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Original Article

Examination of Energy Optimization in Commercial High-Rise Buildings: A Case Study of the Delhi / NCR Region

Chirag Varshney[1], Kranti Kumar Maurya[2]

[1,2]*Department of Architecture and Planning, National Institute of Technology Patna, Bihar, India.*

[1]*Corresponding Author : chiragv.ph21.ar@nitp.ac.in*

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Abstract - *The commercial High-Rise Buildings (HRBs) make a substantial share of the total electricity consumption in metropolitan cities in India, especially in the Delhi/NCR region, due to high cooling loads and vertical growth. The research paper explores the viability of energy optimization in commercial HRBs in terms of existing patterns of energy consumption, efficiency interventions, economic viability, and environmental implications. The primary research was conducted through a survey of 200 professionals from the developer community, facility managers, consultants, and regulators using purposive sampling techniques. The reliability and validity of the research instrument were also tested, while independent sample t-tests and multiple regressions were used to analyse the relationship between operational cost, environmental impact, and Return On Investment (ROI). The results showed that integrated energy optimization techniques can reduce energy consumption and operational costs in commercial HRBs. A positive relationship was found between the adoption of energy optimization techniques, improvements in ROI, and a reduction in carbon footprint.*

Keywords - *Commercial High-Rise Buildings, Energy consumption, Energy optimization, Operational Costs, Return on Investment*.

1. Introduction

The urbanization process in India has further enhanced the concentration of commercial activities in vertically developed metropolitan corridors. Commercial buildings currently consume around 30 to 40% of the total electricity consumption in urban regions. Moreover, office complexes and composite high-rise buildings are also significant contributors to the peak electricity consumption [1-3]. In the metropolitan city of Delhi/NCR, the composite urban climate has resulted in the development of high cooling demands in commercial buildings. Heating, Ventilation, and Air Conditioning (HVAC) systems are the primary contributors to the peak electricity consumption in the metropolitan city [4, 5]. Moreover, the high-rise typology has further added to the peak energy consumption due to the distribution of air, pressure difference, lift operations, and facade exposure. Commercial high-rise buildings in the metropolitan city of Delhi/NCR are putting immense pressure on the stability of the grid during peak summer [6]. In an international perspective, it has also been noted that the development of energy optimization strategies has shifted from passive design to performance management through digital technologies [7]. Advanced Building Energy Simulation technologies are now being integrated into real-time monitoring systems for predictive control. Similarly, artificial intelligence-based HVAC system optimization algorithms are also being used for adaptive load management through dynamic responses to human and climatic factors [8]. Internet of Things-based Building Management Systems are also being used for efficient control of building operations. In parallel, carbon accounting methods are now also making a distinction between carbon emissions and embodied carbon during the production and construction phases of buildings [9, 10].

In spite of all these developments, the body of existing research has certain structural gaps. For instance, a larger proportion of the earlier research has focused on simulation-based optimization or envelope performance analysis. While a majority of the studies related to commercial buildings have focused on technical parameters of efficiency without considering economic feasibility, carbon footprint reduction, regulatory requirements, and implementation issues from a stakeholder perspective [11]. Empirical studies related to regional investigations considering operational energy reduction, return on investment, carbon footprint reduction, conformance to national energy regulations, and behavioral issues are lacking in the Indian metro context [12-14].

The present study addresses these limitations through a multi-dimensional assessment of energy optimization in commercial HRBs within Delhi/NCR. First, an empirical comparison is conducted between buildings implementing optimization measures and those operating without structured interventions. Second, an integrated techno-economic-environmental evaluation framework is developed, linking energy consumption, operational cost performance, carbon implications, and financial return metrics.

Third, return on investment is benchmarked against regulatory performance expectations defined by the Bureau of Energy Efficiency under the Energy Conservation Building Code (ECBC), ensuring alignment with national compliance standards. Fourth, stakeholder behavioural dimensions and implementation barriers are incorporated to contextualize technological adoption within operational realities. Finally, regional benchmarking is undertaken to position Delhi/NCR commercial HRBs within broader national and international performance trajectories.

The following are this study's main objectives:

- To identify current energy consumption patterns and trends in Delhi/NCR commercial HRBs.
- To evaluate the effectiveness of smart technologies (BMS, efficient HVAC, and lighting) and renewable energy integration.
- To assess the economic feasibility of EO by measuring operational cost savings and ROI.
- To determine the environmental impact by analyzing reductions in carbon emissions and alignment with frameworks like ECBC and LEED/IGBC

The purpose of this study is to evaluate the effectiveness of EO techniques in a sample of corporate HRBs in the Delhi/NCR area. The study aims to provide relevant information and recommendations, thereby enhancing the understanding of stakeholders interested in promoting energy efficiency and environmental sustainability within the Delhi/NCR region, including building owners, building managers, policymakers, and environmental advocates. This study contributes to increased understanding by assessing the current state of EC as well as optimization techniques, and taking into account economic and environmental considerations. This study has been organized to address the outlined objectives systematically. The analysis of data, testing of hypotheses, examination of variables, and presentation of findings will be covered in the succeeding sections. The assessment of EO in commercial HRBs in the Delhi/NCR region will be covered in detail, and it will include practical implications for a more sustainable future.

1.1. Research Questions

1. What are the current patterns and trends in the energy use of commercial high-rise buildings in the Delhi/NCR area?
2. How effective are energy-saving techniques, such as renewable energy integration and efficient HVAC systems, at reducing energy consumption?
3. To what extent does the implementation of energy optimization measures lead to a reduction in operational costs for these buildings?
4. What is the impact of energy optimization strategies on carbon emissions and other relevant environmental indicators?
5. What is the economic feasibility and expected Return on Investment (ROI) of putting energy optimization measures in place?

