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Transitioning From Net Zero Energy to Net Zero Carbon Buildings: Integrated Design Strategies, Embodied Carbon Assessment, and Global Case Studies

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Abstract: ***The built environment accounts for approximately 40% of global CO_2 emissions, prompting a shift from Net Zero Energy Buildings (nZEBs) to Net Zero Carbon Buildings (nZCBs). While nZEBs aim to balance operational energy use through efficiency and renewable, nZCBs address total life-cycle carbon emissions, including embodied carbon. This paper offers a comprehensive analysis of global efforts between 2013 and 2024, integrating architectural strategies, life-cycle assessment (LCA) tools, and climate-responsive case studies from India, Turkey, and Australia. It proposes a unified framework to bridge the gap between energy neutrality and full carbon neutrality, emphasizing the role of passive design, digital tools, and policy alignment in realizing sustainable building futures.***

Keywords: Net Zero Energy Buildings =nZEB, Net Zero Carbon Buildings =nZCB, Life Cycle Assessment = LCA

1. Introduction

The built environment plays a vital role in global sustainability challenges, representing nearly 40% of total CO_2 emissions and more than one-third of global energy consumption. Architectural and construction sectors are mainly overwhelmed by climate-change mitigation efforts. In recent years, the notion of Net Zero Energy Buildings has emerged as a transformative design paradigm. These buildings reduce energy demand through efficiency measures and offset the remaining consumption with renewable energy generation therefore helping in achieving a neutral energy balance.

As the climate discourse evolved, researchers and practitioners recognized that operational energy alone does not represent the total environmental burden of buildings. This realization gave birth to the concept of Net Zero Carbon Buildings (nZCBs)- which accounts not only for operational emissions but also for embodied carbon, encompassing material production, transport, construction, maintenance, and end-of-life impacts.

Despite substantial progress in energy efficiency, achieving net-zero performance remains as a complex mechanism of climatic variability, economic constraints, material limitations, and inconsistent assessment frameworks. Global policies such as the EU Energy Performance of Buildings Directive (EPBD), India's ECBC-R, and U.S. DOE's Zero Energy Ready standards- have provided frameworks, yet implementation changes persist. This study aims to explore how integrated design strategies, embodied carbon assessment tools, and global case studies can facilitate the transition from Net Zero Energy to Net Zero Carbon Buildings. The significance of this study lies in its holistic approach, combining practical design strategies and policy frameworks to support the global shift toward carbon-neutral architecture.

This research paper discusses the following questions:

1) How can architectural design strategies, passive systems, and renewable energy integration collectively affect nZEB performance across varying climates?
2) What methods and tools can effectively judge and reduce embodied carbon in materials to support the change from nZEB to nZCB?
3) How can findings from global case studies inform an amalgamated framework for energy and carbon neutrality in future building design?

2. Literature Review and Background

2.1 Evolution of the Net-Zero Concept (2013–2024)

In the last decade there has seen a shift from energy efficiency towards net-zero and carbon balance. Early frameworks such as the International Energy Agency' and the U.S. DOE definition, focused on operational metrics and mechanisms. By the year of 2020, academic and policy discourse merged toward whole-life carbon accounting, encompassing embodied emissions. Studies between 2013 and 2024 e.g., Jaysawal et al., 2022; Eksi et al., 2025 document the actual definition of nZEB: a building that produces at least as much renewable energy as it consumes on an annual basis". On contrast, nZCB implies "no net carbon emissions throughout the building life cycle.

2.2 Policy Drivers and Global Standards

Policy evolution has strongly influenced nZEB application:
- European Union: EPBD (2010, recast 2021) mandates nearly-zero energy standards for all the new buildings constructed henceforth
- United States: DOE's Zero Energy Ready Homes and ASHRAE 90.1 outline developing lower EUI targets.

- India: Energy Conservation Building Code (ECBC) and National NZEB Alliance encourage tropical nZEB design (NZEB India, 2022).
- Australia and Turkey have united nZEB goals within national energy action plans.

2.3 Passive and Active Design Strategies

The first principle of achieving a net-zero energy building balance is demand minimization. Passive design determines the magnitude of heating, cooling, and lighting loads long before mechanical systems are introduced in the systems. Across climates this research identifies four primary determining factors which are orientation, envelope design of building, daylighting, and natural ventilation of the system.

2.3.1 Orientation and Form

Building orientation governs the solar exposure and prevailing-wind direction interaction.

- In tropical regions, elongated east–west plans with minimal window area on those facades reduce direct solar gain.
- In temperate climates, orienting the building toward the equator maximizes winter solar heat gains.

