Integrating Of Building Energy Modelling For Achieving Net Zero Energy Building In Hot Humid Climate

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Abstract- *The building sector significantly contributes to energy consumption, particularly in hot and humid regions where cooling and dehumidification demands are high. In rapidly growing cities like Mumbai, Pune, and Nagpur, high temperatures (30°C–38°C) and humidity levels (70–85%) increase reliance on mechanical cooling, leading to higher energy use. This study presents a structured workflow for climate-responsive building design to achieve Net Zero Energy Building (NZEB) performance. A seven-phase methodology is adopted, including climate analysis using Typical Meteorological Year (TMY) data, baseline model development, and Building Energy Modelling (BEM) using EnergyPlus and DesignBuilder. Passive and active strategies are integrated to optimize performance, followed by solar photovoltaic system implementation. Results show significant energy reduction, enabling NZEB achievement and supporting a climate-specific framework aligned with ECBC guidelines.*

Keywords: Building Energy Modelling, Climate-Responsive Design, Energy Efficiency, Net Zero Energy Building, Solar Photovoltaic

I. INTRODUCTION

The building sector is one of the largest consumers of energy globally, driven by rapid urbanization, population growth, and increasing living standards. In India, this trend is especially evident in cities such as Mumbai, Pune, and Nagpur, where hot and humid climatic conditions significantly increase the demand for cooling and dehumidification. Temperatures ranging from 30°C to 38°C and humidity levels above 70%–85% lead to heavy dependence on mechanical cooling systems, resulting in higher energy consumption and environmental concerns. The building sector in India accounts for nearly one-third of total electricity use, while globally it contributes around 38–40% of energy consumption and approximately 36% of carbon emissions, emphasizing the urgency of improving building energy performance.

Conventional building practices have often overlooked climatic responsiveness, prioritizing aesthetics and functionality over energy efficiency. Features such as excessive glazing, poor insulation, and inadequate shading have intensified heat gain, increasing cooling loads. In hot and humid climates, the makingchallenge is further compounded by high latent heat due to humidity, energy optimization more complex than in other climate zones.

As a result, there is a growing need for climate-responsive design approaches that integrate environmental considerations from the early stages of planning to reduce energy demand and enhance indoor comfort.

This study addresses these challenges by adopting a systematic, simulation-based approach using Building Energy Modelling tools such as EnergyPlus and DesignBuilder. These tools enable detailed analysis of energy consumption, cooling loads, daylighting, and thermal comfort under different design scenarios. The research focuses on integrating passive strategies—such as optimal orientation, improved building envelope, controlled window-to-wall ratio, and effective shading—with active measures like energy-efficient HVAC systems. Furthermore, renewable energy integration through solar photovoltaic systems is evaluated to offset energy demand and achieve Net Zero Energy Building (NZEB) performance.

The study develops a structured framework that combines climate analysis, performance simulation, and energy optimization to propose a practical and replicable NZEB model tailored for hot and humid regions of India. By aligning with Energy Conservation Building Code (ECBC) guidelines, the research ensures regulatory relevance and practical applicability. Overall, this work contributes to sustainable building design by demonstrating how climate-responsive strategies, supported by advanced simulation tools and renewable energy systems, can significantly reduce energy consumption and support the transition toward low-carbon and energy-efficient built environments.

The study is subject to certain limitations - it is limited to selected residential and commercial buildings, excluding institutional and industrial typologies, it considers only operational energy use and does not include embodied energy or total lifecycle carbon impact, economic factors such as cost, payback period, return on investment, and financial feasibility are not addressed, social aspects including user comfort, satisfaction, and occupant behavior are excluded, practical constraints such as construction challenges, material availability, and site conditions are not considered.

The study is guided by key objectives addressing climate-specific Net Zero Energy Building (NZEB) development: i) to study the workflow of climate-responsive building design ii) to evaluate and compare lifecycle energy performance iii) to quantify building energy performance iv) to propose a practical NZEB framework for hot and humid climates. The increasing energy demand in the building sector, especially in hot and humid regions, necessitates a shift toward climate-responsive and performance-driven design. Conventional practices are becoming unsustainable due to rising cooling needs and environmental concerns. By integrating Building Energy Modelling using tools such as EnergyPlus and DesignBuilder with passive strategies and renewable energy systems, NZEBs provide a viable pathway for sustainable and energy-efficient development.

