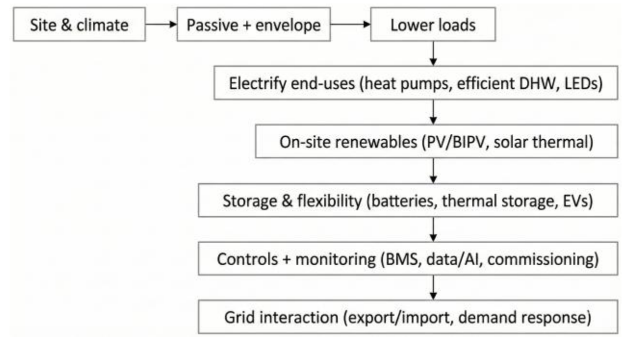

FIGURE II "Reduce → Electrify → Generate → Store → Control" (flow diagram)

This sequencing aligns with net-zero strategy reviews and climate-scenario work on renewable design requirements (Kim et al., 2021; Lou & Hsieh, 2024).

B. Solar PV and BIPV in buildings and urban blocks

PV is typically the primary on-site renewable in dense cities because it can be deployed on roofs, façades, canopies, and parking structures, and can scale from single buildings to portfolios. The urban design dependency is critical: PV yield is constrained by overshadowing from adjacent blocks, so solar access envelopes and massing rules become a "hidden energy code" at district scale (Lou & Hsieh, 2024; Li et al., 2024).

TABLE II
PV/BIPV DESIGN DECISIONS THAT CHANGE YIELD

Design variable	Typical effect on PV feasibility	Why it's urban-design sensitive
Building height/spacing	Can reduce PV output via shading	Street canyon geometry controls solar access (Li et al., 2024).
Roof form and equipment clutter	Reduces available PV area	Competes with HVAC, lift overruns, amenities (Lou & Hsieh, 2024).
Façade orientation	Shifts generation profile	Façade PV can reduce summer overheating and broaden hours of production (Lou & Hsieh, 2024).
District "solar rights" rules	Protects long-term yield	Prevents future infill from shading existing PV (Li et al., 2024).

C. Solar thermal: DHW and low-temperature heat networks

Solar thermal is commonly applied to domestic hot water (DHW) and can also feed low-temperature district loops when coupled with thermal storage. In integrated net-zero approaches, solar thermal can reduce electricity peaks by supplying heat directly, complementing PV (electricity) and heat pumps (electrified heat) (Lou & Hsieh, 2024).

D. Wind energy: selective urban viability

Small/building-integrated wind is highly site-specific due to turbulence and low average wind speeds in dense urban canyons, so it is generally a niche supplement rather than a base strategy compared to PV. It becomes more viable in exposed coastal sites, high-rise roof edges with cleaner airflow, or district-edge locations rather than deep urban cores (Lou & Hsieh, 2024).

E. Heat pumps, geothermal, and "future climate" sizing

Heat pumps are central to net-zero pathways because they reduce delivered energy per unit of heating/cooling through high COPs, thereby reducing renewable capacity required to reach net-zero. However, under future climate scenarios, cooling demand can grow and change the balance of renewable design requirements, reinforcing the need for passive design and urban heat mitigation as "renewable enablers" (Junk et al., 2025; Kim et al., 2021).

F. Biomass and renewable fuels: role as backup/dispatchable supply

System-level modelling of net-zero building sectors frequently highlights the need for dispatchable capacity to cover seasonal gaps and peak loads, where constrained grids or winter heating peaks exist. In urban contexts, biomass/biogas is most defensible as limited peak/backup heat in district plants (with strict air-quality and sustainability criteria) rather than widespread building-level combustion (Chatterjee et al., 2024).

G. Storage and flexibility: batteries + thermal storage + EVs

Net-zero strategies emphasize that storage and demand flexibility increase renewable self-consumption and reduce grid stress. At district scale, thermal storage can be a cost-effective flexibility resource when paired with heat pumps and solar thermal, while batteries and EV charging coordination support PV integration (Qin et al., 2024; Li et al., 2024).