It is found that maximum orientation alone can cut annual cooling energy by about 8–15 %, while poor orientation can increase its demand by up to 20 %. Compact architectural forms also reduce envelope-to-floor-area ratio, lowering transporting loss.

2.3.2 Envelope Performance

Envelope decisions such as insulation, glazing type, and surface color can directly affect thermal loads. High-performance envelopes combine high reflectivity, low-emissivity glazing, and appropriate thermal mass. At the Sierra e Facility case study located in, it uses 18-inch concrete walls with reflective glass and cool roof tiles which in turn reduces external heat gain by about 30–35 % compared with standard construction.

2.3.3 Daylighting and Solar Control

Daylighting provides visual comfort and reduces building energy demand. Studies report that up to 40 % lighting-energy savings in offices using well-designed daylight apertures and light shelves. However, glare controlling mechanism is crucial. Somfy Animeo automated blinds, installed in the Sierra building, tracks the sun to admit diffuse light while avoiding direct beam penetration demonstrating a model of climate-responsive automation. Passive solar control strategies also include overhangs, fins, and vegetation buffers that modulate seasonal sun angles.

2.3.4 Natural Ventilation and Thermal Comfort

Ventilation strategies harness pressure differentials and buoyancy effects to enhance comfort. Cross-ventilation layouts, operable windows, and atria have been used in Hong Kong's CIC Zero-Carbon Building and in multiple Mediterranean case studies. Ceiling fans- often overlooked in commercial projects- extend the comfort band by 2–3 °C, reducing cooling load by 10–15 %.

2.3.5 Active Systems and Controls

Even after passive optimization, mechanical systems remain indispensable. Variable Refrigerant Flow (VRF) systems, heat-recovery ventilation, and Smart building management systems (BMS) are now common in nZEBs. In Sierra's project, the VRF unit achieved an EER = 13.85, about 55 % more efficient than conventional chillers. IoT sensors work upon real time based on CO_2, temperature, and occupancy levels, Also the Izmir's Retrofit employed HVAC and LED systems which ultimately helped in reducing 72% of primary energy.

2.4 Renewable Energy Integration

When the demand is minimized the remaining loads are supplied by the renewable energy systems. Integration methodologies differ according to climate and building types.

2.4.1 Photovoltaic (PV) Systems

- Sierra eFACiLiTY: 60 kW rooftop crystalline PV ,4.3 kW BIPV glass façade, 20 kW bifacial panels covering approximately 80 % of annual energy demand.
- Izmir Retrofit: Roof PV supplying approximately 66 % of annual electricity which are optimized through HOMER Grid simulation.
- Melbourne Homes which are 10–20 kW PV arrays exported 3–37, building consumption, achieve net-positive energy.

System sizing typically aims for Energy Performance Index (EPI) ≤ 60 kWh/m²·yr- Sierra achieved 56.2 kWh/m²·yr, while Turkish and Australian projects achieved < 50 kWh/m²·yr. PV integration can be on-roof, BIPV, or façade mounted. Recent advances include bifacial modules and solar glazing, which add 10–15 % generation yield without extra land use.

2.4.2 Solar Thermal and Hybrid Systems

Solar thermal collectors remain viable for domestic hot water and absorption cooling. Hybrid systems combining PV and solar thermal (PV-T) can increase total efficiency from 17–20% to over 30% (Lou & Hsieh, 2024). Some Chinese zero-carbon public facilities employ PV + battery + solar-thermal for off-grid operation.

2.4.3 Energy Storage and Smart Grids

Battery storage enhances self-consumption but affects economics. The Melbourne study reported payback periods of 43–112 years for Tesla Powerwall systems, underscoring that current batteries serve resilience more than ROI ([28]). Smart grid interconnection with net-metering remains the most cost-effective route to net-zero operation.

2.4.4 System Monitoring

Continuous monitoring ensures that simulated and actual performance align. Advanced metering dashboards track energy generation, load profiles, and occupancy patterns. Sierra's BMS integrates renewable data, lighting control, and IAQ sensors, enabling 64 % lighting-energy savings and optimized HVAC runtime ([29]).

2.5 Life-Cycle Assessment and Embodied-Carbon Background

While nZEBs achieve operational neutrality, embodied carbon can represent 20–40 % of total life-cycle emissions ([28]). Therefore, the transition to nZCBs demands inclusion of manufacturing (A1–A3), transport (A4–A5), use (B1–B7), and end-of-life (C1–C4) stages.

