Assessing Energy Code Compliance of Multistoried Residential Buildings of Ludhiana: Application of ECBC-R and Punjab-ECBC

OPEN ACCESS

Volume: 1

Issue: 2

Period: Mar to Aug 2026

Received: 10.04.2026

Accepted: 20.05.2026

Published: 01.06.2026

E-ISSN: 3108-0383

Citation:
Kapoor, G., & Singhal, M. (2026). Assessing Energy Code Compliance of Multistoried Residential Buildings of Ludhiana: Application of ECBC-R and Punjab-ECBC. *Indian Journal for Net Zero 2070, 1*(2), 11-20.

DOI:
10.34293/ijnz2070.v1i2.11052

Geetanjali Kapoor
Amity School of Architecture and Planning
Amity University, Mumbai, Maharashtra, India
https://orcid.org/0000-0001-7186-4058

Meenakshi Singhal
Department of Architecture, Guru Nanak Dev University, Amritsar, Punjab, India
https://orcid.org/0000-0001-6407-1404

Abstract
Amid the accelerating pace of residential construction and the increasing urgency of energy conservation, it is essential to assess whether contemporary housing developments align with established energy efficiency standards. In India, the Energy Conservation Building Code for Residential Buildings (ECBC-R), introduced by the Bureau of Energy Efficiency (BEE), provides a national framework for promoting sustainable residential design. Complementing this, the Punjab Energy Conservation Building Code (Punjab-ECBC) introduces region-specific performance benchmarks tailored to the composite climate of Punjab. This study evaluates the energy code compliance of three representative multistoried residential buildings—low-rise, mid-rise, and high-rise—located in Ludhiana, Punjab. These typologies reflect the prevailing patterns of urban residential development in the region. Accordingly, this study examines compliance with ECBC-R and Punjab-ECBC to provide a comprehensive evaluation of residential energy performance at both national and state levels. The findings reveal significant gaps in compliance, underscoring the urgent need for enhanced awareness, policy enforcement, and proactive design interventions by architects, developers, and regulatory bodies.

Keywords: Energy Conservation, ECBC, Thermal Transmittance, RETV, Natural Ventilation Potential, Daylight Potential

Introduction

The residential building sector plays a pivotal role in shaping India's energy future, especially as the country confronts rising electricity demand and the environmental implications of rapid urbanization. Buildings currently account for over 30% of India's total electricity consumption, with the residential sector contributing approximately 75% of this share—making it one of the largest contributors to national greenhouse gas emissions. Energy use in this sector grew significantly from 55 TWh in 1996–97 to 260 TWh in 2016–17 and is projected to reach between 630 TWh and 940 TWh by 2032 (BEE, 2018). This surge is driven by increasing urban populations, rising incomes, and the growing penetration of energy-intensive appliances, particularly air-conditioning systems, whose use is expanding in response to rising ambient temperatures and improved economic conditions (Darshan et al., 2022). Additionally, India's diverse climatic zones further complicate the energy efficiency challenge, as buildings in tropical and composite climates typically require greater cooling loads than those in temperate regions (Dalal et al., 2021).

Urbanization trends have triggered a boom in multistoried residential developments, especially in tier-2 cities such as Ludhiana. While high-rise housing models optimize land use, they also increase operational energy demand through dependence on mechanical ventilation, elevators, and active cooling systems (Chaturvedi et al., 2024). To address these challenges and align with national climate goals—including a targeted 33–35% reduction in emissions intensity of GDP by 2030 from 2005 levels—the Government of India has introduced a suite of regulatory and policy instruments. Chief among these are the Energy Conservation Building Code (ECBC) for commercial buildings and the Eco-Niwas Samhita (ENS) for residential buildings. These codes advocate for improved energy performance through better envelope design, energy-efficient lighting, and HVAC system optimization (Bhardwaj et al., 2023). Parallel efforts such as the Star Labelling Programme and the promotion of rooftop solar photovoltaics further support the transition to energy-efficient housing (Dalal & Saini, 2023). However, implementation faces persistent hurdles, including limited awareness among stakeholders, higher initial costs for energy-efficient technologies, and the absence of strong enforcement mechanisms (Tarkar, 2022). Despite these barriers, the benefits of energy efficiency remain compelling—offering not only reduced operational costs but also enhanced building performance and asset value (Khanapure & Shastri, 2023).

