Evaluation of Energy Performance Improvement Potential for High-Rise Residential Buildings Using Energy Efficient Design Strategies

Thesis Submitted By

Gunjan Kumar

Doctor of Philosophy (Engineering)

Department of Mechanical Engineering
Faculty Council of Engineering & Technology
Jadavpur University
Kolkata, India

2024

INDEX NO. 254/18/E

1. **Title of the Thesis:**

   Evaluation of Energy Performance Improvement Potential for High-Rise Residential Buildings Using Energy Efficient Design Strategies

2. **Name, Designation & Institution of the Supervisors:**

   1. **Dr. Sudipta De**
      Professor
      Department of Mechanical Engineering
      Jadavpur University
      Kolkata – 700032, India

   2. **Dr. Biswajit Thakur**
      Associate Professor
      Department of Civil Engineering
      Meghnad Saha Institute of Technology
      Kolkata – 700150, India

3. **List of Publications:** Part of this thesis work has been published in the following journals and conference proceedings:

   A. Book Chapters:

   1. B. Thakur, G. Kumar, S. De. 2023. Emerging Façade Materials and their Processing for Large Apartments: A Comparative Energy and Environmental Performance. Published in **Comprehensive Materials Processing (2nd Edition): Reference Module in Materials Science and Materials Engineering. Elsevier** (ISBN: 9780128035818), 2023. **DOI**: https://doi.org/10.1016/B978-0-323-96020-5.00106-0.

   B. Papers Published in Peer Reviewed International Journals:

   1. G. Kumar, S. De, B. Thakur. 2024. Wall and air conditioner combination for the best energy and economic performance: methodology demonstration for high-rise residential buildings. **Energy Conservation and Management**. 300 (2024) 117909. Elsevier. **DOI**: https://doi.org/10.1016/j.enconman.2023.117909. **Impact Factor: 10.4**

   2. G. Kumar, B. Thakur, S. De. 2021. Energy Performance of Typical Large Residential Apartments in Kolkata: Implementing New Energy Conservation Building Codes of India. **Clean Technologies and Environmental Policy**. 23, 1251-1271. Springer. DOI: https://doi.org/10.1007/s10098-020-02022-7. **Impact Factor: 4.3**

C. **Papers Published in Conference Proceedings:**

1. G. Kumar, B. Thakur, S. De., K. De., M. Sen. 2024. Impact assessment of Eco-Niwas Samhita code compliance on high-rise residential building operational energy consumption and cooling load performance. **8th National and 2nd International Conference on REFRIGERATION AND AIR CONDITIONING, 2024 (NCRAC 2024)**. Organized by IIT Madras, Chennai, India, 13th-15th March, 2024. Abstract Book (Abstract). Paper ID. 307, 61.

2. G. Kumar, B. Thakur, S. De. 2023. Net zero energy assessment of multistoried residential buildings integrated with onsite solar rooftop PV System: A case study**. 9th International Conference of Advances in Energy Research (ICAER 2023)**. Organized by the Department of Energy Science and Engineering, IIT Bombay, Mumbai, India, 12th-14th December, 2023. Abstract Book (Abstract). Paper No. 102, 71.

3. G. Kumar, D. Sen, B. Thakur, S. De. 2020. Investigation on the Impact of Envelope Thermal Insulation on Energy Performance of a Commercial Building in the Warm Humid Climate of Kolkata through Energy Conservation Building Code, 2017. Published in Proceedings of the Second **ASCE India Conference on "Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies" (CRSIDE2020)**. Asok Adak et al. (Eds.). Edition-1, Volume-1. Published by: THINKER. © ASCE India Section. ISBN: 978-81-954551-0-2. AIC2020-11-1094, 7-11.

4. G. Kumar, B. Thakur, S. De. 2020. Impact of Implementation of Eco - Niwas Samhita 2018 on the Cooling and Lighting Energy Consumption for Residential Apartments in Kolkata. **International Conference on Energy and Sustainable Development 2020 (ICESD 2020)**, Jadavpur University, Kolkata, 14th-15th February, 2020. Conference Proceedings (Full Paper). 64-67

5. G. Kumar, B. Thakur, S. De. 2020. Investigation of Energy Performance of a High Rise Residential Building in Kolkata through Performance Levels of Energy Conservation Building Code, 2017. Published in Proceedings of the **7th International Conference of Advances in Energy Research (ICAER 2019)**. Manaswita Bose, Anish Modi (Eds.). Springer Proceedings in Energy (ISSN 2352-2542, ISBN 978-981-15-5955-6, DOI: https://doi.org/10.1007/978-981-15-5955-6).505-513. DOI: https://doi.org/10.1007/978-981-15-5955-6_47.

