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Invited Review Article

State-of-the-Art of Net-Zero building standards and benchmarks in India: A Comprehensive review with notable case studies

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ABSTRACT

India's building sector is expanding under the 2070 net zero pledge, yet the pathway defined by mandatory codes including the Energy Conservation Building Code (ECBC) for commercial buildings, Eco Niwas Samhita (ENS) for residences, and the newer ECSBC, together with voluntary rating systems such as GRIHA, IGBC/LEED-India, EDGE, and operational benchmarking through BEE Star, remains fragmented in practice. Using a PRISMA-adapted approach, we screened 1,245 records from 2010 to 2025, assessed 371 full texts, and synthesised 78 eligible sources, including sixteen exemplars across India's climates and typologies. We compile benchmarks for operational Energy Performance Index (EPI), and envelope parameters such as U-values and Solar Heat Gain Coefficient and present a code-to-outcome crosswalk linking ECBC and ENS baselines and voluntary ratings to operational EPI through BEE Star, clarifying what better than baseline means in operation. Offices and laboratories commonly report 55–80 kWh/m^2·yr EPI when climate-appropriate envelopes with low U-values and effective solar control are paired with efficient cooling systems alongside on-site photovoltaics. Case studies and modelling evidence show photovoltaic and building-integrated photovoltaic are economically viable, though storage costs and tariff structures remain constraints. A brief comparison with the United Kingdom and the United States shows broad alignment on energy targets but weaker requirements in India for airtightness and whole-life carbon. Three evidence gaps persist: routine airtightness testing, multi-year metered end-use datasets, and standardised whole-life carbon accounting. Enforceable next steps include adopting Super-ECBC level U-values as default, mandating ACH_{50} testing and disclosure, and phasing embodied carbon thresholds within ECSBC and ENS.

1. Introduction

India's building sector is expanding rapidly, and the country has announced a national commitment to reach net zero emissions by 2070, which places buildings at the centre of the transition [1,2]. Growth spans hot dry, composite, warm humid and temperate zones and brings pressure to reduce cooling demand, electrify end uses, and integrate renewables without compromising comfort. Policy instruments now include mandatory codes, ECBC and Super ECBC for commercial buildings and ENS for housing, with the newer ECSBC widening scope to sustainability, and operational labels such as BEE Star which expresses outcomes in metered Energy Performance Index. Together these outline a credible net-zero pathway, yet practice remains fragmented, with uneven feedback from post occupancy performance to design and enforcement [3–6].

We use NZEB to denote buildings whose annual operational energy is matched by renewables within a stated boundary, while NZCB extends the scope to whole life carbon. Our primary outcome is the Energy Performance Index (EPI), expressed in kWh/m^2·year; the key envelope descriptors are the U-value (W/m^2·K) and the solar heat gain coefficient (SHGC). In Indian reporting, floor area bases, conditioned versus gross, and climate adjustments are inconsistent which complicates comparison; airtightness, often written as ACH_{50}, is rarely measured despite its impact on sensible and latent loads, and whole life carbon is gaining traction but lacks enforceable thresholds [7,8]. International and regional syntheses confirm that hot and warm climate NZEBs succeed when efficient envelopes are paired with effective ventilation and verified in operation [9,10]. Comparative work also highlights development gaps and opportunities in India relative to other large markets such as China and the United States [11].

We address four review questions (RQ). RQ1 asks how Indian codes

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Nomenclature

ACH_{50}	Air changes per hour at 50 Pa [h^{-1}]
BEE	Bureau of Energy Efficiency
BIPV	Building-integrated photovoltaics
ECBC	Energy Conservation Building Code (commercial)
ECSBC	Energy Conservation and Sustainable Building Code (expanded scope)
EDGE	Excellence in Design for Greater Efficiencies (IFC)
ENS	Eco Niwas Samhita (residential)
EPI	Energy Performance Index [$kWh/m^2\cdot yr$]
GRIHA	Green Rating for Integrated Habitat Assessment
HVAC	Heating, ventilation and air-conditioning
LCA	Life-cycle assessment
MNRE	Ministry of New and Renewable Energy
NZEB	Net Zero Energy Buildings
NZCB	Net Zero Carbon Buildings
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
SHGC	Solar heat-gain coefficient [–]
UT	Union Territory
U-value	Overall heat-transfer coefficient [$W/m^2\cdot K$]
VERVE	Variable Refrigerant Flow
WLC	Whole-life carbon [$kgCO_2e/m^2$]

and voluntary ratings map onto measurable operational outcomes. RQ2 asks which combinations of envelope, systems and photovoltaic choices deliver lower Energy Performance Index across climates. RQ3 asks which short term enforceable parameters would accelerate NZEB uptake process. RQ4 asks where Indian limits exceed or lag international practice and what quantified differences matter most. A brief conceptual frame treats buildings as governed socio technical systems in which policy sets boundary conditions, design optimisation shapes demand, renewables and tariffs shape supply and timing, and metered Energy Performance Index validates performance, while whole life carbon runs in parallel as a materials constraint. NZEB optimisation studies also address parameter uncertainty, component degradation and maintenance, and coordination of building-level design with cluster and grid constraints such as feeder overvoltage [12,13]; however, our study primarily focuses on an building-level embodied and operational carbon workflow.

This review contributes in three ways: a codes-to-ratings-to-outcomes crosswalk, a straightforward normalisation of metrics, and a literature synthesis that ties design choices to reported Energy Performance Index and proposes enforceable next steps for India [4]. The review turns fragmented Indian guidance into an auditable, reusable research framework: a code to rating to outcome crosswalk that links design intent to measured Energy Performance Index, and a harmonised metric set that future studies can use for like for like comparison across climates and typologies [5].

2. Methodology

To ensure transparency and reproducibility, this review follows PRISMA 2020 (Preferred Reporting Items for Systematic reviews and Meta-Analyses. PRISMA is a reporting framework that documents information sources and search strategy, apply two stage screening from title and abstract to full text, and present a flow diagram with counts at each stage (Fig. 1). PRISMA does not require *meta*-analysis when evidence is diverse; here it is applied as a structured reporting guide. The review window is 2010 to August 2025 and the focus is India, with international studies included only where methods or findings are directly transferable to Indian codes, climates, or typologies [14].

2.1. Literature Identification

We searched Scopus, Web of Science, and Google Scholar, and manually reviewed official portals and repositories for the Bureau of Energy Efficiency, the Ministry of Power and MNRE, and programme sites for GRIHA, IGBC and LEED India, and EDGE. Boolean strings combined India, net zero and nearly zero terms, building and climate or typology labels, names of codes and ratings, and outcome terms such as Energy Performance Index, U value, Solar Heat Gain Coefficient, and photovoltaic or BIPV. The search, last updated in August 2025, yielded 1,245 records. After removal of 138 duplicates, 1,107 unique entries remained for screening. Fig. 1 highlights strong thematic links around “building,” “energy,” and “India”, which form the core of the research

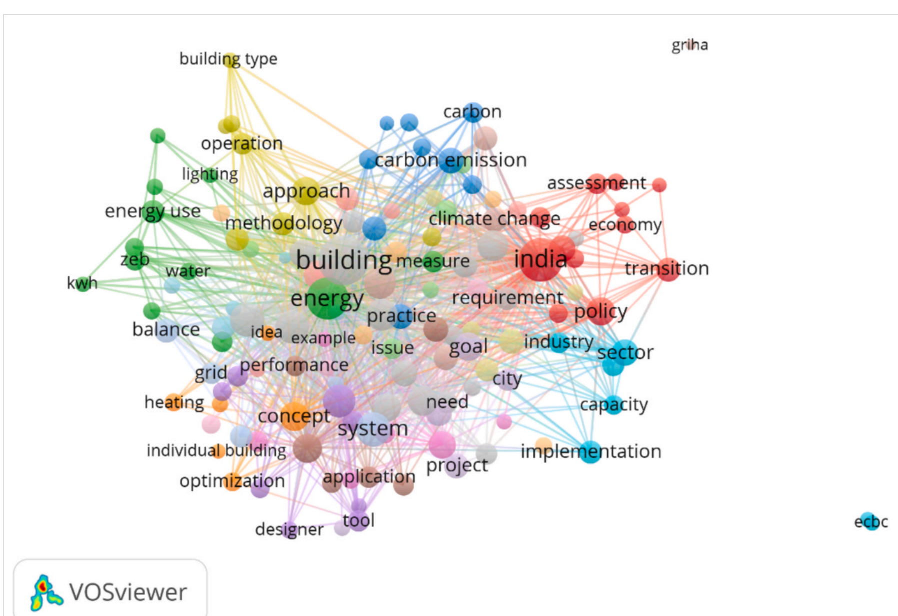

Fig. 1. The keyword network visualisation of Net-zero building research via VOSviewer.

focus. Strong connections exist between carbon emissions, climate change, and policy, showing an emphasis on national transition strategies. Technical terms like system, optimisation, and tool are well-integrated, while terms like GRIHA and ECBC appear weakly linked, suggesting underrepresentation or niche focus areas.

2.2. Screening and Eligibility

Titles and abstracts were screened against preset rules (Fig. 2). We included items that are India relevant and that report or allow extraction of Energy Performance Index or envelope metrics or systems and renewables characteristics or programme thresholds. We excluded items unrelated to buildings in India, non-building energy topics, purely theoretical work without building application, duplicates, and items without clear methods. Screening removed 736 records. We assessed 371 full texts and excluded 293 for insufficient quantitative detail or redundancy. The final corpus contains 78 eligible sources across standards and guidance, benchmarking and technical studies, and case studies. Within this set we identify twenty-four detailed net zero case reports; sixteen Indian exemplars are cited in the synthesis to illustrate patterns. Counts for each stage appear in the PRISMA flow diagram in Fig. 2.