A key policy initiative to address the energy efficiency challenge in India's residential sector is the Energy Conservation Building Code for Residential Buildings (ECBC-R). Propagated by the Bureau of Energy Efficiency (BEE), ECBC-R serves as a foundational benchmark for evaluating the energy performance of residential buildings across the country. In 2018, the Ministry of Power introduced the Eco-Niwas Samhita (ENS) 2018, with Part I focusing specifically on the building envelope—an early-stage design component with significant influence on a building's thermal performance and energy demand. The code places particular emphasis on minimizing heat gain and maximizing natural ventilation and daylight through optimal envelope design. These strategies are especially critical in the context of rising indoor air-conditioning use, which has emerged as a major contributor to greenhouse gas (GHG) emissions in the residential sector. ENS 2018 offers a simplified, easy-to-adopt framework, requiring only basic calculations based on architectural drawings. This makes the code highly adaptable for incorporation into municipal building bye-laws and development control regulations.

The anticipated benefits of widespread ECBC-R implementation are substantial. Between 2018 and 2030, the adoption of ENS 2018 is projected to yield savings of approximately 125 billion kWh of electricity and avoid around 100 million tons of CO_2 emissions (Bhanware et al., 2019). While these savings primarily apply to air-conditioned homes, even naturally ventilated buildings can achieve significant improvements in indoor thermal comfort if they comply with ECBC-R's Residential Envelope Transmittance Value (RETV) requirements. The ECBC-R evaluates residential energy performance based on four critical parameters: (1) Adequacy of natural ventilation potential, (2) Adequacy of daylight potential, (3) Thermal transmittance (U-value) of the roof, and (4) RETV of the opaque building envelope (excluding the roof).

In addition to the national-level code, states are encouraged to adopt context-specific regulations. The Punjab Energy Conservation Building Code (Punjab-ECBC) has been formulated to support energy-efficient construction practices across all building types, including group housing developments. Punjab-ECBC complements ECBC-R by specifying additional performance benchmarks tailored to the region's composite climate. Key parameters under Punjab-ECBC include: (1) Maximum U-factor for roof and opaque wall assemblies, (2) Minimum R-value for insulation of roof and wall assemblies, (3) Maximum U-factor and Solar Heat Gain Coefficient (SHGC) for vertical fenestration, and (4) Minimum Visible Light Transmittance (VLT) for windows.

Goal and Objectives of the Study

The primary goal of this research is to evaluate whether contemporary multistoried residential developments in Ludhiana incorporate energy-efficient design principles in alignment with national and regional energy codes. Within this broader perspective, the study seeks to determine the extent to which prevalent residential building typologies comply with the ECBC-R and Punjab-ECBC norms. By examining low-rise, mid-rise, and high-rise apartment typologies, the study offers insights into the extent of alignment with energy code provisions and identifies critical gaps that require attention from designers, developers, and policymakers.

Methodology

Selection of Case Studies

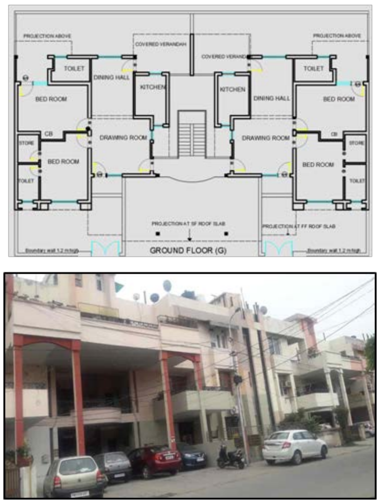
In the urban landscape of Ludhiana, group housing developments constitute approximately 45% of the city's residential fabric, accommodating a substantial proportion of the population both within and beyond municipal limits. Initially developed under the aegis of the Ludhiana Improvement Trust (LIT), many flatted housing schemes feature low-rise and mid-rise typologies with standardized 2-BHK and 3-BHK configurations. However, recent trends indicate a marked shift toward high-density residential formats, including integrated townships and high-rise towers developed by private real estate entities. For the present study, three representative residential blocks were selected as case studies. These exemplify the predominant housing typologies found in Ludhiana's composite climate zone: low-rise (G+2), mid-rise (G+3), and high-rise (G+13). The selection provides a comprehensive basis for evaluating energy code compliance across a spectrum of building heights and design configurations.