4. List of Patents:

Nil

5. List of Presentations in National/International Seminar & Conference:

1. Net zero energy assessment of multistoried residential buildings integrated with onsite solar rooftop PV System: A case study. Authored by: G. Kumar, B. Thakur, S. De. Presented in: **9th International Conference of Advances in Energy Research (ICAER 2023)**. Organized by the Department of Energy

Science and Engineering, IIT Bombay, Mumbai, India, 12th-14th December, 2023.

2. Investigation on the Impact of Envelope Thermal Insulation on Energy Performance of a Commercial Building in the Warm Humid Climate of Kolkata through Energy Conservation Building Code, 2017. Authored by: G. Kumar, D. Sen, B. Thakur, S. De. Presented in: **Second ASCE India Conference on "Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies" (CRSIDE2020).** Kolkata, 2nd-4th March, 2020.

3. Impact of Implementation of Eco - Niwas Samhita 2018 on the Cooling and Lighting Energy Consumption for Residential Apartments in Kolkata. Authored by: G. Kumar, B. Thakur, S. De. Presented in: **International Conference on Energy and Sustainable Development 2020 (ICESD 2020),** Jadavpur University, Kolkata, 14th-15th February, 2020.

4. Investigation of Energy Performance of a High-Rise Residential Building in Kolkata through Performance Levels of Energy Conservation Building Code, 2017. Authored by: G. Kumar, B. Thakur, S. De. Presented in: **7th International Conference of Advances in Energy Research (ICAER 2019)**, VMCC, IIT Bombay, Mumbai, 10th-12th December, 2019.

5. Integrating energy efficiency in residential buildings: A user-centric web interface approach. Authored by: G. Kumar, K. De, A. Roy, S. Bag. Presented in: **International Conference on Chemical and Environmental Sciences (ICCAES 2024)**, Jointly organized by IEM Kolkata and Royal Society of Chemistry, Kolkata, 11th-13th January, 2024.

"Statement of Originality"

I Shri **Gunjan Kumar** registered on 4th May, 2018 do hereby declare that this thesis entitled **"Evaluation of Energy Performance Improvement Potential for High-Rise Residential Buildings Using Energy Efficient Design Strategies"** contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the "Policy on Anti Plagiarism, Jadavpur University, 2019", and the level of similarity as checked by iThenticate software is ___4___ %.

Signature of Candidate:

Gunjan Kumar

Gunjan Kumar
Date: 23/04/2024
Place: Kolkata

Certified by Supervisors:

1. S. De

Dr. Sudipta De
Professor
Department of Mechanical Engineering
Jadavpur University
Date: 23/04/24
Place: Kolkata

2. Biswajit Thakur

Dr. Biswajit Thakur
Associate Professor
Department of Civil Engineering
Meghnad Saha Institute of Technology
Date: 23/4/24
Place: Kolkata

Dr. Biswajit Thakur
Associate Professor
Civil Engineering Department
Meghnad Saha Institute of Technology

(Signature of Supervisors and date with office Seal)

Professor
Dept. of Mechanical Engineering
Jadavpur University, Kolkata-32

MEGHNAD SAHA INSTITUTE OF TECHNOLOGY

Certificate from the Supervisors

This is to certify that the thesis entitled **"Evaluation of Energy Performance Improvement Potential for High-Rise Residential Buildings Using Energy Efficient Design Strategies"** submitted by Shri. Gunjan Kumar, who got his name registered on 4th May, 2018 for the award of Ph.D (Engg.) degree of Jadavpur University is absolutely based upon his own work under the supervision of Dr Sudipta De and Dr. Biswajit Thakur and that neither his thesis nor any part of the thesis has been submitted for any degree or any other academic award anywhere before.