2.3. Data extraction and synthesis

Each included record was reviewed with a structured template that

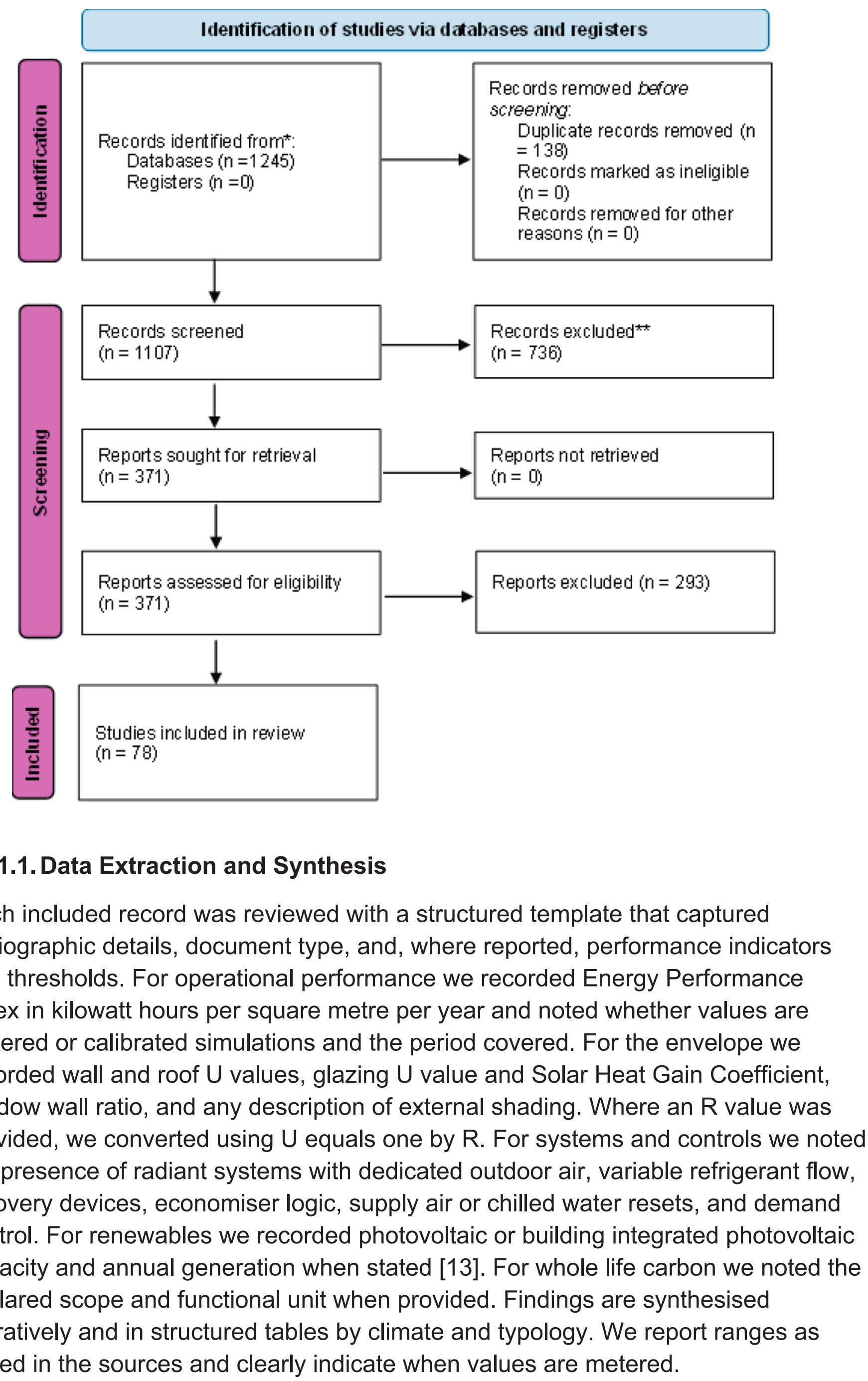

Fig. 2. PRISMA flow chart.

captured bibliographic details, document type, and, where reported, performance indicators and thresholds. For operational performance we recorded Energy Performance Index in kilowatt hours per square metre per year and noted whether values are metered or calibrated simulations and the period covered. For the envelope we recorded wall and roof U values, glazing U value and Solar Heat Gain Coefficient, window wall ratio, and any description of external shading. Where an R value was provided, we converted using U equals one by R. For systems and controls we noted the presence of radiant systems with dedicated outdoor air, variable refrigerant flow, recovery devices, economiser logic, supply air or chilled water resets, and demand control. For renewables we recorded photovoltaic or building integrated photovoltaic capacity and annual generation when stated [13]. For whole life carbon we noted the declared scope and functional unit when provided. Findings are synthesised narratively and in structured tables by climate and typology. We report ranges as stated in the sources and clearly indicate when values are metered.

2.4. Crosswalk construction and synthesis

We prepared a code to rating to outcome crosswalk from official documents and programme manuals so readers can see how ECBC, ENS and ECSBC baselines and voluntary rating thresholds relate to operational outcomes that are reported through BEE Star and, where relevant, Shunya. The crosswalk is used as a reading guide in the results and discussion and does not involve new calculations. Benchmarking and outcome framing draw on Indian technical work so that Energy Performance Index and threshold definitions match local use [4,5,7].

2.5. Case study Selection and analysis

From the twenty-four case study records, we selected sixteen Indian exemplars to cite in the results and discussion to represent a spread of typology and climate and completeness of reporting. These cases are used to illustrate reported Energy Performance Index ranges, envelope and system choices, photovoltaic strategies, and certification status where relevant. We compare cases narratively and in structured tables using values reported in the sources.

2.6. Quality assessment

To keep the evidence base credible while remaining inclusive of practice material, we used a two-tier grading approach. Grade A includes peer reviewed journal articles and official government publications that report primary empirical data or benchmarks. Grade B includes conference proceedings, industry white papers, and third-party case summaries with verifiable data but limited methodological detail. Only Grade A and Grade B sources were retained. For benchmarking context and programme constructs we rely on Indian technical work to ensure local relevance and comparability [4,5,7].

2.7. Novelty and limitation

This review adds three methodological elements within a PRISMA 2020 reporting frame. It includes practice material under a two-tier grading so peer reviewed, and official sources are distinguished from conference and industry items that provide verifiable but less detailed methods. It applies a consistent normalisation so Energy Performance Index is in kilowatt hours per square metre per year, the area basis is flagged as conditioned or gross with conditioned preferred when both are available, U equals one by R where only R values are reported, Solar Heat Gain Coefficient is taken as stated with qualitative notes on external shading, and photovoltaic or building integrated photovoltaic entries capture capacity and annual generation when available. It introduces a code to rating to outcome crosswalk drawn from official documents and programme manuals so ECBC, ENS and ECSBC baselines and voluntary rating thresholds can be read against operational outcomes reported through BEE Star and, where relevant, Shunya. Templates, normalisation steps, and the crosswalk schema are provided in the supplements for reuse [4,5,7].

However, limitations remain in the review. Publications explore successful or certified projects, so weaker outcomes are likely under-represented. Mixed floor area bases and climate adjustments reduce comparability even with careful notation. Whole life carbon reporting is sparse and not standardised, and airtightness is rarely measured, which restricts discussion of sensible and latent load control. Findings are presented as narrative and in structured tables.

3. NZEB policy & codes in India

India's building energy codes and labels have evolved rapidly in the past decade, moving from a narrow focus on energy efficiency to a broader sustainability frame (Fig. 3).

Three pillars now structure the landscape:

1. Mandatory codes (design stage, enforceable once states notify) (ECBC/ECBC+/Super-ECBC; ENS),
2. Voluntary certifications (design and construction, market
3. Outcome based labels (post occupancy, metered proof)

Together, these instruments define design baselines, set optional stretch targets, and offer ways to validate performance in operation.

4. Mandatory energy codes

4.1. Energy Conservation building code (ECBC) and ECSBC 2024

India's Energy Conservation Building Code (ECBC) defines minimum energy performance standards for new large commercial buildings (connected load $\geq$ 100 kW or $\geq$ 120 kVA). Introduced in 2007 by the Bureau of Energy Efficiency (BEE), it covers building envelope, HVAC, lighting, electrical systems, and hot water design [15,16]. Tailored to India's five climatic zones, the code emphasises passive strategies like daylighting and thermal insulation to reduce cooling loads without compromising comfort [17]. ECBC 2017 introduced a tiered structure—ECBC, ECBC+, and Super ECBC, targeting energy savings of ~ 25 %, ~35 %, and $\geq$ 50 %, respectively over conventional buildings [18]. It encouraged on-site renewable energy integration and provided alignment with voluntary green rating systems such as GRIHA and IGBC [19]. However, ECBC focuses on operational energy, not embodied carbon, and remains technology-neutral to support life-cycle cost-effective solutions [20]. Several states have integrated ECBC compliance into their building approval systems, particularly for large commercial projects [21]. Adoption is state led: ECBC becomes enforceable when a state/UT notifies it (often with local adaptations). As of 2023, 23 states had notified ECBC in some form, illustrating steady diffusion but uneven enforcement and incorporated in the By Laws of atleast 1 Municipality [22]. A recent example is Chandigarh's 2024 notification, which clarifies applicability thresholds by connected load, plot size and built-up area—typical of how jurisdictions scope coverage. ECBC and its tiers form design-stage baselines. However, without an operational check, compliance can remain "on paper". Our review therefore links ECBC/Super-ECBC intent to BEE Star so that design targets map to metered EPI outcomes.