2.5.1 Life-Cycle Assessment Framework

ISO 14040 and EN 15978 provide the standardized life cycle assessment process:

1) Goal & Scope Definition – Establishing boundaries like cradle-to-gate or cradle-to-grave.
2) Inventory Analysis – Quantify material and energy flows using databases such as Ecoinvent or EPD.
3) Impact Assessment – Calculate Global Warming Potential in kg CO_2 e.
4) Interpretation – Identify hotspots and mitigation options.

Lou and Hsieh in 2024 introduced the Life cycle emission and the Life cycle energy metrics which helped to have a parallel comparison of energy and carbon in different phases

They found operational energy often contributing about 70–80 % of total, but manufacturing (module A3) dominates embodied carbon impacts.

2.5.2 Tools and Digital Integration

Contemporary tools like One Click LCA, SimaPro, GaBi, Tally help in linking directly to Building Information Models, providing instant real-time feedback on embodied carbon performance. Iddon & Firth in the year 2023 demonstrated BIM-LCA integration yielding five times faster scenario comparison. Also, roles-based frameworks like the Roles paper, 2023 stress upon designating responsibility: architects for design optimization, engineers for systems efficiency, contractors on controlling waste execution, and clients for carbon-conscious commissions.

2.5.3 Strategies for Embodied-Carbon Reduction

Key methodologies which are acquired from global literature are:

- Low carbon concrete, mass timber and recycled steel are used as a material substitute
- Enhancing durability by increasing building longevity to offset initial embodied carbon.
- Promoting re-use through modularity as a prefabrication process significantly decreases waste generation by 20–30%.
- Promoting circularity by enabling component reuse and recovery through disassemblable design processes.

Table 1

Parameter	Sierra eFACiLiTY® (India)	İzmir Retrofit (Turkey)	Melbourne Homes (Australia)
Climate Type	Tropical (Hot–Humid)	Mediterranean	Temperate
Typology	Office (New)	Residential (Retrofit)	Residential (New)
Floor Area	2,322.55 m²	180 m²	250 m²
Year Completed	2017	2025 (modeled)	2024
EPI (kWh/m²·yr)	56.2	50.0 (after retrofit)	35
Renewable Energy	60 + 4.3 + 20 kW PV systems	Rooftop PV 66% supply	10–20 kW PV per home
CO_2 Reduction	78% operational	99.1% operational	100% operational
Embodied Carbon	N/A	N/A	13.1 tCO_2e
Payback Period	—	10 years	4–9 years (carbon)
Monitoring System	Full IoT BMS	Partial	Smart meters & monitoring
Distinct Feature	Fully automated smart building	Feasible low-cost retrofit	Net-positive energy export

3 Methodology

3.1 Research Framework

This study adopts a methodology of quantitative hybrid framework combining literature review, case studies and comparative analysis

The framework consists of four stages:

1) Literature Study: Identifying global definitions, metrics, and performance standards
2) Case Study and Analysis: Examining projects across climatic zones such as tropical, Mediterranean and temperate.
3) Comparative Analysis: Measuring carbon and energy performance indicators
4) Framework Synthesis: Developing a unified design and policy model connecting operational and embodied carbon neutrality.

3.2 Case Study Selection Criteria

Selection was based on these four criteria:

- Documented performance data like energy and performance metrics
- Varying climatic zones to ensure generalizability
- Inclusion of both new construction and retrofits.
- Representation of change from energy-neutral to carbon-neutral building design.

Three case studies which met the requirement.

1) Sierra eFACiLiTY Green Office Building, Coimbatore, India having tropical climate.
2) Residential Retrofit in İzmir, Turkey having Mediterranean climate.
3) Net-Zero Homes, Melbourne, Australia having a temperate climate.

3.3 Data Collection and Analysis

The data was collaboratively collected from educational reports and peer reviewed papers like NZEB Alliance 2022.

Performance criterion are:

- Energy Performance Index (EPI)
- Operational CO_2 Reduction (%)
- Embodied Carbon (tCO_2e)
- Payback Period (years)

4 Discussion and Findings

4.1 Design Integration Across Climatic Contexts

Comparative studies showcase that climate responsive building designs play a vital role in net zero energy building. Studies indicate that in tropical regions like India, design strategies focus on minimizing solar gain in minimizing solar gain through orientation and shading systems. Whereas, in mediterranean and temperate regions like Turkey and Australia

Focus is more towards insulation, air tightness and passive solar heating.