Case Study 1: Rishi Nagar (RB-1) - Located within Maharishi Balmik Nagar, a 256-acre scheme developed by LIT in the early 1990s, Rishi Nagar encompasses a 6.14-acre (24,847.70 sqm) site dedicated to flatted development. This area includes ten low-rise blocks (G+2), collectively housing 180 dwelling units, each with a built-up area of approximately 96.77 sqm. The units are designed without elevator access and are oriented along all four cardinal directions. The layout follows a row housing typology, a pattern echoed in several other LIT schemes throughout the city.

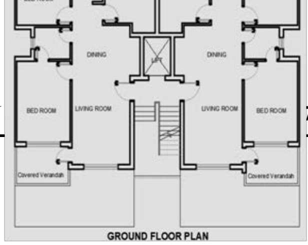
Case Study 2: Royal View Premier (RB-2) - Royal View Premier, a PUDA-approved development by the Omaxe Group, is situated along Pakhowal Road, Ludhiana. The first phase of development spans 36 acres and includes 25 architectural typologies, among which the RB-2 block typology—G+3 mid-rise buildings with elevator access—is selected for this study. Each unit is a 3-BHK with a servant room and a super built-up area of approximately 140 sqm. These residential blocks, arranged in diverse configurations and cardinal orientations, represent the evolving typology of mid-rise, amenity-rich group housing in Ludhiana.

Case Study 3: Grand Duke (RB-3) - Grand Duke is part of the second phase of the Omaxe Group's township development, spanning 65 acres. The RB-3 typology features high-rise towers (G+13) with a cluster-based layout and a central circulation core. Each block comprises 110 dwelling units of 3-BHK configuration, including a servant room, with a built-up area of 110.17 sqm. The towers are repeated across the site with minor design variations and exhibit orientation along all four cardinal directions. This case represents the high-rise residential trend in Ludhiana's expanding urban footprint.

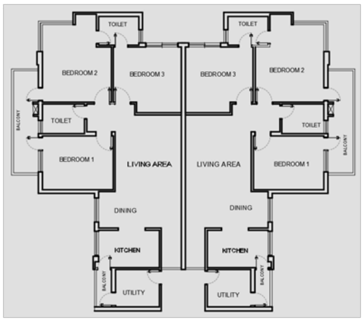
Figure 1 depicts the ground floor plans and views of Selected Residential Blocks RB-1, RB-2 and RB-3. Table 1 summarises the diverse characteristics of three selected case studies.



Rishi Nagar (RB-1)



Royal View Premier (RB-2)



Grand Duke (RB-3)

Figure 1 Ground Floor Plans and Views of Selected Residential Blocks

Table 1 Summary of Selected Case Studies

Selected Residential Blocks	Development Agency	Typology	Number & Category of DUs	Carpet & Gross Area per DU (sqm)
Rishi Nagar (RB-1)	Ludhiana Improvement Trust	Low Rise (G+2); Row Housing	6 nos. 2BHK	80.5 / 96.77
Royal View Premier (RB-2)	Licensed Private Development	Medium Rise (G+3); Row Housing	8 nos. 3BHK	116 / 140
Grand Duke (RB-3)	Licensed Private Development	High Rise (G+13); Cluster Housing	28 nos. 3BHK	98 / 110.17

Source: Author

Method of Compliance Checks

ECBC-R Compliance Evaluation for Composite Climate

Based on the guidelines provided in Eco-Niwas Samhita 2018, the study employs the following method to assess the compliance of selected case studies with ECBC-R standards relevant to composite climate conditions.

Natural Ventilation Potential: Natural ventilation is quantified using the openable window-to-floor area ratio (WFRop), calculated as:

$$WFR_{op} = A_{openable} / A_{carpet}$$

Where:

$A_{openable}$ = Total openable area of windows and ventilators (m2)

A_{carpet} = Carpet area of dwelling units (m2)

Daylight Potential (VLT): Daylight adequacy is assessed using the visible light transmittance (VLT) of transparent/translucent envelope components. VLT requirements are determined based on the window-to-wall ratio (WWR) that is calculated as:

$$WWR = A_{non\text{-}opaque} / A_{envelope}$$

Where:

$A_{non\text{-}opaque}$ = Area of non-opaque building envelope components (m^2)