4.2. Eco Niwas Samhita (Residential building Code)

Recognising that the residential sector accounts for around 75 % of building electricity use in India, the government introduced the Eco Niwas Samhita (ENS) as the national energy code for homes [23,24]. ENS Part 1, launched in December 2018, set the first performance standards for the building envelope aiming to limit heat gain in hot

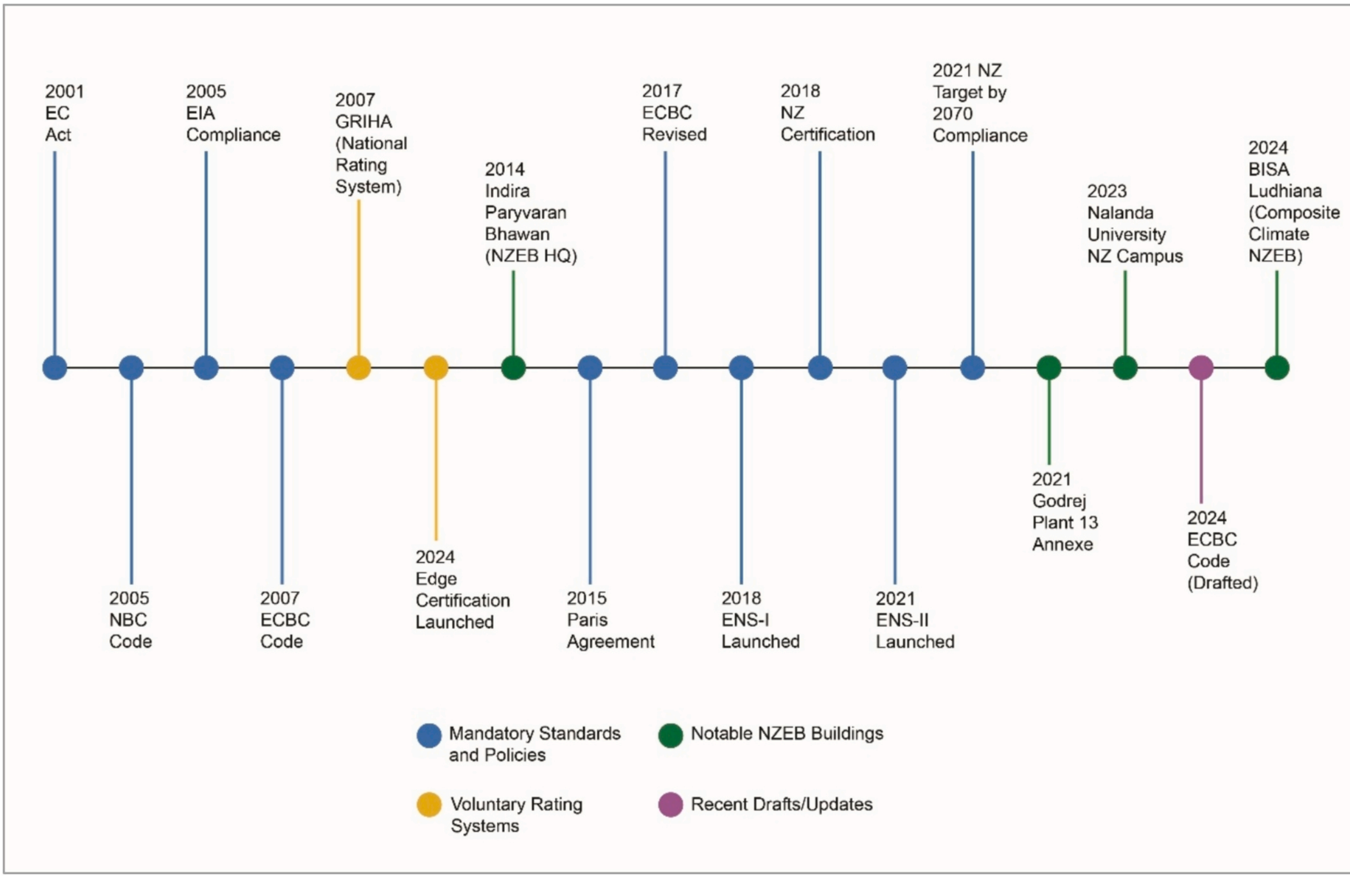

Fig. 3. The evolution of building standards and rating systems in India along with some notable Net-zero buildings built.

climates and heat loss in colder regions, while ensuring daylight and natural ventilation [25]. Passive strategies such as wall and roof insulation, cool roofs, efficient glazing, and window shading are promoted to reduce artificial cooling demand and improve comfort [26]. With urbanisation and rising incomes driving exponential growth in air-conditioning, ENS offers a cost-effective passive strategy to lower peak electricity demand [27]. ENS Part 1 was designed for easy adoption, requiring only basic calculations from architectural drawings rather than detailed simulations [28]. It applies to new residential buildings exceeding defined thresholds and is voluntary or incentivised in several states. Some have already integrated it into local building by-laws [29]. In 2021, ENS Part 2 expanded the code to address lighting, electrical systems, and potentially appliance efficiency [30]. Building on this, the Bureau of Energy Efficiency introduced the ENS 2024 (also referred to as Residential ECSBC) that consolidates Parts 1 and 2 and introduces wider sustainability criteria, including site planning, water use, indoor air quality, and waste management [31]. It applies to residential buildings with a minimum connected load of 100 kW, contract demand of 120 kVA, or plot size $\geq$ 3000 m^2 [32]. The updated code also includes recommendatory annexures for future revisions on topics like retrofitting, smart homes, cool roofs, and embodied energy, signalling a forward-looking roadmap [33]. A home built to ENS standards, with envelope efficiency and rooftop solar, can approach net-zero operational energy [34]. Developed with support from international partners such as Indo-Swiss BEEP and GIZ (German Society for International Cooperation), ENS reflects alignment with global best practices and complements ECBC in promoting net-zero readiness across India's building sector [35]. While ENS primarily targets operational energy, it does not yet regulate embodied carbon.

4.3. *ECSBC 2024 (commercial): From efficiency to sustainability*

To build upon ECBC, the BEE launched the Energy Conservation and Sustainable Building Code (ECSBC) 2024, expanding the scope to include embodied carbon, life-cycle resource efficiency, and circularity in materials [36]. It introduces three tiers: ECSBC-Compliant, ECSBC-Plus, and Super-ECSBC. It crucially, extends beyond energy to include additional sustainability attributes and aims to promote net-zero energy and net-zero carbon buildings [37]. ECSBC 2024 adopts a performance-based approach, enabling flexibility in achieving targets through innovative design [38]. ECSBC 2024 also aligns with the Energy Conservation (Amendment) Act, 2022, which mandates sustainable codes for commercial and residential sectors [39]. While adoption remains state-led, implementation efforts are progressing across India [40], supported by knowledge-sharing platforms and capacity building [41]. Together, ECBC and ECSBC chart India's path toward net-zero-ready commercial buildings by tightening energy performance and embedding broader sustainability goals.

5. Outcome based labels (post occupancy, metered proof)

While BEE Star and Shunya are voluntary outcome labels at national level; they become effectively mandatory when required by a funding programme, tender, or owner policy.

5.1. *BEE Star rating for office buildings*

The Bureau of Energy Efficiency's voluntary Star Rating programme, introduced in 2009, assesses the in-service energy performance of office buildings (and other commercial typologies such as hospitals and shopping malls) with a connected electrical load of at least 100 kW.

Buildings register actual annual electricity consumption, conditioned and total floor areas, operating hours, and climate zone data, which BEE uses to calculate an Energy Performance Index (EPI) in kWh/m2.yr and assign a one-to-five star rating; five-star denotes top-quartile performance in that climatic zone [42]. With effect from 1 January 2022, BEE updated the climate-specific EPI bands for office buildings to reflect evolving benchmarks in the warm-humid, composite and hot-dry zones, tightening thresholds across all star levels and thereby raising the bar for existing building stock [43]. This operational rating complements ECBC/ENS design-stage minimums by revealing real-world performance gap, and it creates a market pull for energy management improvements through public recognition of high performers [44]. A five-star office in a composite climate, for example, now corresponds to an EPI below approximately 65 kWh/m^2.yr (site energy) whereas a one-star rating aligns with much higher consumption; intermediate ratings are distributed linearly between these limits. By benchmarking existing buildings rather than modelling projections, the programme drives continuous retrofit, controls optimisation, occupant engagement, and investment in efficiency measures, all verified through audited data submissions and third-party reviews [45].

5.2. BEE Shunya for net zero and net positive energy buildings

BEE Shunya is a national outcome label that recognises buildings which achieve a verified annual energy balance at or below zero. It shifts attention from relative efficiency to absolute performance by certifying two outcomes. Shunya is awarded when the annual balance, expressed as Energy Performance Index, lies between ten and zero kWh/m^2.yr. Shunya Plus is awarded when the Energy Performance Index is below zero kWh/m^2.yr, because the building exports more renewable energy over the year than it consumes within the defined boundary. The programme sets out a clear application and verification process. Applicants provide contact information, basic building descriptors, and a metering plan that captures all significant end uses. They submit at least one full year of measured electricity consumption, floor area definitions, operating hours, climate information, and evidence of on site or contracted renewable generation that is attributable to the building. The emphasis is on traceable and auditable data, since the outcome is determined by the relationship between measured annual consumption and measured or otherwise verified annual renewable generation. The label does not address time of use effects, grid interaction, or embodied carbon, which are handled by other instruments.

5.3. Voluntary green building rating systems and certifications

In addition to ECBC and ENS, India has a landscape of voluntary green building certifications that complement mandatory codes [46,47]. These programs evaluate performance across energy, carbon, water, materials, indoor environmental quality, waste, and site planning [48]. Though not legally required, they shape market behaviour, with developers using them for credibility and incentives [49]. By exceeding code and promoting advanced efficiency and renewable integration, they support the transition to net zero buildings [50].