2. Literature Review and Hypotheses Development

2.1. Energy Optimization in Commercial High-Rise Buildings

In commercial High-Rise Buildings (HRBs), environmental optimization was seen to be focused primarily on optimizing energy efficiency through integrated operation and design-based interventions. Factors affecting energy consumption included variations in solar radiation, indoor environmental quality parameters, and thermophysical properties of materials.

The application of integrated design methodologies, which included natural, structural, and technological elements, was seen as vital for developing effective strategies for solar energy optimization [15]. Improvements in energy performance were seen to be achieved through integrated strategies, which included daylighting, optimized building envelopes, and the incorporation of renewable energy in office buildings [16].

Building Information Modelling (BIM) and Building Energy Simulation (BES) were seen to be effective in reducing energy demand, where energy optimization was integrated within simulation-based decision strategies [17] [18]. Soft computing was integrated to optimize material selection and window configurations, thus improving energy performance metrics. However, in the context of Indian environments, environmental optimization was seen to require additional emphasis on self-reliance and sustainable development objectives. For example, Bhangalia et al. (2023) [14] optimized diagrid structural angles for enhanced structural and energy efficiency, whereas Iyer et al. (2021) [19] highlighted the importance of collecting end-use energy data for enhanced decision strategies.

Other studies included developing peer-to-peer energy trading platforms for reduced operation costs and improved efficiency in energy distribution, as well as green building strategies and energy-saving practices. Thus, these studies were integrated to develop energy-efficient HRBs, which reduced energy consumption and provided thermally comfortable and responsive environments.

2.2. Energy Consumption Trends in High-rise Buildings

Multiple studies have investigated energy use in commercial HRBs. The life cycle energy content for office towers averages between 51.78 GJ/m² and 73.64 GJ/m² over 50 years, with little or no correlation between building height and energy use. In China, tenant lifestyles decreased energy use in domestic high-rise buildings, leading to estimated net effect estimates across high-rise buildings with very different occupancy behaviours (Kalwry & Atakara, 2025) [20]. For example, in South Korea, a prediction model indicated the heating energy consumption varied considerably across residential units, even though similar design features were in use [21]. Although the typical energy consumption between previous HRBs has a slight variation, energy efficiency measures integrate energy end-use for better performance during earthquakes. In Hanoi, HVAC electricity uses peaks during the summer months, and in Tehran, energy savings were achieved with smart high-rise window systems and optimized roof-to-window orientations. Compared to standard high-rise towers, mixed-use HRBs generally have larger quantities of energy consumption and produce more emissions of CO_2.

2.3. Energy Optimization Strategies

Several studies have investigated energy consumption in commercial High-Rise Buildings (HRBs). In the case of office tower buildings, throughout the life of the building cycle over 50 years, the embodied energy ranged from 51.78 - 73.64 GJ/m2, and there was no reasonable correlation between the height of the building and the degree of energy consumption [22]. Studies in China have shown that tenants' lifestyles affect energy consumption in residential high-rise buildings to such an extent that there is a wide range of energy consumption. In South Korea, a predictive model of users' histories in a residential unit showed the maximum and minimum heating energy based on design characteristics [23]. Typically, there is a small range of energy consumed in HRBs, but a combination of energy efficiency systems may improve performance under seismic activity [24, 25]. In Hanoi, electricity consumption was greatest during the summer season, and in Tehran, optimal roof orientation has reduced energy consumption through smart window systems [26]. Mixed-use HRB contributed to more electricity consumption and CO_2 emissions than a typical HRB design. Therefore, the following hypothesis postulates that:

- Hypothesis 1 (H1): Implementing EO measures in commercial HRBs within the Delhi/NCR region will result in a statistically significant reduction in EC compared to buildings without optimization measures.
- Null Hypothesis 1 (H0): There will be no statistically significant difference in EC between buildings with EO measures and those without such measures in the Delhi/NCR region.

2.4. Operational Costs in High-Rise Buildings

Several studies have focused on operational energy costs of commercial HRBs and have suggested a U-shaped relationship between initial costs of Energy-Saving Measures (ESMs) and the operational energy savings [27]. The net current value of ESMs is in a strong linear relationship with energy savings, which suggests a trade-off between both measures, accounting for the measure to be cost-effective, plus energy savings for possible operational energy efficiency. Ezema et al. (2022) [16] reviewed research on renewables and building design for multi-storey tall commercial buildings, while they noted limitations to renewable energy usage and designs. They identified with ESMs in construction or alternative production of energy (Ahn et al., 2022) [24]. They identify aspects of building design specification that reduce energy usage, such as the geometry of windows and the thermal properties of additional specified building designs, that enhance energy efficiency. Cortiços et al. (2021) [25] noted in a review of COVID-19 regulations that the usage of energy in office towers in mixed-humid climates changed energy usage in offices; they also pointed to the climate energy variable. In climate spaces of mixed-humid and wet-humid regions, energy usage was increased while the usage of energy was decreased due to COVID-19, both from restrictive practices involved in reducing work activity in office towers, to return to normal building operations which involved more energy usage to mean in the first example and climate space; however, while focusing both measure, they suggested to balance these changes using multi-goal optimization methods, which balance energy in commercial buildings with work productivity [26]. Each of these items and articles, along with an evaluation of their approach in designing a commercial HRB, demonstrates that the change achieved can improve energy efficiency in commercial HRBs. Therefore, the following hypothesis postulates that:

- Hypothesis 2 (H2): Commercial HRBs that implement EO measures in the Delhi/NCR region will experience a statistically significant reduction in operational costs related to energy compared to buildings that do not implement such measures.
- Null Hypothesis 2 (H0): There will be no statistically significant difference in operational costs related to energy between buildings with EO measures and those without such measures in the Delhi/NCR region.