$A_{envelope}$ = Total envelope area (excluding roof) of dwelling units (m^2)

Roof Thermal Transmittance: Thermal performance of the roof is represented by U-value, calculated as:

$$U_{roof} = 1/ R_t \text{, where, } R_t = R_{si} + R_1 + R_2 + R_3 + \ldots\ldots + R_{se}$$

And each layer's thermal resistance is given by:

$$R_i = t_i / k_i$$

Where:

t_i = Thickness of material layer (m)

k_i = Thermal conductivity of the material (W/m.K)

Residential Envelope Transmittance Value (RETV): RETV evaluates the overall thermal transmittance of the building envelope (excluding roof), accounting for conduction and solar radiation effects:

RETV = $1/A_{envelope}$ x [{6.06 x ∑_(i=1) n($A_i(_{opaque})$ x $U_i(_{opaque})$ x ω_i)} + {1.85 x ∑_(i=1) n(A_i(non-opaque) x U_i(non-opaque) x ω_i)} + {68.99 x ∑(i=1)n($A_i(_{non-opaque})$ x $SHGC_{i-eq}$ x ω_i)}]

Where:

$A_{envelope}$ = Area of envelope component (opaque or non-opaque) excluding roof (m_2)

U_i = Thermal transmittance of component ($W/m^2.K$)

$SHGC_{i-eq}$ = Equivalent Solar Heat Gain Coefficient

ω_i = Orientation factor

Table 2 mentions the compliance requirements for residential buildings as laid down in the Eco-N_i was Samhita 2018 guidelines.

Table 2 ECBC-R Compliance Requirements for Residential Buildings

Openable Window-to-Floor Area Ratio (WFRop)	Minimum 12.5
Visible Light Transmittance VLT (%)	Minimum 27% for WWR range of 0-0.30 Minimum 20% for WWR range of 0.31-0.40 Minimum 16% for WWR range of 0.41-0.50 Minimum 13% for WWR range of 0.51-0.60 Minimum 11% for WWR range of 0.61-0.70
Thermal Transmittance of Roof (Uroof)	Maximum 1.2 W/m2.K
Residential Envelope Transmittance Value (RETV) for building envelope (except roof)	Maximum 15 W/m2

Source: Eco-Niwas Samhita 2018

Punjab-ECBC Compliance Evaluation

In addition to ECBC-R, the Punjab Energy Conservation Building Code (Punjab-ECBC) offers state-specific prescriptive norms for energy-efficient construction across all building categories, including group housing complexes. The performance of each case study is cross-verified with the thresholds prescribed in Punjab-ECBC (PEDA, 2016), as detailed in Table 3.

Table 3 Prescriptive Criteria for the Punjab-ECBC Compliance of Building Envelope

Maximum U-factor of the Overall Roof Assembly	0.261 W/m².K
Minimum R-value of Roof Insulation Alone	3.5 m².ºC/W
Thermal Transmittance of Roof (Uroof)	Maximum 1.2 W/m2.K
Maximum U-factor of the Overall Opaque Wall Assembly	0.440 W/m².K
Minimum R-value of Wall Insulation Alone	2.10 m².K/W
Maximum U-factor of the Vertical Fenestration	3.30 W/m².ºC
Maximum SHGC of the Vertical Fenestration	0.25 for WWR □ 40 percent 0.20 for WWR > 40 percent and □ 60 percent
Minimum VLT of the Vertical Fenestration	0.27 for WWR 0.0-0.3 0.20 for WWR 0.31-0.4 0.16 for WWR 0.41-0.5 0.13 for WWR 0.51-0.6

Source: PEDA, 2016

Data Inputs for Compliance Checks

Table 4 illustrates the area details for the building envelope components of selected case studies RB-1, RB-2 and RB-3. Table 5 demonstrates the relevant construction material details

Table 4 Area Details for the Building Envelope Components of Case Studies

	Area in m2				
Building Components	**East**	**West**	**North**	**South**	**Total Area**
Area Details for RB-1					