1. ______________________________

Dr. Sudipta De
Professor
Department of Mechanical Engineering
Jadavpur University
Date: 23/04/24
Place: Kolkata

2. ______________________________

Dr. Biswajit Thakur
Associate Professor
Department of Civil Engineering
Meghnad Saha Institute of Technology
Date: 23/4/24
Place: Kolkata

Dr. Biswajit Thakur
Associate Professor
Civil Engineering Department
Meghnad Saha Institute of Technology

(Signature of Supervisors and date with office Seal)

Professor
Dept. of Mechanical Engineering
Jadavpur University, Kolkata-32

MEGHNAD SAHA INSTITUTE OF TECHNOLOGY

Acknowledgments

I am writing to express my deepest gratitude for all quarters of support and guidance throughout the journey of my Ph.D. work and the completion of my thesis.

First and foremost, I would like to express my deepest and most sincere gratitude to my both PhD supervisors, Prof. Sudipta De and Prof. Biswajit Thakur. I am sincerely grateful to Prof. Sudipta De for his initial acceptance and further unwavering commitment to excellence, insightful feedback, and mentorship, which have been instrumental in every stage of my research. Your expertise, encouragement, and unconditional support have significantly enriched the quality of my work, and I am truly fortunate to have had the opportunity to work under your supervision. I would also like to extend my heartfelt appreciation to Prof. Biswajit Thakur for your guidance, support, and expertise throughout this journey. Your unique perspective, dedication, and scholarly insights have provided invaluable contributions to the development and refinement of my research. Your mentorship has been invaluable, and I am deeply grateful for your encouragement, handholding, and lifetime learning.

I am very thankful to the Head of the Department, faculty members of the Mechanical Engineering Department, and fellow lab mates, along with my close friends, for their support, without which the accomplishment of the present work cannot happen. Special thanks to Mr. Soumitra Pati and Mr. Sayan Das for always helping me. My personal gratitude to all other staff of the Heat Power Laboratory of the Mechanical Engineering Department, Jadavpur University, for their help and continuous support.

I also extend my deepest gratitude to my parents, Sri Bijendra Yadav and Smt. Pavitri Kumari, who not only blessed me with their unconditional love and affection but also served as my unwavering role models. I would like to extend a special word of gratitude and admiration to my sister, Dr. Naydu, and my brother, Prof. Anjan, who have been unwavering pillars of support throughout my entire academic and life journey. To my wife, Sapna, and my children, Srishti and Ansh, I am eternally grateful for their unconditional love, understanding, and patience.

Signature:

(GUNJAN KUMAR)

Date: 23|04|2024

Place: Kolkata

Dedicated to

My Parents

Abstract

The inexorable rise in population combined with economic prosperity is driving a fast and unavoidable wave of urbanization, particularly noticeable in developing nations. Due to higher population density and scarcity of available land, high-rise residential and commercial buildings are now increasing in big cities. India too has seen a significant rise in high-rise residential buildings as these cater to the increasing city population density. Building energy efficiency has eventually emerged as a critical issue for such buildings. Energy consumption in these high-rise buildings can vary significantly depending on factors such as location, climate, overall design, construction materials, occupancy, the efficiency of electro-mechanical systems used for building services, and several others. Space cooling for occupants' thermal comfort consumes a major share of energy for high-rise buildings in tropical countries. A review of the scientific literature has revealed 158 country-initiated policy measures to improve energy efficiency in the building sector. In India too, the Bureau of Energy Efficiency (BEE), initiated Energy Conservation Building Codes (ECBC) in 2007 to enhance building energy efficiency in the country. ECBC, 2017 for commercial buildings and Eco-Niwas Samhita, 2018, (Part-I) and Eco-Niwas Samhita, 2021, (Part-II) for residential buildings are the latest codes introduced in India.

Anticipating the enormous potential of energy savings in energy-intensive urban residences, the present study attempts to assess the energy performance improvement potential of typical high-rise residential apartment buildings using early design stage strategies in the warm-humid climate of Kolkata. To determine the optimized solution, the methodology followed is an integrated iterative process involving whole-building energy simulation, parametric analysis, and statistical analysis. The uncertainty in the variables influencing energy performance is probed into through sensitivity analyses. Monte Carlo simulation is used to deal with the risks involved in different variables during techno-economic analysis.