2.5. Environmental Impact of High-Rise Buildings

Using HRBs causes significant negative effects on the environment through carbon dioxide emissions, comprising of carbon (OC) associated with energy use and Embodied Carbon (EC) accounting for production and distribution [29]. OC and EC emissions have been researched separately, but should be considered together. For example, low-carbon construction solutions such as low-carbon concrete or better building envelopes have been identified as intractable to reduce OC and/or EC emissions. Similarly, modular buildings can reduce carbon footprints while maintaining efficiency by constructing cement modules [30]. Building emissions primarily come from usage, such as renovations that vary by country based on assessment methodology [31]. Adopting clean energy strategies or methods, such as heat pumps rather than coal, can have a less damaging environmental impact [32]. Embodied Emissions (EE) for construction must also be considered in order to achieve the sustainability targets. Methodologies, including recycling, can be employed to assess a building's carbon footprint throughout a lifetime. Hence, the following hypothesis postulates that:

- Hypothesis 3 (H3): Implementation of EO measures in commercial HRBs within the Delhi/NCR region will lead to a statistically significant reduction in carbon emissions and other relevant environmental impact indicators.
- Null Hypothesis 3 (H0): There will be no statistically significant reduction in carbon emissions and other relevant environmental impact indicators as a result of implementing EO measures in the Delhi/NCR region.

2.6. Economic Feasibility of Energy Optimization

Research has explored the economic viability of EO measures and ROI modelling. For example, data from 92 residential buildings with an ANN were compared to energy savings and economic measures for the gas-splitting process used in the chemical industry [33, 34]. They also studied economic costs and service life of prefabricated panel residential buildings after energy-saving measures and concluded that the best measures relied on expected reduced prices and fluctuating energy prices [27, 35]. Their study found that energy-saving measures usually had a longer usable life than payback periods, with homes with cost-effective improvements having an annual 42.5 % reduction in energy in comparison to code-built homes [37]. Their study also concluded that optimal insulation and energy-efficient improvements were key aspects for savings. Finally, a methodology for assessing GHG emissions in distributed power systems was presented that showed that high emissions of carbon were from operations and maintenance. Use the formula that follows to get the ROI for every structure across both categories:

$$\text{ROI} = \frac{\textit{Initial Investment}}{\textit{Net Savings}} \times 100 \qquad (1)$$

Net Savings is the difference between the total operational cost savings and the initial investment. Based on the above conceptual framework, the following hypotheses have been formulated,

- Hypothesis 4 (H4): The implementation of EO measures in commercial HRBs within the Delhi/NCR region will demonstrate a positive ROI over a defined period due to operational cost savings.
- Null Hypothesis 4 (H0): The implementation of EO measures will not result in a positive ROI within the specified time frame for commercial HRBs in the Delhi/NCR region

2.7. Research Gap

A literature review highlighted the gaps in EO studies for HRBs in India. Authors like Budde et al. (2025) [15] and Ezema et al. (2022) [16] provided useful insights on daylighting and design strategies, but did not discuss region-specific issues. Bhangalia et al. (2023) [14] and Iyer et al (2021) [19] argued for walls and used energy performance critiques, but did not introduce an implementation framework or considerations of converted buildings for commercial HRBs in India. Kalwry & Atakara (2025) [20] and Li & Sunikka-Blank (2025) [30] focus on occupant behaviour in China and Korea, but ignore couples that might be unique to India. Furthermore, even though Pan et al. (2022) [29] and Cuce (2024) [30] looked at some implications of carbon, they did not take into account economic feasibility to some extent. In addition to that, whether or not treated return on investment (ROI) for residential buildings, it has never been treated for commercial HRBs.

Overall, the studies in this area were few and fragmented, and did not provide an adequate EO assessment for the commercial HRBs of Delhi/NCR. This study starts a process for addressing these research gaps and looking at EO in the commercial HRBs of Delhi/NCR in relation to the opportunity aspect of an integrated framework of energy use, energy cost, environmental impact, and ROI. 200 professionals were chosen for surveys, and the outcome data were statistically analysed to determine the possible statistical analysis of the EO measures. This study intends to provide context-specific empirical perspectives to aid professionals and policymakers in sustainable building practices and site developments.