Total roof area	-	-	-	-	268.80
Total wall envelope area	10.54 x 11.8 = 124.37	10.54 x 11.8 = 124.37	10.54 x 21.8 = 229.77	10.54 x 21.8 = 229.77	708.28
Non-opaque (window + ventilator + door)	6.24	45.12	139.2	105.64	296.20
Opaque wall envelope area	-	-	-	-	412.02
Area Details for RB-2					
Total roof area	-	-	-	-	240
Total wall envelope area	12.5 x 14.5 = 181.25	12.5 x 14.5 = 181.25	12.5 x 16.67 = 208.37	12.5 x 16.67 = 208.37	779.26
Non-opaque (window + ventilator + door)	32.45	32.45	92.48	73.12	230.51
Opaque wall envelope area	-	-	-	-	788.75
Area Details for RB-3					
Total roof area	-	-	-	-	384.0
Total wall envelope area	17.0 x 46.0 = 782.0	17.0 x 46.0 = 782.0	16.0 x 46.0 = 736.0	16.0 x 46.0 = 736.0	3036.0
Non-opaque (window + ventilator + door)	218.26	32.45	99.68	218.26	804.72
Opaque wall envelope area	-	-	-	-	2231.28

Source: Calculated values

Table 5 Construction Materials for the Selected Case Studies

Building element	Building material specification
Construction Materials Details for RB-1	
Walls	230 mm thick walls of solid burnt clay with 12 mm thick cement plaster on external and internal sides
Roof	110 mm thick RCC slab with layers of 3 mm tar felt, 75 mm mud phuska and 37 mm brick tiles above it, and 12 mm thick internal plaster
Windows	5 mm thick single clear glass (SHGC - 0.80, VLT - 85 %)
Doors (opaque)	Wooden flush door and frame
Construction Materials Details for RB-2	
Walls	230 mm thick walls of solid burnt clay with 12 mm thick cement plaster on external and internal sides
Roof	100 mm thick RCC slab with layers of 3 mm tar felt, 20 mm cement screed above, and 12 mm thick internal plaster
Windows	5 mm thick single clear glass (SHGC - 0.80, VLT - 85 %)
Doors (opaque)	Wooden flush door and frame
Construction Materials Details for RB-3	
Walls	200 mm thick walls of Aerated autoclaved concrete (AAC) Block with 12 mm thick cement plaster on external and internal sides

Roof	12 mm Cement Mortar, 75 mm Brick Tile, 200 mm thick RCC slab with layers of 10 mm tar felt, and 10 mm thick internal plaster
Windows	5 mm thick single clear glass (SHGC - 0.80, VLT - 85 %)
Doors (opaque)	Wooden flush door with Metal frame (Aluminium Powder Coated)

Source: Ludhiana Improvement Trust & Omaxe, Ludhiana

Results of Compliance Checks

Compliance Checks based on ECBC-R

Section 3.2.1 clearly elucidates how the energy calculations for ECBC-R compliance check were undertaken for the residential developments located in the composite climate zone of India. To ease out the process, the Bureau of Energy Efficiency (BEE) has launched “Eco-Niwas Samhita Online Compliance Tool” (ENS Online Tool) for evaluating the energy performance of residential building envelopes, and judging compliance against the national benchmark. Once all the required data as mentioned in Tables 4 and 5 is entered, the Eco-Niwas Samhita compliance tool automatically evaluates the performance of building envelope against the benchmarks as described in Table 2. The tool undertakes a rigorous assessment of data; and informs whether each parameter meets the required thresholds by generating compliant or non-compliant status for each. The compliance status generated by the ENS Online Tool for the base cases RB-1, RB-2 and RB-3 is shown in Table 6.

Table 6 ECBC-R Compliance Results of Base Cases RB-1, RB-2 and RB-3

	Respective Values and Compliance Status					
Criteria	**Base Model RB-1**		**Base Model RB-2**		**Base Model RB-3**	
Openable Window-to-Floor Area Ratio (WFRop)	21.35	Compliant	11.08	Non Compliant	12.0	Non Compliant
Visible Light Transmittance VLT (%)	85	Compliant	85	Compliant	85	Compliant
Thermal Transmittance of Roof (Uroof)	2.02	Non Compliant	3.086	Non Compliant	2.07	Non Compliant
Residential Envelope Transmittance Value (RETV) for building envelope (except roof)	18.56	Non Compliant	18.05	Non Compliant	19.9	Non Compliant

Source: Eco-Niwas Samhita Compliance Check Tool

Compliance Checks based on Punjab-ECBC

Compliance checks with Punjab-ECBC generated outputs in terms of thermal transmittances (U-value) of roof, opaque wall assembly, and non-opaque wall components, as depicted in Table 7.