Studies have been carried out to assess the extent of possible improvement in the energy performance of typical high-rise residential buildings of Kolkata through the implementation of Eco-Niwas Samhita, 2018 (Part-1) and ECBC, 2017. The results demonstrate the substantial savings potential in overall operational energy consumption (8-26%) and even more in cooling energy consumption (11-36%) for high-rise residential buildings by adhering to these standards. Statistical association of the energy performance with different variables regarding building geometry and envelope material properties is also investigated. Residential envelope transmittance value (*RETV*), roof thermal transmittance value (U_{roof}), and visible light transmittance (*VLT*) amongst envelope material properties and Roof area (A_{roof}), and Envelope area ($A_{envelope}$) amongst building geometry parameters are identified as the key influencing factors. The critical factors influencing energy performance are identified through sensitivity analyses. It identifies that the thermal properties of the envelope materials (in terms of *RETV*) and the efficiency of the HVAC systems (in terms of *EER*) are going to play critical roles in cooling energy optimization.

The combined energy efficiency and environmental performance study compared the operational and embodied energy performance and associated greenhouse gas (GHG) emissions for typically practiced exterior wall assembly materials along with recent research trends for sustainable alternatives. Autoclaved aerated concrete block (AACB) walls demonstrated the highest energy efficiency and GHG emission reduction among alternatives, with a 10% operational and 13% overall improvement in energy performance and a 10% operational and 10% overall decrease in GHG emissions compared to existing typically practiced burnt clay brick walls. Fly ash brick and AACB walls displayed moderate

enhancements in embodied energy performance compared to brick walls, indicating their potential as viable alternatives with improved sustainability characteristics. Conversely, dense concrete block walls and solid burnt clay brick walls exhibited the poorest performance in terms of energy efficiency and GHG emission reduction.

The choice of external wall materials and its construction layer, paired with the corresponding air conditioning system as active cooling integration, is optimized for the best energy efficiency while minimizing cost for high-rise developments. This energy-cost optimization study confirms that the combination of autoclaved aerated concrete block (AACB) wall and 5-star split air conditioner emerges as the optimum, being 38% more energy efficient and 24% more cost-effective than the typically practiced baseline option. The required initial higher capital investment is well compensated for lower annual expenditure for operational energy when fifteen years' cash flow is considered.

Finally, the outcomes of this thesis have the potential to contribute to the possible design strategies and show pathways for low-energy, low-carbon, and economically feasible high-rise buildings. The final outcome also contributes to a deeper comprehension to align design practices with regulatory codes from the outset and highlight the importance of embodied energy for further code improvement.

Title of the Thesis

Evaluation of Energy Performance Improvement Potential for High-Rise Residential Buildings Using Energy Efficient Design Strategies

Contents

List of Tables

List of Figures

List of Symbols and Notations

Symbols and Notations	Description
%	Percent
kWh	Kilowatt-hour
TWh	Terawatt-hour
EPI	Energy performance Index
$H_{building}$	Height of building (m)
H_{Floorg}	Typical Floor to Floor Height (m)
$A_{bult-up}$	Built-up area (m^2)
$A_{conditioned}$	Conditioned Area (m^2)
$A_{envelope}$	Envelope Area (m^2)
$A_{envelope}$	Envelope Area (m^2)
A_{opaque}	Opaque Wall Area (m^2)
$A_{Non-opaque}$	Window (Non- Opaque Area (m^2)
$A_{openable}$	Openable Window (Non- Opaque Area (m^2)
WFR_{OP}	Openable Window to Floor Area Ratio (%)
WWR	Window wall ratio (%)
AZ	Azimuth of the Longer Axis (Degree)
r	Pearson correlation coefficients
r_s	Sperarman rank correlation coefficients
U_{roof}	Roof Thermal Transmittance value (W/m^2K)
U_{wall}	Thermal transmittance of the external wall(W/m^2K)
ω_i	orientation factors
U_{glass}	Thermal transmittance of the glass(W/m^2K)
t	Thickness of material layer
R_{si}	Interior Surface film thermal resistance
R_{se}	Exterior Surface film thermal resistance
Ki	Material thermal Conductivity ((W/mK)
Ri	Material Resistance (m^2K/ W)
R_T	Total Thermal resistance (R_T)
$EPI_{cooling}$	Cooling energy performance Index
$EPI_{lighting}$	Internal Lighting energy performance Index
$T_{simulated}$	Simulated Temperature
$T_{Measured}$	Measured Temperature
CF	Calibration coefficient
R^2	Coefficients of determination
$SHGC_{non-north}$	Solar heat gain coefficient of the non-north
$SHGC_{equivalenti}$	solar heat gain coefficient
WWR_{North}	Window wall ratio North (%)
WWR_{South}	Window wall ratio South (%)
WWR_{east}	Window wall ratio East (%)
WWRwest	Window wall ratio West (%)
EE_{coef}	Embodied Energy Coefficient
c	Specific Heat capacity
r	Density (Kg/m^3)