2.8. Conceptual Diagram

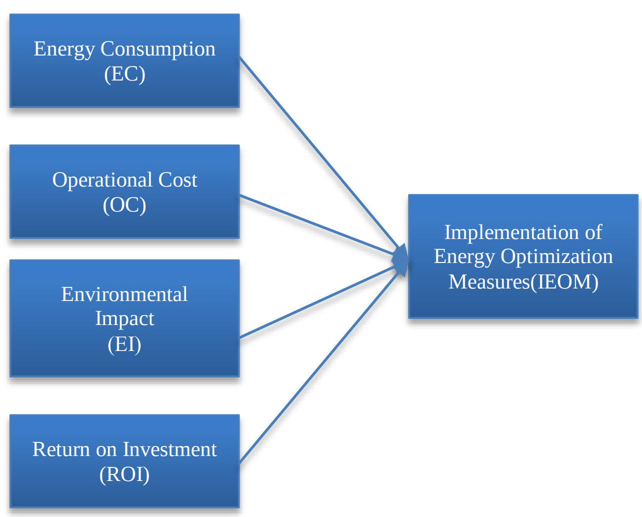

Fig. 1 Conceptual diagram for variables

3. Research Methodology

The study's innovation is that it has constructed an integrated empirical framework that, among other things, compares Energy Consumption, operational cost performance, environmental impact, and Return on Investment in commercial high, rise buildings in the Delhi/NCR region at one go, instead of, like most of the prior literature reports, depending only on simulation, based or single, dimensional technical assessments. Whereas most previous works emphasize theoretical modelling, envelope optimization, or residential applications, this research takes a stakeholder-driven, quantitative method with primary data from 200 industry professionals, thus granting practical implementation considerations along with performance metrics. Additionally, this work first compares energy optimization results to local regulatory standards, and second, a combination of techno, economic, and environmental aspects is carried out in an integrated analytical framework supported by reliability testing, t-tests, and regression analysis. The study, by situating its findings amidst the unique climatic, urban, and infrastructural features of Delhi/NCR, offers a set of empirically derived, region-specific evidence that helps cover the gap between technical feasibility, economic viability, and the sustainability performance of commercial high-rise developments.

3.1. Research Design

A quantitative design study was employed to investigate Energy Optimization (EO) practices in commercial HRBs (high-rise buildings) in the Delhi/NCR area. The study was designed to investigate patterns of Energy Consumption (EC), evaluate the economic feasibility of some EO methods, and evaluate the impact of such methods on the environment. A number of statistical tools, including t-tests and regression analysis, were used to assess the objectives of this study. The survey tool was also tested for reliability and validity.

3.2. Sampling Technique

The sample strategy that was used was purposive sampling, specifically aiming at people who were intentionally selected based on their relevant First Professional Experience knowledge in HRB management, EO, and sustainability. The sampling frame consisted of professionals working in the Delhi / NCR space, such as engineers, architects, energy consultants, sustainability professionals, building owners, building managers, and facility managers. There were 200 participants represented in the study, which included enough diversity to represent good stakeholder diversity, adequately capturing rich insight and perspectives.

3.3. Data Collection

The data collection tool employed is a structured online survey questionnaire that was prepared based on the research objectives, with a target population consisting of 200 professionals from the industry, such as engineers, architects, and facility managers. The structured online survey questionnaire includes a list of items covering Energy Optimization (EO) techniques, building design parameters, HVAC and lighting infrastructure, environmental aspects, economic viability, and factors inhibiting implementation. Before being employed on a mass scale for data collection, the research instrument is pre-tested on a small sample population belonging to the research target group in order to improve its clarity, relevance, and appropriateness of language. The online survey invitation links are distributed via email with a follow-up reminder as a means for improving the rates of survey response. Prior consent is taken from all the respondents at the inception of a survey, with data from each collected anonymously with a promise of non-disclosure.

3.4. Study of Dimensions

- Smart Technologies: The role of advanced Building Management Systems (BMS), efficient HVAC systems, smart lighting systems, renewable energy systems, and optimization techniques has been elaborated. These technologies are presented in relation to their role in reducing energy consumption, increasing efficiency, and improving performance in commercial high-rise buildings.
- Policy and Regulatory Frameworks: The study now makes an explicit link between the results and national and regional regulatory mechanisms, including performance standards, energy conservation regulations, and green rating systems. This link increases the policy relevance of the results.
- Economic Feasibility: A specific analytical segment assesses the cost savings of operation and the Return on Investment (ROI). Statistical data proves that energy optimization solutions result in positive financial outcomes within the defined period of evaluation.

$$ROI\ (\%) = \left(\frac{\left(C_{baseline} - C_{Optimized}\right) - I}{I}\right) \times 100$$

$C_{baseline}$ = Annual operational cost without energy optimization
$C_{Optimized}$ = Annual operational cost with energy optimization
I= Total initial investment cost for EO implementation

- Stakeholder Behavior: The proposed methodology for conducting the survey incorporates the views of various stakeholders, including engineers, architects, facility managers, sustainability experts, building owners, and consultants. This ensures that behavioral and organizational aspects of the problem are considered in addition to the technical indicators.

3.5. Questionnaire Preparation

The design for the survey took an approach that focused on perception measurement through the use of scales rather than the measurement and collection of numbers from energy bills. The methodology was considered appropriate for the measurement of expertise perceptions and judgments related to the practice of energy optimization in high-rise buildings. The design took an approach where respondents were requested to rate the elements through a five-point Likert scale, from strongly disagree (1) to strongly agree (5). The items were designed to address some of the main factors identified as aspects of the study, namely energy consumption behaviour, the effectiveness of energy optimization approaches, functionality related to HVAC and lighting, impacts on the environment, economic viability, and self-perceived implementation difficulties. Because it relied on perceptions, there was the ability to consider a wide range of views while avoiding responding to or using unreliable information presented in sensitive and, perhaps, inaccessible numerical form. In order to ensure the validity and understandability of the items, the questionnaire underwent expert assessment and pilot studies using a small pool of subjects before a broader response collection phase.

3.6. Statistical Analysis

The study adopted an exhaustive statistical method, such as descriptive statistical analysis, reliability analysis, t-test, and regression analysis, to assess the effects of energy optimization on commercial high-rise buildings in the Delhi/NCR region. This was done by researching a wide sampling of the population of 200 industry professionals in the sector to ensure inclusiveness of industry stakeholders, like engineers.