5.4. GRIHA: India's indigenous green building rating

The Green Rating for Integrated Habitat Assessment (GRIHA) is India's indigenous green building system, developed by The Energy and Resources Institute and endorsed by the MNRE. Tailored to India's diverse climates and socioeconomic contexts, it evaluates environmental performance across the full life cycle from design and construction through operation [51]. The standard GRIHA framework comprises 34 criteria spanning site planning, energy efficiency, water and waste management, and sustainable materials; projects accrue points against defined benchmarks to achieve a one to five star rating, subject to minimum thresholds for certification [51]. Design guidance prioritises passive strategies, including orientation, shading, daylighting, and natural ventilation, to curb cooling loads, alongside the integration of on-site renewables such as solar photovoltaic and solar hot water. It also promotes local, low impact materials and robust construction and operational waste practices to lower embodied energy and emissions [51]. The latest GRIHA v2019 incorporates life cycle assessment and life cycle cost analysis, placing equal emphasis on embodied and operational carbon, and encourages alternative materials and recycled content to reduce whole life impacts [52]. GRIHA offers variants for specific contexts, including SVAGRIHA for small projects, GRIHA for Existing Buildings, GRIHA for Affordable Housing, and the Decarbonizing Habitat Programme, which helps organisations assess and reduce footprints through cost effective strategies [53]. GRIHA is recognised as India's national rating and is often mandatory for government buildings; the Central Public Works Department and several states typically require $\geq$ 3 star performance, driving exemplars such as the Indira Paryavaran Bhawan in New Delhi (net zero energy; 5 star GRIHA) [61]. Incentives at central and state levels further encourage uptake. With 1,000 + registered projects, GRIHA is shaping both operational and embodied carbon outcomes in India, providing a context specific benchmark and practical pathway toward net zero ready buildings [54].

5.5. IGBC green building certifications and LEED India

The Indian Green Building Council (IGBC), established in 2001 under the Confederation of Indian Industry, helped launch the LEED rating system in India and has since developed its own ratings for varied typologies, including Green New Buildings, Green Homes, Green Factories, and Green Campuses. IGBC frameworks align with international practice yet adapt to Indian conditions. Certification levels, Certified, Silver, Gold, and Platinum, are awarded via points across Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality, with mandatory prerequisites in each system [55]. For operational carbon, IGBC emphasises demand reduction and renewable integration; higher tiers typically require surpassing ECBC benchmarks through efficient HVAC, LED lighting, and on-site renewables. The Energy and Atmosphere category is strongly weighted and includes credits for energy optimisation and renewable generation [63]. For embodied impacts, IGBC encourages recycled-content and locally sourced materials and certified wood, while LEED v4/v4.1 (used in India) adds credits for whole-building life-cycle assessment and for products with verified lower environmental impact [56]. IGBC also offers Net Zero certifications for energy, water, and waste; under Net Zero Energy, a building must demonstrate 100 % on-site or off-site renewable supply meeting annual demand after substantial demand reduction. LEED certifications in India are administered by Green Business Certification Inc. In 2024, India ranked third globally for LEED, with 370 certified projects totalling about 8.5 million gross square metres. Most were in Operations and Maintenance, followed by Interior Design and Construction, and Building Design and Construction [57,58]. This momentum underscores India's increasing alignment of operational and embodied performance with net-zero ambitions.

5.6. EDGE: Resource efficiency for affordable green buildings

EDGE (Excellence in Design for Greater Efficiencies) is a newer green building certification system gaining traction in India, especially for housing and mid-tier commercial projects. Developed by the International Finance Corporation, it is designed as a simple, quantifiable tool to drive resource-efficient design in emerging markets [59]. Unlike broader rating systems, EDGE concentrates on three areas: energy savings, water savings, and reduction in the embodied energy of materials. Projects must show at least a 20 percent reduction in each category relative to a typical local baseline, with compliance validated by an auditor; meeting these thresholds earns EDGE certification, $\geq$40 percent qualifies for EDGE Advanced, and a defined combination of performance with renewable supply or qualified green power or offsets can achieve EDGE Zero Carbon [60]. EDGE provides a free, cloud-based software where designers input building parameters and select measures such as wall insulation, efficient HVAC, solar hot water, low-flow fixtures, and recycled steel; the tool calculates percentage improvements across energy, water, and materials and clarifies cost–benefit trade-offs to support least-cost design[61]. Certification through GBCI is comparatively quick and economical, which underpins its growing adoption [62]. For decarbonisation, the energy criterion guarantees a minimum 20 percent cut in operational energy; deeper impact is achieved when efficiency is coupled with on-site photovoltaics, green power, or offsets to reach EDGE Zero Carbon. The water criterion also reduces energy tied to supply and treatment. Notably, EDGE uniquely requires a 20 percent reduction in the embodied energy of materials, making it one of the few systems with a mandatory embodied-carbon performance target; typical strategies include hollow blocks, lower-energy cement, and recycled steel [63]. In India, EDGE has been applied across residential, commercial, healthcare, and hospitality sectors, including mid-rise apartments and affordable housing in cities such as Ahmedabad, Pune, and Bengaluru, often supported by SBI Green Bonds and multilateral funding schemes [64]. As an accessible benchmark for entry-level green buildings, EDGE bridges operational and embodied carbon domains and supports progress toward net-zero-ready buildings.

5.7. Comparative analysis: Mandatory codes, voluntary ratings, and outcome labels

Mandatory codes set the legal design baseline. ECBC for commercial buildings and ENS for housing specify envelope and systems requirements, for example maximum U-values for walls and roofs, Solar Heat Gain Coefficient limits for glazing, lighting power density limits, and a simplified envelope transmittance metric in housing. Compliance can be prescriptive or whole building performance based. Embodied carbon is not yet regulated; ECSBC 2024 widens scope to sustainability attributes and establishes a pathway toward whole life carbon requirements [65 38]. Adoption and enforcement are state led via notification, with applicability typically framed by electrical load or contract demand thresholds and, in some jurisdictions, area triggers [32]. Super ECBC functions as a design-stage, net zero–ready enhanced standard.

Voluntary certifications organise higher ambition and market signals. GRIHA v2019 brings life cycle assessment and life cycle cost into scope. IGBC and LEED India use points with tiered levels and offer optional whole building LCA and environmental product declaration credits; both reward energy optimisation and renewables, and both have net zero offerings, with LEED Zero requiring twelve months of measured performance. EDGE is numerical and streamlined, requiring at least twenty percent savings in energy, twenty percent in water, and twenty percent in the embodied energy of materials relative to a local baseline; EDGE Advanced recognises at least forty percent, and EDGE Zero Carbon couples high efficiency with one hundred percent renewable supply or qualified green power or offsets [66 67 68]. In practice, EDGE is generally the fastest and lowest cost route, GRIHA and IGBC sit in the middle, and LEED is the most documentation intensive but carries international recognition [49 55,69 57]. Outcome labels verify in-use results. BEE Star Rating assigns one to five stars from metered EPI with typology and climate schedules and three year validity; office bands were tightened from January 2022 across warm humid, composite, and hot dry zones [42 43 70 71]. BEE Shunya recognises absolute annual balance, with Shunya when EPI lies between ten and zero $kWh/m^2.yr$ and Shunya Plus when EPI is below zero via net export, based on a defined metering plan and one full year of measured consumption plus verified renewable generation. BEE Star answers relative in-use efficiency; Shunya answers annual net zero or net positive balance. Codes apply to new construction above state thresholds and are embedded in permits; voluntary systems are open to many types, for example affordable housing using EDGE and flagship offices using IGBC or LEED. BEE Star currently covers major commercial types with explicit schedules, and both Star and Shunya can be required by owners or programmes although voluntary nationally [34,65]. Together these tools close the design to performance loop. Costs mirror this progression, with ECBC and ENS at moderate complexity, EDGE and BEE Star generally low cost and fast to document, GRIHA and IGBC mid-range, and LEED higher effort reflecting its global scope [22 50 55 57 65 69,72]. Tables 1-5 summarise these differences and provide the quantitative schedules for EPI handling and envelope limits where applicable.

5.8. From standards to outcomes: The crosswalk

The following crosswalk translates mandatory and voluntary commitments into a single pathway from design intent to verified in use performance.

a. Baseline to ECBC, ENS or ECSBC via prescriptive or performance path, recording envelope U and SHGC, system efficiencies, and renewables as the design claim.
b. Optionally add GRIHA, IGBC, LEED or EDGE for points and third-party review; GRIHA 2019 also credits commissioning, metering, and LCA.
c. Plan BEE Star early, align sub metering and M and V, and target typology EPI bands updated January 2022.
d. For NZEB, apply Shunya for EPI 10 to 0, or Shunya + for EPI below 0, and retain renewal evidence.

6. Integrated strategy for Indian net-zero buildings

6.1. Passive design

Cooling and dehumidification dominate loads in composite, hot-dry and warm-humid zones, so energy demand need to be reduced by designing climate-led form and fabric [9,73]. Early design decisions also include orienting elongated plans to limit east and west exposure, moderating surface-to-volume ratio, and controlling window-to-wall ratio to about 20–40 % with external shading sized to sun angles [9,74,75]. Facades that combine lower SHGC on east and west with tightened wall and roof U-values beyond code minima deliver persistent reductions in peak and annual cooling, especially in composite climates [76,77]. Daylight savings are reliable when glare is managed by fixed external devices sized for Useful Daylight Illuminance bands of 100–2000 lx and paired with realistic dimming controls [78]. Airtightness is pivotal yet under-reported; specifying a continuous air barrier and testing at handover would curb latent loads and reheat penalties, particularly in warm-humid zones [9].