Table 7 Punjab-ECBC Compliance Results of RB-1

Building Component	**Material Layers**	**Thickness (m)**	**Conductivity (W/m-K)**	**Density (Kg/m³)**	**Specific Heat (J/Kg-K)**	**U-Value (W/m²-K)#**
Punjab-ECBC Compliance Results of RB-1						
Roof Assembly	Brick tile	0.037	0.798	1892	0.88	2.02
	Mud Phuska	0.075	0.519	1622	0.88	
	Tar felt1	0.015	0.479	2.3 in Kg/m2	0.88	
	RCC Slab	0.11	1.58	2280	0.88	
	Inner Plaster	0.012	1.02	1800	0.90	

External Wall Assembly	Internal Cement Plaster	0.012	1.02	1762	0.90	2.174
	Solid Burnt Clay Brick	0.20	0.98	1760	0.80	
	External Cement Plaster	0.012	1.02	1762	0.90	
Window Material	Exterior Glazing	WWR	SHGC 0.8	VLT 0.9	0.90	4
Punjab-ECBC Compliance Results of RB-2						
Roof Assembly	Cement Screed	0.020	0.72	1500	0.72	3.086
	Tar felt 1	0.030	0.479	2.3 in Kg/m2	0.88	
	RCC Slab	0.10	1.58	2280	0.88	
	Cement Plaster	0.012	1.02	1762	0.90	
External Wall Assembly	Internal Cement Plaster	0.012	1.02	1800	0.90	2.174
	Solid Burnt Clay Brick	0.23	0.98	1920	0.80	
	External Cement Plaster	0.012	1.02	1800	0.90	
Window Material	Exterior Glazing	WWR	SHGC 0.8	VLT 0.85	-	5.8
Punjab-ECBC Compliance Results of RB-3						
Roof Assembly	Cement Screed	0.012	1.40	1648	0.92	2.07
	Brick Tile	0.075	0.81	1892	0.84	
	Tar Felt	0.010	0.17	2.3 in Kg/m2	0.88	
	RCC Slab	0.200	1.58	2280	0.88	
	Cement Plaster	0.010	1.02	1762	0.90	
External Wall Assembly	Internal Cement Plaster	0.012	1.02	1762	0.90	0.768
	Wall (AAC)	0.200	0.13	642	0.794	
	External Cement Plaster	0.012	1.02	1762	900	
Window Material	Exterior Glazing	WWR	SHGC 0.8	VLT 0.85	-	5.8

Source: BEE, 2021; # Calculated Values

Discussion

Observations from ECBC-R Compliance Results

Following are the observations from Table 6 regarding ECBC-R compliance of the three base cases.

Openable Window-to-Floor Area Ratio (WFR_{op}): The minimum WFRop needs to be 12.5 to ensure compliance with standards of natural ventilation. As observed, the minimum value is exceeded in RB-1, while RB-2 and RB-3 fall short of it. This suggests that natural ventilation in RB-2 and RB-3 is inadequate, leading to increased reliance on mechanical cooling, and the consequent increased energy costs. RB-1 shows compliance to standards for natural ventilation.

Visible Light Transmittance (VLT): The VLT in all the three base cases achieved a value that is well above the minimum thresholds recommended for various window-to-wall ratios. This signifies ample daylight penetration and reduced reliance on artificial lighting. However, Eco-Niwas Samhita 2018 guidelines recommend that the WWR in residential buildings may not generally exceed 0.40, so as to minimize heat gain through non-opaque elements, and prevent visual discomfort due to excessive daylighting.

Thermal Transmittance of Roof (U_{roof}): The Uroof value in all the three base cases exceeds the permissible limit of 1.2 W/m2.K, indicating insufficient or inappropriate thermal insulation, causing excessive heat transfer and higher cooling energy demand.

Residential Envelope Transmittance Value (RETV) for Building Envelope (except roof): The RETV value in all the three base cases exceeds the permissible limit of 15 W/m2, rendering all the three base cases RB-1, RB-2 and RB-3 non compliant. This indicates insufficient or inappropriate thermal insulation, leading to excessive heat transfer and higher cooling energy demand.