4.2 Energy- Carbon Relationship

Operational energy and carbon are linked tight, yet the relationship weakens as electricity grids tend to decarbonize. Melbourne's case demonstrates that even with zero operational emissions, embodied carbon persists as a major share of life-cycle impact about 20 - 40%. Hence, net-zero energy no longer guarantees net-zero carbon. Thus, a life-cycle perspective is very essential.

4.3 The Embodied Carbon Imperative

From the literature and case study data we get to know that manufacturing module A3 contributes for the highest share of the carbon being embodied.

- Concrete and steel together account for about 50–60% of the carbon embodied emissions.
- By replacing traditional concrete with 50% SCM and using timber frames can cut this by 25–35% in total.
- BIM–LCA integration enables quantification of these benefits early in design (Iddon & Firth, 2023).

However, challenges persist:

- Lack of harmonized carbon databases.
- Limited availability of Environmental Product Declarations (EPDs) in developing economies.
- Cost perception barriers among developers.

Hence, policies mandating upfront carbon reporting and EPD-based procurement are crucial for mainstreaming nZCBs.

4.4 Stakeholder Roles and Collaboration

The roles-based analysis paper highlights that net-zero success depends on a cross-disciplinary unified framework.

- Architects focus on passive design and LCA-driven material selection.
- Engineers make sure that high-efficiency systems and renewable technologies are integrated
- Contractors practice low-waste, modular construction and document material provenance.
- Clients and Policymakers verify carbon budgets, incentives, and long-term performance

All these together convert sustainability from a design goal into a tangible, measurable result.

4.5 Economic and Policy Perspectives

Economic viability remains the keystone, İzmir and Melbourne cases indicate that:

- Energy efficiency and solar PV systems offer quick payback periods (less than 10 years).
- Battery storage is still less cost-effective but improve energy reliability
- Government incentives like feed-in tariffs and tax credits strongly affect project feasibility.

Globally, regulations and standards are also changing:

- The EU Taxonomy (2022) and RIBA 2030 Climate Challenge now include embodied carbon targets.
- India's ECBC 2022 and the NZEB Alliance encourage renewable energy and passive design suited to tropical climates.
- Australia's NABERS and NatHERS systems link building energy ratings to their carbon impact.

These instruments pave the way for standardized net-zero metrics globally.

5 Unified Framework for Transition

5.1 Phase 1: Energy Efficiency and Passive Optimization

- Implementing bioclimatic design principles tailored to local climate.
- Integration of daylighting, natural ventilation, and passive shading using simulation-based envelope

5.2 Phase 2: Active System Efficiency and Control

- Selecting highly-performing HVAC and lighting systems
- Usage of BMS and IoT platforms for adaptive control and feedback.

- Electrify heating and cooling to line up with renewable supply potential.

5.3 Phase 3: On-Site Renewable Integration

- Optimizing PV system design using HOMER to balance the annual load.
- Exploring hybrid systems like PV, solar thermal, battery for increased resilience and durability
- Design grid interconnection for net-metering and smart controlment systems.

5.4 Phase 4: Embodied carbon management

- Conducting early-stage life cycle assessment
- Setting an embodied carbon budget i.e kg CO2/m^2 GFA at the concept stage.
- Prioritizing material reuse, recycling and achieving modular construction and circularity.

5.5 Phase 5: Verification and Feedback

- Commission energy systems after occupancy and verifying actual EUI vs. design EUI.
- Monitoring and recording of life-cycle carbon with the help of the building's lifespan.
- Sharing data with open databases to support future benchmarking and research

5.6 Phase 6: Policy and Market Integration

- Integrating carbon reduction targets in building codes and certification frameworks.
- Providing financial support for buildings that achieve verified net zero carbon state.
- Providing carbon-offset mechanisms only for emissions that cannot be avoided.

This iterative process ensures that the change from net-zero energy to carbon neutrality becomes easily measurable across different contents

6 Conclusion

This study shows that converting from Net Zero Energy to Net Zero Carbon Buildings does not solely depend on technology, but the environment plays a key role. Starting from Coimbatore's high-tech tropical office to Melbourne's temperate net-positive homes, various evidence demonstrates that integrated design, renewables sources, life-cycle carbon management can supply climate-oriented performance.

Key takeaways from this research includes the following:

1) The passive design should be prioritized before renewable energy comes next, which reduces energy demand before supply
2) Tools like BIM, LCA and simulation based plays a vital role in achieving the goal
3) Setting up compulsory carbon enclosure and net-zero targets must guide industry adoption.
4) Collaboration across governance ensures that zero energy transforms into zero carbon.

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