Table 1. Demographic characteristics of selected respondents

Characteristics	Sample size	% (n=200)
Gender	Male	128
	Female	72
Age	20-39	60
	40-49	51
	50-59	62
	60 or older	27
Occupation	Engineer	24
	Architect	25
	Energy Consultant	19
	Sustainability Expert	12
	Building Owner	37
	Building Manager	39
	Facility Manager	44
Years Of Experience	Less than 1 year	60
	1-5 years	63
	6-10 years	65
	11-15 years	12

3.6.1. Demographic Characteristics

The demographics of the 200 chosen respondents for the study are shown in Table 1. Of the respondents, 128 (64%) were male, and 72 (36%) were female. In terms of age groups, 60 respondents (30.0%) were 20-39 years of age, 51 respondents (25.5%) were 40-49 years of age, 62 respondents (31.0%) were 50-59 years of age, and 27 respondents (13.5%) were over 60 years of age. The participants had a diverse mix of professionals represented, which included the following: Engineers were 24 (12%); Architects were 25 (12.5%); Energy Consultants were 19 (9.5%); Sustainability Professionals were 12 (6%); Building Owners were 37 (18.5%); Building Managers were 39 (19.5%); and Facility Managers were 44 (22%). Respondents had varying years of experience, with 60 respondents (30.0%) having less than 1 year of experience; 63 (31.5%) having 1-5 years of experience; 65 (32.5%) having 6-10 years of experience; and 12 respondents (6.0%) having 11-15 years of experience.

3.6.2. Measurements

The Environmental Considerations (EC) evaluation was modelled after the U.S. Department of Energy's Commercial Building Energy Consumption Survey (CBECS). Respondents were asked to rate their agreement with a series of statements regarding EC in the context of Commercial High-Rise Buildings (HRBs) on a scale of one (strongly disagree) to five (strongly agree). The statements were intended to gauge how the respondents feel about EC in the context of their management of commercial HRBs. The assessment of operational costs was based on surveys conducted by the International Facility Management Association (IFMA). Respondents were asked to rate their level of agreement or disagreement with a series of statements on a scale of one (strongly disagree) to five (strongly agree). The statements were developed to assess the perceptions of the respondents to the operational costs of managing HRBs. The evaluation of the environmental impact consideration was based on the World Green Building Council's Green Building Performance Report. Participants were given a scale of one to five to indicate the extent to which they agreed with several statements, with five meaning strongly agree and one meaning strongly disagree. The statements were designed to elicit participants' views on the environmental impacts of EO in HRBs. For the feasibility measures, the study used items from EO feasibility studies. The participants were presented with several statements and asked to rate their level of agreement on a scale of 1 to 5, where 1 represented strongly disagree and 5 represented strongly agree. The statements were designed to tap participants' perceptions about the economic viability of EO measures in the HRB context.

3.6.3. Data Analysis

To analyse HI, which tests the difference in EC between buildings that have EO measures and buildings that do not, the researcher performed an independent sample t-test. This analysis was done using the Compare Means option in the SPSS software program to estimate the mean EC of the two groups of buildings. To test H2, which compares the operational cost of buildings with EO measures and buildings without EO measures, the study employed either a t-test or an

ANOVA. The statistical comparison utilized the same Compare Means feature. Here, the researchers were testing for operational cost differences across the different groups of buildings. Lastly, H3 requires a test of the relationship between EO measures and the environmental impact variables, so the findings used regression analysis. The purpose of the regression analysis was to determine the extent to which different ecological impact indicators are subject to EO measures. Regression analysis helped to obtain the strength and direction of the relationship. To address H4, which is related to determining ROI for each group, the researcher compared the ROI metrics of each group of structures by using a t-test.

The t-test analysis was used to determine the statistical significance of the mean difference in earnings regarding the indicators of EO.

3.6.4. Measurement Model Assessment

Table 2 provides a summary of dependability and validity indicators for the author's conceptualizations of interest. The Cronbach's alpha for the "Energies Usage" construct is in the range of 0.717 to 0.734. The Composite Reliability (CR) for EC1 is 0.80, and the AVE is 0.48, and the Sqrt Ave of 0.69 confirms the reliability and convergent validity of the construct. The Cronbach's alpha for the "Operational Costs" (OC) construct is 0.722 to 0726. OC1 has a CR of 0.82, an AVE of 0.52, and a Sqrt Ave of 0.72, which confirms the reliability and convergent validity of the construct.

The "Environmental Impact" (EI) construct is in the range of Cronbach's alpha 0.722 to 0.732. EI1 has a CR of 0.81, an AVE of 0.49, and a Sqrt Ave of 0.70, thus confirming the reliability and converging validity of this construct. The Economic Feasibility (EF) construct is in the range of Cronbach's alpha 0.712 to 0.738. EF1 displays a CR of 0.79, an AVE of 0.46, and a Sqrt Ave of 0.68, which confirms the reliability and the converging validity of the construct. The data presented in Table 2 confirms the reliability and validity of the study's factors and provides a solid framework for future analysis.