Observations from Punjab-ECBC Compliance Results

The results indicate an absolute non-compliance of RB-1, RB-2 and RB-3 in respect of the Punjab-ECBC requirements, since the maximum U-factor values for the overall roof assembly (0.261 W/m^2.ºC), overall opaque wall assembly (0.440 W/m^2.ºC), and vertical fenestration (3.30 W/m^2.ºC) could not be reached.

Conclusion

This study evaluates the energy code compliance of three representative multistoried residential buildings in Ludhiana—low-rise, mid-rise, and high-rise—under the frameworks of both ECBC-R and Punjab-ECBC. The selected codes provide prescriptive benchmarks for key parameters such as the openable window-to-floor area ratio (WFRop), visible light transmittance (VLT), roof thermal transmittance (Uroof), and the Residential Envelope Transmittance Value (RETV) for non-roof envelope components. Punjab-ECBC further specifies performance thresholds for overall roof assembly, opaque wall assembly, and vertical fenestration.

While both codes serve as essential tools for sensitizing architects, builders, and developers toward energy-conscious design, the findings from this study reveal notable gaps in compliance across all case studies. In particular, consistent non-conformities were observed in parameters such as Uroof and RETV, which are critical for enhancing thermal comfort and reducing energy loads. These shortcomings underscore the urgent need for capacity building, stricter enforcement, and greater awareness within the design and construction community.

The insights gained through this dual-layered compliance assessment highlight the pressing need to integrate passive design strategies—such as enhanced natural ventilation, improved roof insulation, and optimized envelope performance—into residential construction practices. Moreover, encouraging innovation in materials and technologies through regulatory frameworks can stimulate market transformation and broader acceptance of energy-efficient solutions.

By simultaneously evaluating adherence to both national (ECBC-R) and state-level (Punjab-ECBC) standards within the specific context of a composite climate, this research contributes to the growing body of knowledge on climate-responsive residential architecture in India. It reinforces the importance of regulatory alignment and localized strategies in driving the transition towards more sustainable and energy-efficient urban housing.

References

BEE (2018). Eco-Niwas Samhita 2018 (Energy Conservation Building Code for Residential Buildings) Part I: Building Envelope. Bureau of Energy Efficiency, Ministry of Power, Government of India.

BEE (2021). *Energy Conservation Building Code 2017*. 2nd revision. Bureau of Energy Efficiency, New Delhi.

Bhanware, P. K., Jaboyedoff, P., Maithel, S., Lall, A., Chetia, S., Kapoor, V. P., Rana, S., Mohan, S., Diddi, S., Siddiqui, A. N., Singh, A., & Shukla, A. (2019). Development of RETV (residential envelope transmittance value) formula for cooling dominated climates of India for the proposed energy conservation building code for residential building (ECBC-R). P*roceedings of the 16th Conference of IBPSA*, 16, 3976–3983.

Bhardwaj, S., Tewari, D., & Natarajan, B. (2023). *Energy Efficiency (EE) for Climate Action: Evolution of India's EE Policies and Way Forward*. In: Taghizadeh-Hesary, F., Zhang, D. (eds) The Handbook of Energy Policy. Springer, Singapore.

Chaturvedi, P. K., Kumar, N., & Lamba, R. (2024). Finding the Gaps in Design Strategies and Technological Advancements for Net-Zero Energy Buildings Development in India. *Energy & Environment, 35*(7), 3880-3920.

Dalal, R., & Saini, D.K. (2023). Mitigation of the Impacts of Electric Vehicle Charging on Energy-Star Ratings for Residential Buildings in India. *Clean Energy, 7*(5), 981–993.

Darshan, A., Girdhar, N., Bhojwani, R., Rastogi, K., Angalaeswari, S., Natrayan, L., & Paramasivam, P. (2022). Energy Audit of a Residential Building to Reduce Energy Cost and Carbon Footprint for Sustainable Development with Renewable Energy Sources. *Advances in Civil Engineering*, 2022, 1–10.

Khanapure, V., & Shastri, S. (2023). A Sustainability Assessment Framework for High-Rise Residential Projects: A Case of India. *The International Journal of Construction Management, 24*(5), 495-502.

PEDA (2016). Punjab Energy Conservation Building Code. Punjab Energy Development Agency, Chandigarh.

Tarkar, P. (2022). Energy Efficient Buildings in India: Key Area and Challenges. *IOP Conference Series: Earth and Environmental Science 1084*(1).