II. METHODOLOGY

The research adopts a structured and simulation-based methodology consisting of multiple phases to evaluate and optimize building energy performance. Initially, climatic data for selected cities is collected using Typical Meteorological Year datasets, which provide reliable long-term weather conditions. These datasets include parameters such as temperature, relative humidity, and solar radiation, which are critical for accurate energy simulation.

A baseline building model is developed using conventional design parameters, including standard materials, occupancy schedules, and HVAC systems. This model represents typical building practices and serves as a reference for comparison. Building Energy Modelling tools are then used to simulate the baseline energy performance, focusing on annual energy consumption, cooling loads, and thermal comfort conditions.

The study adopts a systematic and structured seven-phase methodological framework to achieve Net Zero Energy Building performance. The first phase involves climate data collection and analysis. The second phase consists of baseline building modelling. The third phase focuses on energy performance evaluation. The fourth phase includes the implementation of passive design strategies. The fifth phase involves the optimization of active building systems. The sixth phase addresses the integration of solar photovoltaic systems. The seventh phase is dedicated to the final assessment of Net Zero Energy Building performance. These phases are carried out sequentially to ensure a logical progression of the research. The framework enables a comprehensive evaluation of building energy performance. It also ensures consistency and accuracy in the simulation process. The structured approach supports effective decision-making. Overall, the methodology provides a clear pathway toward achieving energy-efficient and sustainable building design in hot and humid climates.

Phase 1: Climate Data Collection and Analysis

This phase studies climate data to support NZEB design for hot and humid regions. TMY data is used to understand temperature, humidity, sunlight, and wind. Cooling needs and heat gain are analyzed. Solar path and shading help plan ventilation and design. These results guide building envelope and energy-efficient design decisions.

Phase 2: Baseline Building Modelling

In this phase, basic building models are created for typical homes and commercial buildings in India. Common materials, wall properties, window sizes, and daily use patterns are included. Heat from people,lights, and equipment is considered. Normal HVAC systems are used. These models act as a base for comparing later improvements.

Phase 3: Energy Performance Evaluation

In this phase, the energy performance of baseline buildings is studied for hot and humid conditions. Simulations estimate yearly energy use, cooling demand, and EUI. Cooling and moisture loads are analyzed. Indoor comfort is also checked. These results act as a benchmark to compare improved building design performance later.

Phase 4: Integration of Passive and Active Design Strategies

In this stage, improved design methods are added to the basic models. Passive steps like better orientation, insulation, cool roofs, shading, and proper windows are used. Efficient systems like HVAC, LED lights, and smart controls are included. These changes help reduce cooling load and overall energy use in buildings.

Phase 5: Comparative Performance Analysis

This phase compares the baseline and optimized building models to quantify the impact of integrated design strategies. Simulation results are analyzed to evaluate reductions in annual energy consumption, peak cooling loads, and operational costs. Improvements in thermal comfort and reduction in discomfort hours are also assessed.

Phase 6: Renewable Energy Integration

After reducing energy demand, this phase evaluates the potential of on-site renewable energy systems to achieve net-zero energy balance. Rooftop solar photovoltaic (PV) systems are analyzed based on available roof area, panel efficiency, and solar radiation levels. Simulations estimate annual electricity generation and its ability to offset building energy consumption. Grid interaction and net metering benefits are also considered to enhance economic viability. The results demonstrate that solar PV systems can effectively meet the remaining energy demand.

Phase 7: Framework Development & Recommendation

The final phase integrates the results from previous stages to develop a comprehensive NZEB framework for hot and humid climates. Performance targets aligned with ECBC guidelines are proposed to ensure energy efficiency and regulatory compliance. Design recommendations are provided for architects, engineers, and policymakers to support practical implementation. The framework offers a scalable pathway for developing sustainable, low-energy buildings in India.

Subsequently, climate-responsive passive design strategies are integrated into the model. These include optimization of building orientation, improvement of envelope insulation, reduction of window-to-wall ratio, and incorporation of shading devices. These strategies aim to minimize heat gain and reduce cooling demand. In addition to passive measures, active system improvements such as energy-efficient HVAC systems and lighting are implemented to further enhance performance.

Finally, renewable energy integration is carried out through rooftop solar photovoltaic systems. The PV system is designed and sized based on the building's energy demand to achieve net-zero energy balance. The optimized model is then simulated and compared with the baseline model to quantify performance improvements.