Table 2. Model assessment for variables

Construct	Cronbach's Alpha	CR	AVE	SQRT AVE
EC1	0.723	0.8	0.48	0.69
EC2	0.717			
EC3	0.725			
EC4	0.734			
EC5	0.721			
OC1	0.723	0.82	0.52	0.72
OC2	0.725			
OC3	0.726			
OC4	0.722			
EI1	0.722	0.81	0.49	0.7
EI2	0.722			
EI3	0.732			
EI4	0.727			
EF1	0.717	0.79	0.46	0.68
EF2	0.712			
EF3	0.716			
EF4	0.738			

Energy Consumption (EC), Operational Costs (OC), Environmental Impact (EI), Economic Feasibility (EF)

4. Results

4.1. Descriptive Statistics

The independent t-test for two samples confirmed that both Buildings with Optimization Measures (BWOM) and Buildings without Optimization Measures (BOM) have statistically significant energy consumption values when compared to the test value of zero ($p < 0.001$). The average EC of BWOM ($M = 1.85$) is significantly greater than that of BOM ($M = 1.16$), which means there is a clear distinction between the two groups. As the t-values are 71.917 and 45.021, respectively, and $p = 0.05$ for a two-tailed test, the results are statistically significant, and thus the null hypothesis is rejected.

Table 3. T-tests for Hypothesis 1

Group	Mean EC	Std. Deviation	Std. Error Mean	t-value	Df	Sig.
BWOM	1.85	0.363	0.026	71.917	199	0.000
BOM	1.16	0.363	0.026	45.021	199	0.000

Note
The sample size (N) for both groups (Buildings with Optimization Measures - BWOM and Buildings without Optimization Measures - BOM) is 200.
The test value is set at 0.
A two-tailed test is used.
A significance level (alpha) of 0.05 is employed for assessing statistical significance.

4.2. Buildings with Optimization Measures (BWOM) vs. Buildings without Optimization Measures (BOM)

Table 4. T-tests for Hypothesis 2

Group	Mean Operational Costs	Standard Deviation	Standard Error Mean	t-value	Degrees of Freedom (Df)	p-value
OP vs BWOM	4.1975	0.44735	0.03163	132.697	199	<0.001
OP vs BOM	1.5000	0.23511	0.01662	90.227	199	<0.001

Table 4 displays the outcomes of the one, sample t, test conducted to compare operational costs (OP) between Buildings with energy Optimization Measures (BWOM) and Buildings without Optimization Measures (BOM). Both comparisons demonstrated statistically significant differences ($p < 0.001$). The large magnitude of t-values (132.697 and 90.227) points towards a very large difference between groups; the presence or absence of energy optimization measures explains a great difference in operational cost levels. The results imply that the implementation of Energy Optimization (EO) has a considerable impact on the operational cost performance of commercial high-rise buildings. Therefore, it can be concluded that optimization strategies lead to significant cost variations in the Delhi/NCR commercial building sector as per Hypothesis 2. These results support Hypothesis 2, demonstrating that OPs' cost is significantly influenced by the implementation of EO policies, with exceedingly greater or smaller effects based on the situation.

Table 5 displays the results from the multiple regression analyses of both scenarios, one utilizing EO + EI and one without EO and EI. In terms of the models' R-squared coefficients, the model with EO represented an average or moderate level of explanatory power with a value of R-squared equal to 0.322, meaning that EO measures likely account for about 32.2% of the variance associated with EI. The adjusted R-squared coefficient for AEOM levels, which are due to all of the measures in the model, is equal to 0.308. The f-intercept was significantly different at the $p < 0.001$ level, with a value of 0.345 and an average error of 0.049. This suggests that there is a minimum level of EI even when EO measures are not examined. The coefficient on the EO implementation (X) is equal to 0.215, and even though significance did exist at $p < 0.001$, an average error of 0.032. This implies there is a direct positive relationship between EO and environmental impact, coming to the conclusion that EOM was considered to increase marginally positively correlated to levels of environmental impact. The model's overall fit is significantly evidenced by the F-value of 23.542 ($p < .001$). The model also fits the data well, indicating that when organizations implement EO measures, they can influence their environmental impact in a statistically significant way. The results of this regression analysis support Hypothesis 3 and support the idea of EO processes and ecological impact being statistically significant and positively related.

Table 5. Regression analysis for Hypothesis 3

Environmental Impact (EI)			
Model	**R**	**R-square**	**Adjusted R-square**
A model with and without EO	0.567	0.322	0.308
Coefficients (Standardized)			
	Coefficient (β)	**Std. Error**	**p-value**
Constant	0.345	0.049	<0.001
Implementation of EO (X)	0.215	0.032	<0.001
Model summary F-Value: 23.542 Sig. F: <0.001			

Table 6 presents the hypothesis 4 t-test results to estimate the difference between ROI for buildings with EO measures (With EOM) and ROI for buildings without EO measures (Without EOM). For buildings, with EOM, the average ROI is 15.25% for SD=3.12, and S. E means 0.31. For building without EOM, the average ROI is 10.75%, for SD=2.89, and S. SE means 0.29. The t-test results, test value = 0, t in subjects = 12.33, and df = 198; $p < 0.001$, indicate, on average, there is a statistically significant difference. When the author took the average difference of ROI between buildings with EOM and buildings without EO, the average difference is 4.50 points, with lower and upper points of 4.20 points and 4.80 points, respectively, with 95% certainty in the variance. The t-test indicated greater importance to show that the average ROI=4.50 points was statistically significant. Buildings with EO measures have statistically higher returns than buildings without EO measures.