6.2. Active HVAC systems

System choices that recur in lower-EPI projects decouple sensible and latent loads and maintain high part-load efficiency [10,78]. Radiant cooling or heating with a Dedicated Outdoor Air System and heat or enthalpy recovery tempers outdoor air efficiently while handling zone sensible loads with low fan energy, provided moisture-aware commissioning is in place [9,79]. Where central plants are used, variable-flow water-cooled chillers with condenser-water reset and tuned sequences outperform nameplate-only upgrades[80,81]. Variable-refrigerant-flow systems perform well when ventilation is provided separately via treated fresh air or a small DOAS [82,83]. Electrification with air-source, ground-coupled, or solar-assisted heat pumps reduces operational carbon and can improve seasonal performance in northern and mixed climates [84]. Control logics that repeatedly lower EPI include economiser when psychrometrics allow, supply-air and chilled-/condenser-water temperature resets, static-pressure and pump VFD control, CO_2-based demand-controlled ventilation, humidity-led DOAS control to avoid terminal reheat, and occupancy-based setbacks with window interlocks

Table 1
Comparison between mandatory codes, voluntary ratings, and outcome labels.

Parameter	ECBC (2017)	ECSBC (2024)	ENS (2018/21)	ENS (2024)	GRIHA	IGBC/LEED-India	EDGE	BEE Star Rating	BEE Shunya
Applicability	Commercial ≥ 100 kW	Commercial expanded	Residential threshold	Residential ≥ 100 kW	All building types	All building types	All building types	Existing offices, malls, hospitals, BPOs ≥ 100 kW	Any building with auditable metering data
Administering Body	BEE	BEE	BEE	BEE	TERI/GRIHA	IGBC & GBCI	IFC/GBCI	BEE	BEE
Primary Carbon Focus	Operational only	Operational + embodied	Operational envelope	Operational + partial embodied	Both (LCA v2019)	Both	Both (20 % embodied)	Operational only	Operational only
Operational Measures	Prescriptive U-values; EPI ≈110	Enhanced targets	U_env ≤ 1.3; U_roof ≤ 1.2	Performance-based	Point-based credits	Point-based credits	20 % energy reduction	EPI benchmarking (1–5 stars)	None; compliance is by measured annual balance
Embodied Measures	None	Annexures recommend	None	Annexures recommend	Mandatory LCA & materials	Optional LCA & EPDs	20 % embodied reduction	None	None
Renewable Integration	Promoted	Stronger emphasis	Promoted	Encouraged	Required for higher ratings	Encouraged	Optional Zero Carbon	Not applicable	Yes, on site or contracted
Compliance Style	Prescriptive & performance	Performance-based	Simplified prescriptive	Performance-based	Point-based rating	Point-based rating	Numerical targets	Performance benchmarking	Measured annual consumption and verified annual renewable generation
Certification Levels	N/A	N/A	N/A	N/A	1–5 Stars	Certified Platinum	Certified Zero Carbon	1–5 Stars	Shunya and Shunya Plus
Net-Zero Alignment	Net-zero ready	Net-zero roadmap	Foundation for net-zero homes	Net-zero readiness	Decarbonising programme	Platinum tiers	Entry-level net-zero	Continuous improvement	Certifies net zero energy and net positive energy outcomes
Ease & Cost	Moderate	Moderate–High	Low	Moderate	Moderate	Moderate–High	Low	Low	Low to moderate
Envelope U-value requirement	U_env ≤ 1.8; U_roof ≤ 1.2	To be defined	U_env ≤ 1.3; U_roof ≤ 1.2	To be defined	Aligns with ECBC	Per ASHRAE 90.1	Baseline + 20 %	N/A	N/A
EPI benchmark (kWh/m^2·yr)	≈110	Not specified	Not specified	Not specified	Not specified	Not specified	20 % reduction target	Climate & AC-adjusted EPI bands	Shunya if EPI lies between ten and zero; Shunya Plus if EPI is below zero

in mixed-mode buildings [9,78,81].

6.3. Renewables

Solar readiness of roofs and façades is best treated as a design constraint from concept stage, with roof layouts that minimise service clutter and parapets or plant screens proportioned to avoid self-shading of collector fields [85,86]. Where roof area is limited, facade integrated photovoltaics can provide additional capture while serving as fixed external shading, particularly on east and west elevations in cooling dominated climates [85,87]. Photovoltaic capacity should be sized against expected specific yield and prevailing tariff and storage conditions, and studies show that production–storage optimisation improves the probability of achieving an annual net zero balance when considered alongside passive and HVAC choices [88]. Incorporating life cycle assessment at the same stage helps ensure that envelope and renewable selections which reduce EPI do not increase embodied impacts unnecessarily [89].

7. Net-Zero case studies in India

7.1. Certified Net-Zero buildings

7.1.1. Indira Paryavaran Bhawan, new Delhi

The ministry headquarter uses two north–south wings around a courtyard with high performance insulation, reflective roof finishes, daylight shelves, radiant cooling, natural ventilation and a large rooftop photovoltaic field [90] (Fig. 4 [91]). A geothermal precool loop with 180 bores at about 80 m tempers condenser water and reduces tower load. Annual generation slightly exceeds use and reported Energy Performance Index is about 44 kWh/m^2.yr. Integrated BMS, rainwater harvesting, wastewater recycling, low-flow fixtures, and robotic parking further boost sustainability. The building holds GRIHA 5-star and IGBC Platinum ratings [92].

What worked: Wall U value: 0.22 W/ m^2.K, lighting power density: 5 W/m^2, radiant plus dedicated outdoor air, PV ≈ 930 kWp producing ≈ 1.43 GWh per year.

Against benchmarks: Composite office Super ECBC proxy ≈ kWh/ m^2.yr and BEE Star five star ≈ ≤ 65; achieved ≈ 44, margin ≈21.

Pathway: publish airtightness and full fabric performance; commit to BEE Star renewal on a three-year cycle.

Table 2
EPI Handling Across Major Indian Standards.

Benchmark / Standard	EPI	How EPI is managed	Relation to ECBC	Office (Composite) (kWh/m^2·yr)	School/ University (kWh/ m^2·yr)	Hotel (kWh/ m^2·yr)	Hospital (kWh/ m^2·yr)	Private Homes (kWh/m^2·yr)
ECBC 2017	Yes	Defines standard EPI by building type & climate	Original source	130	110	200	210	Not covered
Super-ECBC (ECBC +)	Yes	Tightens allowed EPI ratio (≤0.78)	Upgrade of ECBC	101.4	85.8	156	163.8	Not covered
Eco Niwas Samhita (ENS)	–	Focus on envelope RETV	Residential-specific	N/A	N/A	N/A	N/A	N/A
BEE Star Rating (Offices)	Yes	Measured operational EPI	Independent	≤90	Not covered	Not covered	Not covered	Not covered
BEE Shunya	Yes	Annual net balance from measured consumption	typically pursued after code compliance	Shunya = 10 to 0; Shunya Plus = less than 0	Not specified	Not specified	Not specified	Shunya = 10 to 0; Shunya Plus = less than 0
GRIHA v2019	Yes	Own benchmark EPIs by typology	Independent	90	90	250	275	70
IGBC Net Zero Energy	Yes	Requires EPI ratio ≤ 0.95 vs ECBC baseline	Uses ECBC	123.5	104.5	190	199.5	Not covered
IGBC Net Zero Carbon	Yes	Same as Net Zero Energy	Uses ECBC	123.5	104.5	190	199.5	Not covered
EDGE	–	% savings from dynamic baseline	Own system	Varies (120–160)	Varies	Varies	Varies	Varies (50–70)

Table 3
EPI Handling Across Major Indian Climates.

Building Type	**Composite (kWh/m^2·yr)**	**Hot-Dry (kWh/m^2·yr)**	**Warm-Humid (kWh/m^2·yr)**	**Temperate (kWh/m^2·yr)**	**Cold (kWh/m^2·yr)**
Large / Medium Office	130	140	120	110	100
School / University	110	115	105	95	90
Hotel (3-star +)	200	210	190	180	170
Hospital	210	220	200	190	180

Table 4
U-Value Handling Across Major Indian Standards.

Benchmark / Standard	Mentions U-values?	How U-values are managed	Relation to ECBC	Wall U-Value Limit (W/m^2·K)	Roof U-Value Limit (W/m^2·K)	Window U-Value Limit (W/m^2·K)	Glazing SHGC Limit
ECBC 2017	Yes	Mandatory maximum U-values for walls, roofs, windows.	Original source.	0.440 (Composite)	0.409 (Composite)	3.3 (with shading)	≤ 0.25 (non-shaded)
Super-ECBC (ECBC +)	Yes	Tighter U-values required.	Upgrade of ECBC.	0.320 (Composite)	0.261 (Composite)	2.6 (with shading)	≤ 0.25
IGBC Green Building Ratings	Yes	Points awarded for better-than-ECBC U-values.	References ECBC generally.	Meet or beat ECBC	Meet or beat ECBC	Meet or beat ECBC	≤ 0.25–0.27
Eco Niwas Samhita (ENS) 2018	Yes	Sets U-values for roof and fenestration; RETV for walls.	Residential-focused.	RETV ≤ 15 W/m^2 (walls)	0.409 (roof)	3.3 (windows)	≤ 0.25
BEE Star Rating	Indirect	Focuses on operational energy, not envelope.	Independent.	N/A	N/A	N/A	N/A
BEE Shunya	Indirect	No U-value prescriptions	Independent	N/A	N/A	N/A	N/A
GRIHA v2015/ v2019	Yes	Prescribes maximum U-values independently.	Similar to ECBC.	0.45 (Composite)	0.41 (Composite)	≤ 3.3	≤ 0.25
IGBC Net Zero Ratings	Indirect	Focus on overall EPI, envelope via ECBC path.	Indirect via ECBC.	Follows ECBC/ Super-ECBC	Follows ECBC/ Super-ECBC	Follows ECBC/ Super-ECBC	Indirect
Eco Niwas Samhita (ENS) 2018	Yes	Sets U-values for roof and fenestration; RETV for walls.	Residential-focused.	RETV ≤ 15 W/m^2 (walls)	0.409 (roof)	3.3 (windows)	≤ 0.25
EDGE	Indirect	No prescriptive U-values	Independent baseline in EDGE; used alongside ECBC	N/A	N/A	N/A	N/A

7.1.2. Godrej plant 13 Annexe, Mumbai

A deep retrofit of a cafeteria and office achieved IGBC Net-Zero Energy Platinum energy without structural change [93] (Fig. 5. [91]). Upgrades included LED lighting, reflective finishes, adjustable shading and variable speed chillers and pumps tuned by modelling. Energy Performance Index fell from above 200 to about 75 and a near one megawatt bifacial PV system balances annual use and exports surplus [93].