Symbols and Notations	Description
EPI_OE	Operational Energy Performance Index, kWh/m^2/Year
EE_Ext_Wall	Embodied energy for the exterior walls, kWh/m^2
OE_Life	Total Lifetime Operational Energy Consumption, kWh/m^2
RSL	Reference service life
EPI_Cumulative	Cumulative Energy Performance Index, kWh/m^2
GHG_OE_Life	GHG emission due to operational energy life time, kg CO_2 eq/m^2
GHG_Embodied_Ext_Wall	Exterior Wall Embodied GHG Emission, kg CO_2 eq/m^2
GHG_Cumulative	Cumulative GHG emission, kg CO_2 eq/m^2
OE_Annual	Annual operational energy consumption, kWh/Year
$C_{Wall\text{-}Mat}$	Average material cost rates, INR/m^3
$C_{Wall\text{-}Con}$	Construction cost rates, INR/m^3
CC_Wall	Wall capital cost, INR/m^2
SHG_{opaqu}	Solar heat gain through the opaque envelope
Q_{sensible}	Sensible heat
Q_{latent}	Latent heat
DBT	Dry bulb temperature, °C
WBT	Dry bulb temperature, °C
RH	Relative Humidity, %
CC_AC	AC variations capital cost, INR/m^2
C_OE	Annual operational energy costs
r	Annual inflation rate, %
i	Discount factor, %
C_Total_PV	Present value for total expenditure, INR/m^2
σ	Standard deviation
μ	Normal distributions with mean
N_{AC_TF}	Split air conditioners, required for Typical floor of the concerned building
N_T	Number of typical floors
N_{AC_B}	Total number of split air conditioners required for that building
C_{AC}	Split air conditioners Average market price

List of Abbreviations

Abbreviated Form	Full Form
NBC	National Building code
ECBC	Energy conservation building code
ENS	Eco-Niwas Samhita
EEM	Energy efficiency measures
HVAC	Heating ventilation and Air conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIS	Bureau of Indian Standards
BEE	Bureau of energy efficiency
ISEER	Indian seasonal energy efficiency ratio
IGBC	Indian green building council
LEED	Leadership in energy and environmental design
GHG	Greenhouse gas
NDC	National Determined contribution
CESC	Calcutta Electricity corporation
GRIHA	Green rating for integrated habitant assessment
CII	Confederation of Indian industry
CDD	Cooing degree day
HDD	Heating degree day
ICAP	India cooling action plan
GSR	Global status report
UHI	Urban heat island
ROI	Return on investment
PMV	Predicted mean vote
AEEE	Alliance for an energy efficient economy
BEES	Building energy efficiency standards
AC	Air conditioner
AAC	Aerated autoclaved concrete
CSEB	Compressed stabilised earthen block
EPS	Expended polystyrene
OFTC	Optical fire-based translucent concrete
REHB	Recourse Efficient hollow brick
FAB	Fly ash brick
RCC	Reinforcement cement concrete
OPC	Ordinary portant cement
PCM	Phase change materials
RAC	Room air conditioner
EPI	Energy performance Index
NPV	Net present value
EE	Embodied energy
OE	Operational energy
LPD	Lighting power density
EPD	Equipment power density
NCEL	National center for environmental data
USA	United States of America