TABLE III
STORAGE TYPES AND BEST USE-CASES

Storage	Best scale	Best paired with	What it solves
Battery storage	Building/district	PV/BIPV	Shifts daytime PV to evening loads; peak shaving (Qin et al., 2024).
Thermal tanks	Building/district	Solar thermal, heat pumps	Cheap kWh storage for heat; DHW smoothing (Lou & Hsieh, 2024).
Seasonal thermal (limited contexts)	District	Solar thermal + district loops	Addresses winter heat gap but needs large volume and planning (Lou & Hsieh, 2024).
EVs (managed charging/V2G-ready)	City/district	PV, grid DR	Flexible demand + potential storage; requires policy/controls (Li et al., 2024).

V. CITY AND URBAN DESIGN STRATEGIES THAT ENABLE RENEWABLES

A. Data-driven planning to scale net-zero

City-scale decarbonization increasingly relies on GIS/BIM/remote sensing/AI to (a) map rooftop potential, (b) prioritize retrofit clusters, (c) monitor net-zero performance, and (d) coordinate infrastructure upgrades. Digital-twin approaches are positioned as a way to coordinate building portfolios, district systems, and policy targets in a single operational framework (Ramnarine et al., 2025; Li et al., 2024).

B. Urban heat island mitigation as renewable capacity reduction

Urban heat island intensity affects cooling demand, which in turn drives PV and grid capacity needs. Urban design measures, tree canopy, high-albedo surfaces, shading devices, and ventilation corridors, can reduce ambient temperatures and thus lower electricity demand, improving the feasibility of achieving net-zero with available renewable area (Kim et al., 2021; Junk et al., 2025).

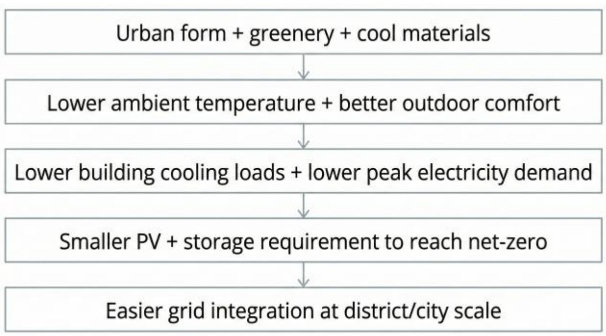

FIGURE IIIII URBAN DESIGN → LOAD REDUCTION → RENEWABLE FEASIBILITY (FLOW DIAGRAM)

This chain is consistent with urban heat island adaptation/mitigation work and renewable design requirement analysis under future climate (Junk et al., 2025; Kim et al., 2021).

VI. INTEGRATED FRAMEWORK (WHAT TO DO, WHEN)

A. Decision matrix: stage vs scale

TABLE IV
NET-ZERO INTEGRATION CHECKLIST (CROSS-SCALE)

Stage	**Building decisions**	**District/city decisions**
Masterplan	Orientation, massing for solar access, passive shading	Solar access rules; renewable zoning; district energy corridors (Li et al., 2024).
Concept	Envelope targets, passive cooling, electrification plan	Microgrid feasibility; thermal loop planning (Lou & Hsieh, 2024).
Schematic	PV/BIPV layout; solar thermal; heat pump sizing; storage	Interconnection design; demand response participation (Qin et al., 2024).
Delivery	Commissioning, metering, performance targets	City monitoring dashboards; portfolio retrofit sequencing (Li et al., 2024).
Operation	Continuous tuning and maintenance	Digital twin / GIS-based tracking, policy feedback loops (Ramnarine et al., 2025; Li et al., 2024).

B. Carbon accounting alignment

Embodied carbon reductions (materials + construction) and operational net-zero (renewables + electrification) must be accounted for jointly to avoid shifting impacts (e.g., very high embodied carbon for marginal operational gains). The Heliyon LCA case study demonstrates that quantified scenario comparison is feasible and can deliver substantial reductions when applied early (Dsilva et al., 2023).

VII. CONCLUSION

Achieving net-zero status in the built environment requires a paradigm shift from isolated building optimization to a systems-level integration of construction materials, energy generation, and urban morphology. This review highlights that while operational efficiency remains vital, the relative importance of embodied carbon is escalating, necessitating early-stage Lifecycle Assessment (LCA) interventions that can yield significant verifiable reductions before construction begins. Furthermore, the successful deployment of renewable technologies, particularly solar PV and heat pumps, is intrinsically linked to urban design decisions regarding density, orientation, and shading. Ultimately, a resilient net-zero future depends on aligning these physical design strategies with digital monitoring frameworks and climate-adaptive planning to ensure that today's interventions remain effective under future environmental conditions.

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