What worked: EPI: 75 kWh/m^2.yr, PV: 120 kWp, zonal sub metering, sequenced commissioning. Reuse of the existing shell cut embodied carbon by ~ 30 %.

Against benchmarks: Warm humid office Super ECBC proxy ≈ 60; achieved 75, gap ≈ 15.

Pathway: add dedicated outdoor air with heat or enthalpy recovery

Table 5
Climate-Specific Envelope U-Values (ECBC 2017).

Building Element	Composite ($W/m^2·K$)	Hot-Dry ($W/m^2·K$)	Warm-Humid ($W/m^2·K$)	Temperate ($W/m^2·K$)	Cold ($W/m^2·K$)
Wall	0.440	0.440	0.440	0.440	0.330
Roof	0.409	0.409	0.409	0.409	0.261
Window (with shading)	3.3	3.3	3.3	3.3	2.6
Window (without shading)	3.3	3.3	3.3	3.3	2.6

Fig. 4. Indira Paryavaran Bhawan, New De.

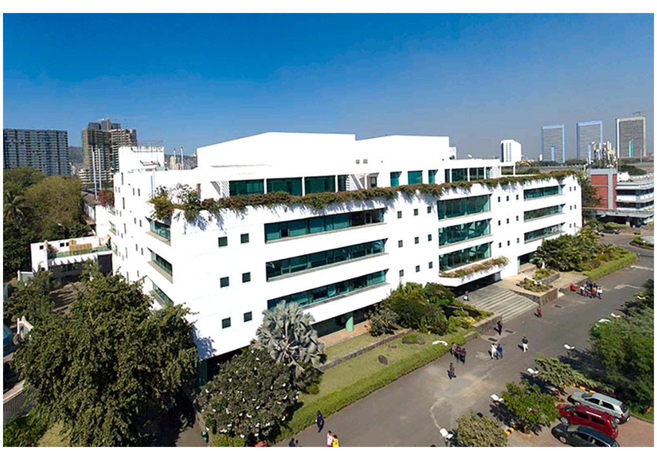

Fig. 5. Godrej Plant 13 Annexe, Mumbai.

for latent control, specify and test airtightness.

7.1.3. Badriya Juma Masjid, Kundapur

Laterite mass, jaali screens for cross-ventilation, a 21-metre wind tower to draw monsoon breezes and a vegetated wall provide comfort with fans and minimal mechanical cooling [94] (Fig. 6. [91]). Lighting is very efficient, and a hybrid of photovoltaics and a small wind turbine covers demand with margin. Community-driven reuse of 80 % demolition debris minimized embodied impacts. The mosque holds IGBC Net-Zero Energy Platinum certification [94].

What worked: EPI: 3 kWh/m^2.yr, wall U value ≈ 1.5 W/m^2.K, lighting power density ≈ 1.4 W/m^2, PV plus wind: 7 kW generating 6.02 MWh per year versus use of 4.41 MWh, embodied energy reduction.

Fig. 6. Badriya Juma Masjid, Kundapur.

Against benchmarks: far below any assembly proxy and de facto net positive.

Pathway: document seasonal indoor conditions and moisture management details for replication.

7.1.4. Net zero carbon homes Pilot, Mohali

Attached two bedroom homes (Fig. 7. [91]) use autoclaved aerated concrete walls, polystyrene-insulated green roofs, modest window to wall ratio and cross ventilation, with heat pump water heating, simple building management and a small PV array [95]. Fly-ash cement, recycled aggregates, and bamboo-ply panels cut embodied energy by ~ 70 %, earning GRIHA 4-star and EDGE certification [96].

What worked: wall U-value 0.79 W/m^2.K, roof U-value 0.24 W/m^2.K, window to wall ratio ≈ 28 %, PV ≈ 8.5 kW generating 7,452 32 kWh/yr, Energy EPI: 32 kWh/m^2.yr.

Against benchmarks: consistent with an ambitious residential pathway although ENS benchmarks use different constructs.

Pathway: reporting whole life carbon and seasonal metered profiles.

7.1.5. Atal Akshay Urja Bhawan, new Delhi

Atal Akshay Urja Bhawan (Fig. 8. [91]) is a net-positive energy tower

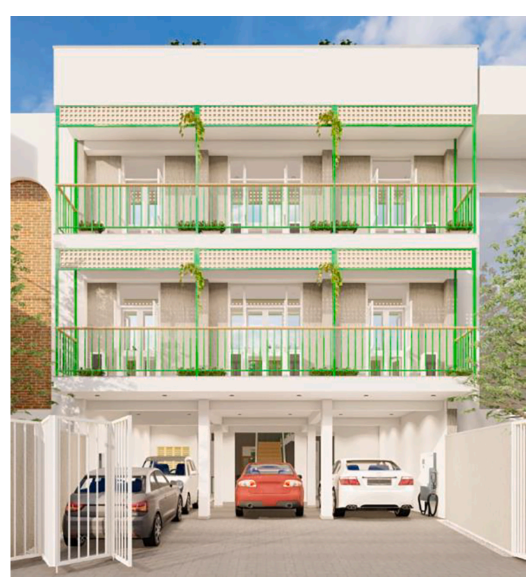

Fig. 7. Net Zero Carbon Homes Pilot, Mohali.

Fig. 8. Atal Akshay Urja Bhawan, New Delhi.

[97]. External jaali screens and a south solar canopy limit solar gain and produce power. Hybrid plant with radiant ceilings, dedicated outdoor air with heat recovery, DOAS with heat-recovery wheels and three-stage evaporative cooling reduces cooling energy by 33 % [98]. Lighting power density is low with high daylight autonomy and arrays reportedly export a surplus.

What worked: PV on site ≈ 1.1 MW with total generation ≈ 1.9 GWh per year and surplus ≈ 0.3 GWh, lighting power density ≈ 3.77 W/m^2, daylight autonomy ≈ 90 percent.

Against benchmarks: likely better than the ≈ 65 Super ECBC proxy for composite offices; EPI: 47 kWh/m^2.yr.

Pathway: publish Energy Performance Index and fabric and airtightness to anchor against BEE Star and international targets.

7.2. Non-Certified Net-Zero buildings

7.2.1. Rajkumari Ratnavati Girls' School, Jaisalmer

An oval sandstone school uses clerestories, jaali and shaded courts to deliver comfort through passive airflow and high daylight in a hot dry desert setting. [99 100]. 35 kW solar canopy shades classrooms and generates 30–40 kW peak. Water use is minimised with rain and reuse.

What worked: ACH by design > 6, daylight autonomy ≈ 90 percent, PV canopy ≈ 35 kW with expected 50 to 60 MWh per year.

Against benchmarks: demand is far below typical school proxies, and the annual balance is positive.

Pathway: add Energy Performance Index on conditioned area and summer indoor conditions to support scale up.

7.2.2. Net zero energy Archive Center, Mumbai

This 1,625 m^2 archive center was designed to maintain documents at 18 °C and 40 % RH, using envelope optimization, solar hot water, GSHPs, LED lighting, and a PV array [101]. Comprehensive climate analysis informed energy conservation measures, achieving a modeled net-zero energy balance under IGCC prescriptive baselines [101].

What worked: controlled temperature and humidity set points with efficient plant, mixed renewables.

Against benchmarks: model-based net zero; metered Energy Performance Index is required for comparison.

Pathway: publish EPI on a stated area basis and add dedicated outdoor air with recovery if not present.

7.2.3. CEPT University Living Lab, Ahmedabad

The 498 m^2 Living Lab integrates passive design and active systems, achieving 58 kWh/m^2.yr, an 86 % reduction vs. similar labs [102]. The compact laboratory uses clerestories and light shelves, hybrid ventilation with night purging, radiant slabs and a variable refrigerant system with a dedicated outdoor air unit for peaks. Lighting controls are calibrated to daylight and the building is instrumented.

What worked: EPI ≈ 58 kWh/m^2 yr, PV ≈ 27 kW producing ≈ 45 MWh per year with ≈ 15 percent export, VRF coefficient of performance ≈ 3.5, natural ventilation ≥ 6 air changes per hour, lighting power density ≈ 4.7 W/m^2.

Against benchmarks: below the ≈ 65 Super ECBC proxy for composite offices.

Pathway: publish U values and airtightness to strengthen transferability.

7.2.4. Jaquar Group Headquarters, Manesar

A large campus uses a near one megawatt PV canopy over sheds and parking to supply about one hundred and twenty two percent of annual use. The office reduces envelope area and uses low SHGC glazing with louvers, waste heat recovery chillers, multi zone variable refrigerant flow and low lighting power density with sub metering.