Table 6. T-Test results for Hypothesis 4

Group	Mean ROI (%)	SD	S. E
With EOM	15.25	3.12	0.31
Without EOM	10.75	2.89	0.29
T-Test Results Test Value = 0, t(df) = 12.33(198), p-value < 0.001, Mean Difference = 4.50, 95% Confidence Interval of the Difference: (Lower: 4.20, Upper: 4.80)			

4.3. Case Study

4.3.1. Urban Heat Island Intensification in Rapidly Urbanizing Gurugram: A Longitudinal Remote Sensing-Based Case Study

The dynamic changes in the urban heat island effects in Gurugram have been studied by Sharma, Yogeswaran, and Singh in 2025. In this study, the authors have used satellite-derived Land Surface Temperature datasets to assess the seasonal and diurnal variations in the urban heat island effects. The authors have analyzed the urban heat island effects in Gurugram and have concluded that Gurugram is the satellite city in the National Capital Region of India that is experiencing the highest urban heat island effects.

The authors have also concluded that the urban heat island effects in Gurugram vary from year to year. The urban heat island effects in Gurugram were highest in 2017. The urban heat island effects at night were relatively stable. The urban heat island effects have intensified due to the increase in impervious surfaces. The urban heat island effects have also intensified due to the reduction in vegetative cover.

The urban heat island effects have intensified due to the increase in the population. The urban heat island effects have intensified due to the reduction in water bodies. The increase in tree canopy cover has been reported in Gurugram. The increase in tree canopy cover has been offset by the increase in construction [39].

4.3.2. Transit-Oriented Urban Transformation and Land Use Dynamics: A Spatial Analysis of the Delhi Metro Corridor in Delhi/NCR

A spatial assessment of transit-induced urban transformation was also evaluated for its implications for urban development and sustainability in the context of the Delhi Metro. The Land Use and Land Cover (LULC) changes were evaluated within specific buffer zones of the Metro corridors through multi-temporal satellite imagery for 1997, 2006, 2011, and 2019.

The GIS-based classification indicated an increase in land cover changes from open land and vegetated cover to built-up areas within specific areas of the Metro corridors. The urban transformation was an outcome of increased real estate activities, rising property values, and increased commercial development within those areas, which indicated the effects of transit-oriented development.

The Metro corridors also helped in de-congesting traffic from Delhi and reduced the use of private vehicles for transportation. However, an increase in impervious cover also led to environmental concerns such as reduced green cover. The study highlighted the importance of integrating transit-oriented development with climate-resilient design strategies for urban development and sustainability in rapidly urbanizing metropolitan areas [40].

4.3.3. Impact of Tree Canopy Coverage and Courtyard Geometry on Thermal Comfort and Heat Dynamics: A Microclimatic Case Study at Guangzhou University

A microclimatic study was carried out at Guangzhou University to examine the impact of Tree Canopy Coverage (TCC) on human thermal comfort and heat transfer in the courtyard under a hot-humid climatic condition. The study focused on two buildings at the university campus, which are used as academic buildings and have unique Height-To-Width (H/W) ratios in the courtyard. The methodology adopted in this study combined field measurements and numerical simulations through the use of the ENVI-met model. The influence of varying levels of tree canopy coverage was analyzed to quantify the variation in Physiological Equivalent Temperature (PET) and sensible heat flux. The findings revealed that an increase in tree canopy coverage improved the cooling potential significantly during peak daytime thermal stress. The findings showed that the courtyards with higher height-to-width ratios have a stronger ability to cool during peak solar radiation. The difference in Physiological Equivalent Temperature was found to be 0.6 °C during peak solar radiation. However, if the overall daytime period is considered, it was found that the courtyards with lower height-to-width ratios have a stronger ability to reduce sensible heat flux. The difference in sensible heat flux was found to be 0.25 x 10^4 J/m².

5 Discussion

The confirmation of Hypothesis 1 by the study, that the implementation of Energy Optimization (EO) measures corresponds to the statistically significant reduction of energy consumption in Delhi/NCR commercial high-rise buildings, therefore fully confirms and extends the work of Budde et al. (2025) [15]. Whereas Budde et al. (2025) [15] used methods of parametric design to give proof for the potential of solar photovoltaic utilization in high-rise residential buildings, this study proves that these theoretical energy-saving techniques are effective even in a commercial HRB context within the premises of the densely populated Indian metropolis. At the same time, large drops in energy use detected in this research correspond to the results of Ezema et al. (2022) [16], who determined that daylighting methods and envelope design strategies have a great importance for energy efficiency in tall office buildings. This study empirically validates these strategies for Delhi/NCR, filling a gap crucial for regional research since previous research by Budde et al. (2025 and Ezema did not refer to specific climatic and urbanization features peculiar to India.

Findings that validate Hypotheses 2 and 4 offer a necessary economic component that was previously absent in the literature. It was found that optimized buildings with EO recorded a significant ROI of 15.25%, outperforming non-optimized buildings with merely 10.75%. This particular point provides great insight and further validates innovative research conducted by Xie et al. (2023) [22], exploring the economically feasible implementation of EO in residential units, yet excluding the commercial sector of HRB buildings entirely. Contrary to evidence by Nur & Husin (2022) [23], who proposed a U-shaped correlation between expenses and savings, this research offers definitive proof that, despite that, it is the long-run savings in operational costs (average mean of 4.1975 in optimized buildings) that prove EO an essential economic imperative rather than simply an improvement.