III. DATA ANALYSIS AND INTERPRETATION

The data analysis phase forms a critical component of this study, as it systematically evaluates the simulation outputs obtained from six building models representing residential and commercial typologies across the selected hot and humid climatic regions of Mumbai, Pune, and Nagpur. The analysis focuses on key performance indicators including Energy Use Intensity (EUI), cooling load contribution, thermal comfort, energy savings, lifecycle performance, and the feasibility of achieving Net Zero Energy Building (NZEB) targets. These indicators provide a comprehensive understanding of how various design interventions influence overall building performance.

The baseline energy performance assessment reveals a significant variation in Energy Use Intensity across the six models, reflecting the combined effects of climatic conditions and building typology. The EUI values range from 104.0 kWh/m²/year for the Pune residential model to 257.5 kWh/m²/year for the Nagpur commercial model, indicating that commercial buildings and hotter climates tend to exhibit higher energy demand. A detailed breakdown of energy consumption shows that cooling is the dominant end-use across all models, contributing approximately 65% to 78% of the total annual energy consumption. This clearly establishes that buildings in hot and humid climates are highly cooling-dependent, primarily due to elevated ambient temperatures, high humidity levels, and increased solar heat gains through the building envelope.

Following the implementation of climate-responsive passive design strategies and high-efficiency active systems, a substantial improvement in energy performance is observed across all models. The optimized models demonstrate energy savings ranging from 31.3% to 39.2% when compared to their respective baseline conditions. These improvements are primarily attributed to reductions in solar heat gain through optimized building orientation, enhanced insulation properties, shading devices, and controlled window-to-wall ratios. The impact of these measures is particularly evident in the reduction of cooling loads, which decrease by approximately 33.4% to 42.6% across the models. In addition, peak cooling demand is reduced in the range of 4.1 kW to 15.4 kW, which not only lowers energy consumption but also enables the downsizing of HVAC systems, leading to further operational efficiency.

Thermal comfort analysis further supports the effectiveness of the implemented strategies. The optimized models exhibit a significant increase in indoor comfort hours, ranging from 18% to 28% improvement compared to baseline models. Moreover, the fluctuation in indoor operative temperature is reduced from a variation of ±4.2–6.4°C in baseline conditions to a narrower range of ±1.8–2.8°C in optimized buildings. This indicates a more stable and comfortable indoor environment, achieved through better control of heat gain and improved building envelope performance.

The lifecycle energy analysis conducted over a 20-year period highlights the long-term benefits of the proposed design approach. The cumulative energy savings across all six models are estimated to be approximately 34.76 MWh, representing a 35.7% reduction in lifecycle energy consumption. In addition to environmental benefits, the analysis also indicates significant economic advantages, with total cost savings estimated at ₹2.95 crore over the lifecycle period. These findings emphasize the financial feasibility and sustainability of adopting energy-efficient building strategies in real-world applications.

The integration of rooftop solar photovoltaic systems plays a crucial role in achieving NZEB targets. The analysis shows that renewable energy generation is sufficient to offset annual energy consumption in four out of the six models. All residential models successfully achieve net-zero energy status, with the Nagpur residential model generating up to 142% of its annual energy demand, thereby producing surplus energy. Among commercial buildings, the Pune commercial model achieves near net-zero performance with an energy offset of 99.7%, while the remaining models show substantial progress toward NZEB targets. These results demonstrate that rooftop solar PV systems are highly effective in compensating for residual energy demand after optimization.

Overall, the data analysis establishes a strong relationship between climate-responsive design, energy efficiency, and renewable energy integration. The findings confirm that a systematic combination of passive design measures, efficient building systems, and solar energy utilization can significantly enhance building performance and enable the achievement of Net Zero Energy Buildings in hot and humid climates.

IV. RESULTS AND DISCUSSION

The results of the study are based on simulation analysis of six building models representing residential and commercial typologies across Mumbai, Pune, and Nagpur under hot and humid climatic conditions. The baseline assessment indicates that all models exhibit high energy consumption, primarily due to cooling loads, which dominate overall energy use. Energy Use Intensity (EUI) varies significantly across models, with higher values observed in commercial buildings and in regions with more severe climatic conditions. The detailed baseline energy performance parameters, including EUI and cooling load distribution, are presented in Table 1: Baseline Energy Performance of Six Building Models**.**