What worked: PV ≈ 971 kWp, annual demand ≈ 1.5 GWh, generation ≈ 122 percent of demand, glazing SHGC ≤ 0.25, VRF coefficient of performance > 3.8, lighting power density < 6 W/m^2, sub-metering drove 20 % additional savings [103].

Against benchmarks: net positive annual energy.

Pathway: disclose Energy Performance Index with area basis and any airtightness testing.

7.2.5. Lodsi community Project, Uttarakhand

An adaptive reuse of a stone gaushala into a production centre uses thick masonry and deep overhangs to stabilise indoor conditions in a temperate setting [104]. A fifty kilowatt PV system with batteries produces about twice the annual demand and rain storage supports process water.

What worked: wall U ≈ 0.8 W/m^2. K, PV ≈ 50 kWp generating ≈ 60 MWh per year versus use ≈ 30 MWh, rain storage ≈ 50 cubic metres, EPI 35.

Against benchmarks: net positive on an annual basis.

Pathway: simple airtightness metrics and seasonal monitoring would inform hill region replication.

7.2.6. SODHA BERS Complex, Varanasi

A multi storey building in a composite climate combines Trombe walls, earth berming, wind towers, solar water heating, photovoltaic panels and a photovoltaic thermal dryer. Reported energy savings exceed fifty percent and the economic payback is about twenty years [105].

What worked: layered passive solar measures with modest renewables, savings > 50 percent.

Against benchmarks: not yet framed as Energy Performance Index.

Pathway: report EPI on conditioned area and add a dedicated outdoor air unit with recovery for winter and monsoon control.

7.2.7. BISA Building, Ludhiana

A composite climate office verified annual demand of about 432,742 kWh and installed on site PV of 300 kWp to reach net zero on energy. The monitored Energy Performance Index is about 80 kWh/m^2.yr [106] with an optimised envelope and efficient plant.

What worked: PV ≈ 300 kWp, annual demand ≈ 433 MWh, measured EPI ≈ 80 kWh/m^2·yr.

Against benchmarks: above the ≈ 65 Super ECBC proxy for composite offices yet net zero on annual balance.

Pathway: further envelope tightening and moisture control, airtightness testing, and BEE Star submission.

7.2.8. Residential NZEB, Ahmedabad

An optimisation led single family house combined passive features with a rooftop photovoltaic system to reduce electricity from about 9,330 kWh per year to about 38 kWh per month. The case shows the potential for near net zero performance in a hot dry city when demand is lowered, and generation is planned from the outset.

What worked: right sized PV coupled with shading and envelope optimisation.

Against benchmarks: residential code uses different constructs; express as EPI when floor area is available.

Pathway: publish Energy Performance Index per square metre and include embodied carbon notes.

8. Net zero energy Retrofit, Bangalore

A small commercial retrofit framework couples rooftop PV, envelope upgrades, daylight controls and an EnergyPlus workflow to approach net zero in a temperate setting [107]. The scheme offers a staged plan with savings estimates and control sequences.

What worked: integrated passive measures and PV with a calibrated simulation loop.

Against benchmarks: model-based assessment; metered EPI is needed for comparison.

Pathway: implement a dedicated outdoor air system and airtightness testing and submit to BEE Star.

8.1. Net zero energy Neighbourhoods, Ahmedabad

A model based study of three clusters shows that shared PV of about 500 kWp with twenty percent envelope U value improvement and micro grid controls can reach annual net zero with paybacks of five to seven years that shorten with programme support [108].

What worked: shared generation, moderate envelope improvement, smart controls.

Against benchmarks: neighbourhood scale rather than building scale.

Pathway: pilot with metered data and include feeder and transformer impacts.

8.2. Nalanda University Campus, Rajgir

A large campus plan combines multi megawatt solar farms and biogas with compressed stabilised earth blocks, water bodies and traditional water systems. The target is net zero energy, water, emissions and waste at campus scale with phased delivery [109–111]..

What worked: generation about 6.5 MW solar farms plus about 5 MW building PV and about 1.5 MW biogas, low carbon materials.

Against benchmarks: campus scale outcomes lie beyond current labels; report building level Energy Performance Index where possible.

Pathway: define staged embodied carbon caps by building class and publish metered outcomes during occupancy.

The case studies are compared by operational performance (EPI), code benchmarks (ECBC-2017; Super-ECBC), BEE 5-Star, and PV/balance, as presented in Table 6.

9. Key Insights by region

Composite climates (Delhi, Mohali) use balanced passive strategies, courtyards, high-mass envelopes, cool roofs, and moderate PV systems (930 kW [97]; 8.5 kW [90,112] to achieve low EPIs (≈55 and kWh/m^2. yr, respectively) without explicit embodied-carbon mandates.

Warm & humid zones (Mumbai) require airtight, thermally insulated envelopes with daylighting and adjustable shading, supported by large PV (975 kW) to offset cooling loads. Retrofit shell reuse yields ~ 30 % embodied-carbon savings [93].

Coastal humid contexts (Kundapur) maximize natural ventilation via wind towers and jaali screens, enhanced by evaporative cooling walls. Hybrid PV + wind systems meet full demand and export surplus, while on-site debris reuse minimizes embodied impacts [105].

Table 6
Indian NZEB Case Studies: EPI and Code Crosswalk.

Case	Type/ Climate	EPI (kWh/m^2. yr)	ECBC baseline	Performance basis	Super-ECBC target	Gap to Super-ECBC (kWh/ m^2.yr)	BEE 5★ status	PV & balance
Indira Paryavaran Bhawan	Office (Composite)	44	130	Metered	101.4	−47.4	Pass (≤65)	930 kWp; 1430 MWh/yr; surplus
Godrej Plant 13 Annexe	Office retrofit (Warm-humid)	75	120	Metered	93.6	−18.6	N/A	975 kWp; 800 MWh/yr; balance/slight export
Badriya Juma Masjid	Religious/community (Warm-humid)	3	N/A	Metered	N/A	N/A	N/A	10 kWp; 6.02 MWh/yr; surplus
Net Zero Carbon Homes Pilot (Mohali)	Residential (Composite)	32	N/A (ENS)	Metered	N/A	N/A	N/A	8.5 kWp; 7.452 MWh/yr; ~net zero
Atal Akshay Urja Bhawan	Office (Composite)	47	130	Unclear	101.4	—	Unknown	1100 kWp; 1900 MWh/yr; surplus ~ 300 MWh
Rajkumari Ratnavati Girls' School	School (Hot-dry)	Not disclosed	115	Unclear	89.7	—	N/A	35 kWp; 50–60 MWh/yr; expected positive
Net Zero Energy Archive Center	Archive (Warm-humid)	Not disclosed	N/A	Modelled	N/A	N/A	N/A	GSHP; PV + SWH; modelled NZE
CEPT University Living Lab	Lab/Education (Hot-dry)	58	140	Metered	109.2	−51.2	—	27 kWp; 45 MWh/yr; ~15 % export
Jaquar Group Headquarter	Office campus (Composite)	Not disclosed	130	Metered	101.4	—	Unknown	971 kWp; ~122 % of demand
Lodsi Community Project	Production centre (Temperate)	35	N/A	Metered	N/A	N/A	N/A	50 kWp; 60 MWh/yr; ~2 × demand
SODHA BERS Complex	Mixed-use (Composite)	Not disclosed	N/A	Modelled	N/A	N/A	N/A	Savings > 50 %; payback ~ 20 yrs
BISA Building	Office (Composite)	80	130	Metered	101.4	−21.4	Fail (>65)	300 kWp; 433 MWh/yr; net zero balance
Residential NZEB (single family)	Residential (Hot-dry)	Not disclosed	N/A (ENS)	Metered	N/A	N/A	N/A	Near NZE; ~38 kWh/ month grid
Net Zero Energy Retrofit (framework)	Small commercial (Temperate)	Not disclosed	N/A	Modelled	N/A	N/A	N/A	Modelled approach; add DOAS
Net Zero Energy Neighbourhoods	Neighbourhood model (Hot-dry)	N/A (district scale)	N/A	Modelled	N/A	N/A	N/A	500 kWp; modelled net zero
Nalanda University Campus	Campus (Composite)	N/A (campus scale)	N/A	Modelled	N/A	N/A	N/A	6.5 MW farm + 5 MW buildings + 1.5 MW biogas; targets NZE

Arid/hot-dry regions (Jaisalmer) leverage high thermal mass (sandstone), clerestories, and deep courtyards to buffer extreme temperatures. Solar canopies provide shading and generate significant surplus energy [99].

Temperate/mixed climates (Punjab) showcase that high-insulation envelopes with modest PV achieve deep operational cuts, while low-carbon materials deliver ~ 70 % embodied-energy reduction [95].

10. Comparison of Net-Zero building Standards: India, UK & US

While this review focuses on India's net-zero building standards and benchmarks, it is useful to briefly compare these with leading frameworks in the UK and the US to explore India's relative progress. Table 7 collates key performance metrics such as operational energy targets (EPI), U-values, solar heat gain coefficients, airtightness thresholds, and heating-demand limits across India's Super-ECBC and GRIHA Net-Positive track [113,114], the UK's LETI/RIBA 2030, Passive House UK, Future Homes Standard [115–118], and US programs such as ASHRAE 90.1, DOE Zero Energy Ready Home, Passive House US, and LEED Zero [68,119–122]. This comparison reveals that Indian codes now align closely on EPI targets yet still allow more permissive U-values and generally lack mandated airtightness or explicit heating-demand caps unlike major international.

Table 7
Net-Zero Building Standards: India, UK & US.