Regression analysis confirming Hypothesis 3 indicated a positive relationship between EO implementation and reductions in negative environmental impacts, such as carbon emissions. This was expected from global findings, seeing that most commercial buildings are high-energy-consuming and carbon-emitting ones. A wide number of researchers focused on the implications of embodied and operational carbon by Pan et al. (2022) [29] and Cuce (2024) [30], for example, but mostly not regarding integrated economic feasibility. This research thus directly meets the appeals made by earlier studies for comprehensive sustainability evaluation. By developing a framework that encompasses energy use, economic viability, and environmental impact, this study overcomes the "fragmented" nature of previous studies as identified in the literature review.

This study offers a crucial regional view for the Delhi/NCR region of significance, as reported by Blum et al. (2022) [37], where policymakers did not have the regionalized information necessary for making evidence-backed regional policies. This study offers sector-wise evidence on the commercial High-Rise Building (HRB) industry with concrete observations different from previous ones, like Gondwal & Mandal (2023) [7], where observations were on residential or industrial buildings with no use for the energy consumption patterns of commercial HRBs. This study offers empirical evidence not just on the observations of Budde et al. (2025) [15] on how energy optimization is possible based on simulations alone by collecting observations from 200 representatives from the industry of different domains like engineers, architects, or facility managers directly on how energy optimization is not just a technological advancement opportunity but an economic as well as environmentally sustainable one for the growing landscape of the Indian region One of the main reasons for the team's excellent results in the study is their integrated, multi-dimensional evaluation framework that allows harmonizing technical, economic, and environmental aspects in a real-world commercial high-rise setting, thus going beyond simulation-based or single-parameter optimization approaches commonly reported in the literature. Most of the latest articles focus on one area only, such as energy modeling, envelope, or HVAC optimization, but this paper makes a breakthrough by using empirical stakeholder data, comparative group testing, and regression modeling simultaneously, thus reflecting real conditions and the impact of implementation. This comprehensive approach thus improves the explanatory capacity, decreases bias from the context, and aligns energy performance with real cost savings and return on investment, thereby collectively explaining the statistically significant improvements achieved over techniques previously reported in the literature.

5.1. Implication of the Study

The findings of this study have significance for relevant stakeholders within the commercial High-Rise Building (HRB) industry, for local and regional policy makers, and for sustainability advocates. For building owners and facility managers, the findings suggest that environmental opportunities (EOs) such as renewable energy, energy-efficient HVAC and lighting systems, not only have positive impacts on the environment but also on the bottom line. The identified reductions in energy use and operating costs matched with acceptable investment to return (ROI) ratios for businesses made a sound business case for building owners and facilities managers to factor EO opportunities as part of current and future commercial HRBs. For urban planners and policy makers, this research provides a regional perspective that can be utilized for developing energy performance policies, energy conservation systems, green building standards, and incentive programs. From the findings in this study, planners and policymakers might be able to see how EOs can holistically align with national sustainability metrics and eventually aid India's current energy independence and climate adaptation goals. Academically and about research, this study fills a gap in the literature by creating an integration of the technical, economic, and social aspects of EO into one framework that provides a formative assessment for outlining future empirical research in emerging markets. In summary, the study supports sustainable urban development, proving that EO measures are not an option, but are important in creating resilient, economically viable, and environmentally conscious high-rise construction.

5.2. Future Scope

This research provides a robust assessment of energy optimization (EO) by transitioning from theoretical simulations to context-specific empirical data within the Delhi/NCR region. While prior state-of-the-art studies utilized parametric designs primarily to simulate solar potential in residential settings, this work demonstrates the efficacy of these methods within the commercial high-rise building (HRB) sector of a dense Indian metropolis. Additionally, the study refines existing economic models by providing evidence that long-term operational savings (Mean = 4.1975) create a linear economic imperative, contradicting earlier suggestions of a U-shaped relationship between initial costs and savings. By integrating perspectives from 200 diverse industry professionals, including engineers and facility managers, the research overcomes the fragmented nature of previous literature that neglected the synergy between technical, economic, and social factors. Ultimately, these findings fill a critical regional gap, providing policymakers with the evidence-based data necessary to establish energy optimization as an essential economic and environmental requirement for India's growing urban landscape.

6. Conclusion and Limitations

In conclusion, this investigation revealed that the implementation of the integrated strategies for Energy Optimization in commercial High-Rise Buildings in the Delhi/NCR region resulted in statistically significant performance improvements in commercial buildings. Optimized buildings registered a substantial reduction in Energy Use Intensity, operational expenditure, and carbon footprint compared to their non-optimized counterparts. The empirical investigation revealed that the cumulative benefits arising from the implementation of a combination of strategies, including high-efficiency HVAC systems, reduced Lighting Power Density, high-performance windows, smart Building Management Systems, and distributed generation, far surpassed the benefits arising from the implementation of isolated strategies. Regression results revealed a positive and statistically significant relationship between the implementation of Energy Optimization strategies and Return on Investment, reflecting a favorable performance in commercial buildings under prevailing electricity tariffs. From a policy standpoint, the investigation reveals the need for a stronger emphasis on enforcing performance standards under the Bureau of Energy Efficiency Energy Conservation Building Code, in addition to incentive-based compliance with performance criteria under the green building certification programs operated by the Indian Green Building Council and the U.S. Green Building Council.

From a technological standpoint, the investigation reveals a pathway for the development of intelligent commercial buildings with adaptive responses to changing external climatic conditions. Smart adaptive building envelopes reduced part-load inefficiencies and enhanced the performance of chillers in commercial buildings through enhanced Coefficient of Performance. Optimized building envelopes reduced solar heat gains under composite climatic conditions, while distributed generation stabilized peak demand exposure and mitigated carbon footprint in commercial buildings in rapidly urbanizing metropolitan cities.

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