Table 1: Baseline Energy Performance of Six Building Models

City & Building Type	Total Energy (kWh/yr)	Cooling Load (kWh)	EUI (kWh/m²/yr)	Peak Load (kW)
Mumbai - Residential	42,850	28,400	142.8	18.2
Mumbai - Commercial	1,12,300	74,600	224.6	48.7
Pune - Residential	31,200	18,900	104.0	12.8
Pune - Commercial	87,450	52,300	174.9	34.5
Nagpur - Residential	48,600	34,100	162.0	22.6
Nagpur - Commercial	1,28,750	88,500	257.5	56.3

The implementation of climate-responsive passive design strategies results in a substantial reduction in heat gain and cooling demand. Improvements in building orientation, insulation, shading, and window-to-wall ratio contribute to a significant decrease in cooling loads across all models. The extent of cooling load reduction achieved through passive strategies is summarized in Table 2: Impact of Passive Design Strategies on Cooling Load Reduction**.**

Table 2: Impact of Passive Design Strategies on Cooling Load Reduction

City & Building Type	Baseline Cooling Load (kWh)	Optimized Cooling Load (kWh)	Peak Load Reduction (kW)	Reduction (%)
Mumbai - Residential	31,480	20,960	4.8	33.4%
Mumbai - Commercial	78,320	49,710	12.6	36.5%
Pune - Residential	27,560	17,840	4.1	35.3%
Pune - Commercial	68,450	41,380	11.2	39.5%
Nagpur - Residential	39,210	23,060	5.9	41.2%
Nagpur - Commercial	91,740	52,680	15.4	42.6%

While a comparative graphical representation is shown in figure below.

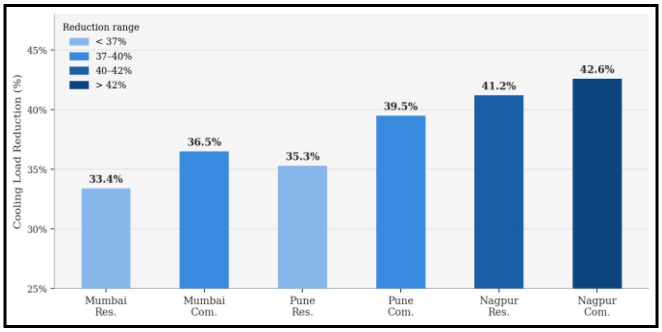

Figure 1: Cooling Load Reduction across Six Models

Further optimization through energy-efficient HVAC systems and lighting leads to additional reductions in overall energy consumption. The combined effect of passive and active strategies results in considerable energy savings and improved building performance.

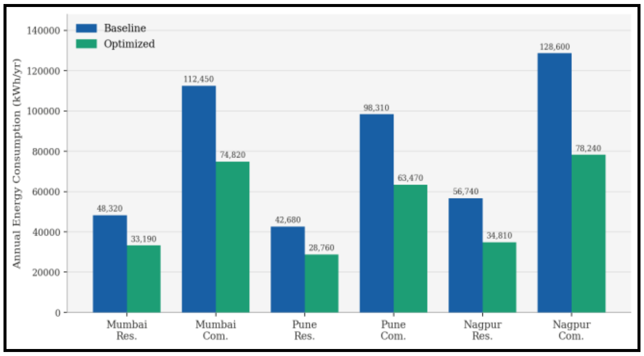

Figure 2: Annual Energy Consumption - Baseline vs. Optimized

The integration of rooftop solar photovoltaic systems enables renewable energy generation to offset building energy demand. The results show that all residential models achieve net-zero energy status, while commercial models approach near-zero performance. The detailed analysis of solar energy generation and energy offset is presented with a graphical representation provided in below.

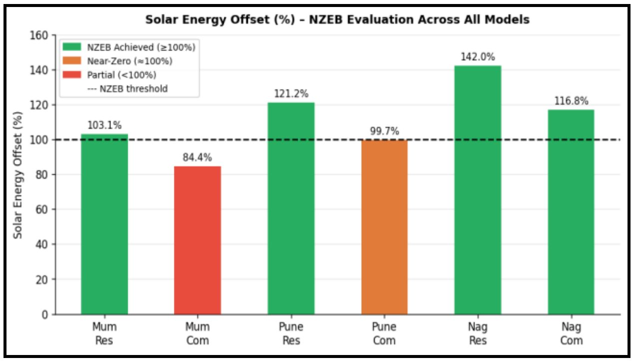

Figure 3: Solar Energy Offset (%) – NZEB Evaluation

Overall, the results confirm that the integrated approach of passive design, efficient systems, and renewable energy is highly effective in achieving Net Zero Energy Building performance in hot and humid climates.