Parameter	Best Indian Standard (Super-ECBC, GRIHA Net-Positive)	Best British Guidance (LETI, RIBA 2030, Passive House UK, Future Homes Standard)	Key American Standards (ASHRAE 90.1, DOE ZERH, Passive House US, LEED Zero)
EPI (Offices) (kWh/m^2·yr)	~ 60–70 (site energy)	~ 55–65 (delivered)	ASHRAE 90.1 baseline ~ 100–120; DOE ZERH offsets all via renewables
Wall U-Value (W/m^2·K)	≤ 0.32 (Super-ECBC +)	≤ 0.15–0.18	Passive House US: ≤ 0.15 [118]; DOE ZERH (IECC R-30): ~ 0.033
Roof U-Value (W/m^2·K)	≤ 0.26 (Super-ECBC +)	≤ 0.11–0.15	Passive House US: ≤ 0.11 [118]; DOE ZERH (IECC R-49): ~ 0.023
Window U-Value (W/m^2·K)	≤ 2.6 (shaded)	≤ 1.0–1.2 (triple glazing) [114]	Passive House US: ≤ 0.80 [118]; DOE ZERH (ENERGY STAR): ~ 1.10
SHGC Limit	≤ 0.25 (composite climate)	≤ 0.30 (orientation-dependent)	Region-specific, typically ≤ 0.25–0.30
Airtightness (ACH@50 Pa)	Not specified	≤ 0.60 (Passive House UK)	Passive House US: ≤ 0.60 [118]; DOE ZERH: ≤ 2.0
Heating Demand (kWh/m^2.yr)	Not specified	≤ 15 (Passive House) [114]	Passive House US: ≤ 15 [118]
Residential EPI (kWh/m^2.yr)	~ 25–35 (pilot NZ homes)	~ 35–50 (LETI/UKGBC)	DOE ZERH: PV must offset annual use; Passive House US: ~ 25–35 [118]

11. Cross-Cutting Themes, Challenges, and opportunities

11.1. Integrated passive design as the Foundation

Every successful net-zero building in India began with passive strategies: optimal orientation, high-performance envelopes, daylighting, and natural ventilation. In New Delhi's Indira Paryavaran Bhawan and Atal Akshay Urja Bhawan, courtyards and light-shelves drive down cooling and lighting loads, while in Jaisalmer's Rajkumari Ratnavati School and Uttarakhand's Lodsi Project, thick local masonry (high thermal mass) and strategic shading controls heat and radiation. By cutting baseline energy demand often by 50 % or more, these measures reduce the size and cost of active and renewable systems required to achieve net-zero .

11.2. Renewables integration and Multi-Functional PV

Solar photovoltaics (PV) dominate on-site electricity generation. The solar canopy at Indira Paryavaran Bhawan or the dual solar-shade roof at Atal Bhawan, illustrate how PV can serve as both energy generator and architectural element. Godrej's Plant 13 and Jaquar's Manesar headquarters demonstrate that large-scale PV, up to nearly 1 MW, can render even energy-intensive facilities net-positive. Hybrid systems, incorporating small wind turbines at the Badriya Masjid, further boost resilience in coastal climates.

11.3. Attention to embodied carbon

While most projects qualitatively addressed embodied impacts through local or recycled materials (e.g., AAC blocks with fly-ash, laterite stone, reclaimed timber), only the Mohali housing pilot quantified a 70 % embodied-energy reduction. The lack of consistent Life Cycle Assessment highlights a major opportunity: mainstreaming embodied-carbon caps, as proposed in the ECSBC 2024, will be critical to ensure truly net-zero-carbon buildings .

11.4. Monitoring, Controls, and commissioning

Data-driven controls are indispensable to realise design intents. CEPT's Living Lab leveraged 900 sensors to optimize mixed-mode ventilation; Godrej's retrofit used sub-metering for ongoing fine-tuning; nearly every certified project employed a Building Management System. Equally vital is third-party commissioning and post-occupancy verification where practices still uneven across India's construction industry [123].

11.5. Scaling and replication Challenges

Thes case study projects showcase feasibility, but large-scale adoption requires overcoming barriers: high up-front costs for advanced envelopes and PV, limited local expertise in passive/radiant systems, and fragmented enforcement of ECBC and ENS. Financing mechanisms like green loans, accelerated depreciation, FAR bonuses have helped pioneers, yet broader awareness campaigns and capacity-building initiatives are needed to embed net-zero as standard practice.

11.6. Policy and market opportunities.

The synergy between tightening codes (ECBC+, ENS uptake) and voluntary certifications is driving buildings toward net-zero readiness. Upcoming policy moves like mandatory disclosure of whole-life carbon, embedding LCA in codes, and community-scale net-zero mandates can accelerate momentum. Market instruments such as carbon credits for surplus generation, property-tax rebates, and fast-track approvals for net-zero projects can further tip the balance.

12. Government policies and incentives Supporting Net-Zero/ Green buildings

India's federal and state governments have woven together regulatory, fiscal, and procedural incentives to accelerate green and net-zero building adoption. By offering extra development rights, fee waivers, concessional finance, tax benefits, expedited clearances, and mandatory green building mandates, public policy now substantially improves the business case for high-performance buildings, driving a registered green footprint past 929 million m2 by 2023 [124].

12.1. Additional FAR/FSI and ground coverage

The Ministry of Urban Development directs local authorities to grant free-of-cost additional Floor Area Ratio (FAR) or ground coverage, ranging from 1 % to 5 %, for projects certified under GRIHA, LEED, or IGBC systems on plots over 3,000 m^2 [125]. Some states have amplified these incentives; Punjab permits an extra 5 % FAR for GRIHA-rated buildings [126], Haryana's 2017 Building Code rewards up to 25 % additional FAR for IGBC Gold/Platinum or GRIHA 4–5-star projects [126], and West Bengal has offered up to 10 % extra FAR based on pre-certification by green rating agencies [125].

12.2. Reduction in Fees, Charges, and Taxes

Municipal bodies like Pimpri-Chinchwad and Pune waive or discount building plan scrutiny fees and development premiums. Pimpri-Chinchwad offers up to 50 % reduction on plan fees and a sliding property-tax rebate tied to GRIHA star ratings [127]. Punjab's Urban Development Department exempts 100 % of plan scrutiny fees for IGBC-rated projects, alongside its FAR bonus[128].

12.3. Preferential Financing

The Indian Renewable Energy Development Agency extends soft loans (as low as ~ 7 % interest with moratoriums) for renewable energy and efficiency measures, including rooftop solar on green buildings [129]. Concurrently, commercial lenders such as SBI, Union Bank, HDFC,IIFL Home Finance, provide concessional "green home loans" with marginally reduced rates for GRIHA or IGBC-certified residential projects [125,126]. In 2025, Standard Chartered bank and IGBC have signed a MoU to promote Green loans for rated green buildings in India.

12.4. Tax benefits and depreciation

Under the Income Tax Act, businesses investing in renewable-energy systems such as solar PV, solar thermal, and waste-to-energy equipment can claim 100 % accelerated depreciation in the first year, effectively subsidizing net-zero building components [129].

12.5. Faster approvals and compliance Relief

The Ministry of Environment, Forest and Climate Change offers a fast-track environmental clearance route for pre-certified IGBC/LEED Gold or GRIHA 4-star and above projects, shortening timelines significantly [130]. Several states mirror this via single-window NOC exemptions and priority permit routing for green-rated schemes.

12.6. Public sector Leadership and mandates

Public-sector undertakings and government departments set the example. The CPWD mandates a minimum 3-star GRIHA rating on all new central government buildings [131], and since 2009, the Union Cabinet requires all new PSU structures to secure at least a 3-star GRIHA certification [132].

13. Conclusion

India's building sector has made notable progress toward net-zero performance by layering prescriptive codes, voluntary certifications, high-profile demonstrations, and enabling policies. Mandatory standards like ECBC and ENS have driven reductions in operational energy through envelope U-value and EPI targets, while GRIHA, IGBC/LEED-India, and EDGE have pushed projects "beyond code" with tiered energy benchmarks, on-site renewables, and the early incorporation of life-cycle assessments for materials. Notable projects, from the geothermal-cooled Indira Paryavaran Bhawan to the passive-mass Badriya Juma Masjid, prove that even extreme climates can host buildings with EPIs as low as 3–55 kWh/m2·yr and, in many cases, net-positive energy balances. Retrofit examples like Godrej Plant 13 and the Lodsi community centre show that existing stock can be transformed through targeted envelope upgrades, efficient systems, and robust monitoring, often without major structural changes.

Yet significant gaps remain. Most codes still focus almost exclusively on operational carbon, with embodied carbon largely absent from regulatory baselines and only selectively rewarded in voluntary ratings. As buildings become ever more efficient in use, the share of carbon locked in materials and construction processes can rise to 20–30 % or more of lifetime emissions, an issue too seldom quantified or constrained. Enforcement of existing codes is uneven across states, and uptake of voluntary certifications remains concentrated among flagship developments rather than the broader mass of new construction. Financial incentives and expedited permitting have spurred early adopters, but the incremental benefits often fail to trickle down to smaller projects or affordable housing.

A fully integrated net-zero trajectory for India will require mandating life-cycle carbon limits in building regulations, expanding LCA-based credits in rating systems, and strengthening compliance mechanisms at the local level. Equally important is scaling up retrofit incentives to address the vast existing building stock and developing market instruments, such as embodied-carbon credits, to reward low-impact materials and circular-economy practices. Super-ECBC-level U-values should be adopted as default, ACH50 testing and disclosure should be required for all projects, and the proposed code-to-outcome crosswalk should be used to report metered EPI with end-use breakdowns against ECBC/ENS baselines in future studies. Only by coupling world-class operational efficiency with rigorous embodied-carbon management and universal code enforcement can India ensure that every new building, from homes to hospitals, advances the nation's 2070 net-zero goal.

CRediT authorship contribution statement

Eshrar Latif: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Vaibhav Jain:** Writing – review & editing, Validation, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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