V. CONCLUSION

The study confirms that achieving Net Zero Energy Buildings in hot and humid climates is both technically feasible and practically achievable through an integrated design approach. The results demonstrate that climate-responsive passive strategies play a crucial role in reducing cooling demand and improving overall building performance. The incorporation of high-efficiency active systems further enhances energy savings and operational efficiency. The integration of rooftop solar photovoltaic systems enables effective offset of remaining energy demand, supporting the achievement of net-zero energy balance. Building Energy Modelling proves to be a reliable and powerful tool for evaluating design alternatives and optimizing building performance at the pre-construction stage. The findings highlight the importance of a systematic and data-driven approach in sustainable building design. The consistency of results across multiple building models reinforces the applicability of the proposed framework. Overall, the study provides a practical pathway for designing energy-efficient buildings in hot and humid climatic conditions.

VI. FUTURE SCOPE

The findings of this study provide multiple directions for future research and application in the field of energy-efficient buildings. The proposed framework can be extended to additional building typologies such as educational, healthcare, mixed-use, and industrial buildings, each with unique energy characteristics. Further studies should incorporate calibrated models based on real building data to improve accuracy and support retrofit strategies. The integration of energy storage systems can be explored to address the mismatch between solar energy generation and building demand. Future research may also assess the impact of climate change scenarios on building performance and NZEB feasibility over long-term periods. In addition, the inclusion of embodied carbon and lifecycle assessment will enable a comprehensive evaluation of sustainability. The concept of district-level NZEB implementation can be investigated for dense urban areas where individual buildings face limitations. The study also highlights the need for policy development and regulatory support to promote NZEB adoption. Finally, the methodology can be applied to other climatic zones in India to validate its broader applicability and effectiveness.

REFERENCES

[1] F. Bdeir and C. Nasrallah, “Net-zero-energy building: A case study using Ecotect software under Beirut weather conditions,” 2025.

[2] P. K. Chaturvedi, N. Kumar, and R. Lamba, “Identification of climate adaptive multivariate optimization methodologies for the design of NZEB in India,” 2024.

[3] U. Azam, M. Farooq, M. A. Munir, A. U. Rehman, M. Imran, F. Riaz, and M. Sultan, “Modelling framework for reducing energy loads to achieve net-zero energy building in semi-arid climate: A case study,” 2023.

[4] C. Taser and N. Hafizi, “Net-zero energy residential buildings in hot and humid climates: A systematic review and meta-analysis of design strategies and performance frameworks,” 2024.

[5] S. H. Alyami, N. Ashraf, A. Almutlaqa, and A. M. Alqahtany, “Likelihood of reaching zero energy building design in hot dry climate: Saudi Arabia,” 2021.

[6] W. Feng, Q. Zhang, H. Ji, R. Wang, N. Zhou, Q. Ye, B. Hao, Y. Li, D. Luo, and S. S. Y. Lau, “A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings,” 2019.

[7] B. Singh, S. Sharma, and P. Syal, “Defining design criteria of net zero energy building for composite climate zone,” 2019.

[8] K. Sudhakara, M. Winderld, and S. S. Priya, “Net-zero building designs in hot and humid climates: A state-of-the-art review,” 2019.

[9] L. Wells, B. Rismanchi, and L. Aye, “A review of net zero energy buildings with reflections on the Australian context,” 2018.

[10] A. J. Marszal, P. Heiselberg, J. S. Voss, et al., “Zero energy building – A review of definitions and calculation methodologies,” 2011.

[11] P. Torcellini, S. Pless, and M. Deru, “Zero energy buildings: A critical look at the definition,” 2006.

[12] S. I. Kaitouni, M. O. Mghazli, A. Nait-Taour, N. Es-Sakali, M. El Mankibi, M. Ahachad, and J. Brigui, “Empirical validation and analysis of the energy performance of an ecological net zero energy building (NZEB) in Benguerir-Morocco,” 2023.

[13] D. Gatt, C. Caruana, and C. Yousif, “Building energy renovation and smart integration of renewables in a social housing block toward nearly-zero energy status,” 2020.

[14] A. Mohamed, A. Hasan, and K. Siren, “Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives,” 2014.

[15] K. R. Babu, “Implementation of net zero energy building (NZEB) prototype with renewable energy integration,” 2018.

[16] B. Singh, S. K. Sharma, and P. Syal, “Net zero energy building (NZEB) design,” 2021.