Abbreviated Form	Full Form
MCS	Monte carlo simuloation
WWR	Window wall ratio
SHGC	Solar heat gain coefficient
VLT	Visible light transmittance
RETV	Residential envelope transmittance value
SGU	Single glazed unit
DGU	Double glazed unit
SGG	Saint-Gobain Glass
ASI	Asahi Glass Limited
SCB	Solid concrete block
DCB	Dense concrete block
SBCM	Solid burnt clay brick
CMU	Concrete masonay units
PFA	Pulverized fly ash
PPC	Portland pozzolana cement
ACP	Aluminium composite panel
EER	Energy efficiency ratio
CPWD	Central public works department
TETD	Total equivalent temperature differential
SHGF	Solar heat gain factor
VRF	Variable refrigerant flow
SCF	Shading correction factor

Organization of the Thesis

The present research work is aimed at studying the energy performance improvement potential for high-rise residential buildings by applying different energy efficient design strategies. The whole work is organized into seven chapters.

Chapter 1: Introduction
This chapter serves as a foundational exploration into the realm of building classification, offering insights into the diverse landscape of building energy scenarios, the intricate interplay of driving policies, and the ever-pressing issue of environmental impact. By exploring into these key areas, readers are provided with a comprehensive understanding of the multifaceted dynamics, shaping the built space today.

Chapter 2: Literature Survey
Within this chapter lies a thorough examination of the existing body of literature surrounding methods aimed at enhancing the performance of building energy. Through meticulous review and analysis, this section illuminates the various strategies, techniques, and innovations that have been explored in the quest for more efficient and sustainable building energy practices. Research gaps are identified through the review and study objectives are set.

Chapter 3: Methodology
In this pivotal chapter, the focus shifts towards the practical aspects of research methodology, detailing the intricate processes involved in the collection and analysis of building data. Furthermore, this section offers valuable insights into the creation of building models and the meticulous execution of building energy simulations, laying the groundwork for the subsequent phases of the study.

Chapter 4: Assessment of Building Energy Performance and Critical Influencing Parameters
In this chapter a comprehensive assessment of building energy performance, with a focus on the critical influencing parameters that shape outcomes is presented. Through rigorous analysis and evaluation, this chapter sheds light on the impact assessment of significant regulatory frameworks such as the Eco-Niwas Samhita and ECBC of India, offering valuable insights into their efficacy in driving building operational energy performance.

Chapter 5: Impact of Variation in Exterior Wall Assemblies on Energy and Environmental Performance
Dedicated to a careful examination of exterior wall assemblies, this chapter serves as a platform for comparative analysis, exploring the intricate distinctions of energy and environmental performance across diverse configurations. By accounting for embodied energy and other pertinent factors, readers gain a deeper understanding of the complexities involved in optimizing building envelope design for enhanced sustainability.

Chapter 6: Impact of Combined Variation in Air Conditioners and Exterior Wall Assemblies on Energy and Economic Performance
This chapter represents a significant advancement in the study, delving into the combined impact of air conditioner specifications and variations in wall material compositions on overall energy consumption and economic viability. Through rigorous analysis and modeling, readers may gain valuable insights into the intricate interplay between these two most

important variables, paving the way for more informed decision-making in the design and operation of high-rise residential buildings.

Chapter 7: Conclusion and Future Scope of Work
At the end of the thesis, this final chapter offers a reflective synthesis of key findings and insights gathered throughout the study. Additionally, the possible future endeavours for further development of knowledge in this area of study, identifying avenues for further research and innovation in the ongoing quest for more sustainable and efficient building energy practices are stated in this chapter.

At the end of the thesis in the 'Reference' section a list of reviewed literature and other references used in the present research work is given.

Chapter 1

Introduction

1.0 Introduction

Currently, the issue of energy efficiency is a topic of extensive global discourse, with several researches being carried out (Doraj et al., 2021). Energy is crucial for the socio-economic progress of the nations. Hence, energy policymakers attach great importance to managing and optimizing energy usage as a means of ensuring energy security (Moreira et al., 2022). To reach the 2050 goal of net zero emissions, energy efficiency is regarded as the first fuel in the energy transition. The building industry exerts a significant influence on the environment, as it is directly or indirectly responsible for 39% of the global release of greenhouse gases (GHG) and 36% of global energy use (GlobalABC, 2020). In densely populated cities, buildings can contribute up to 75% of carbon emissions and 60% of overall electricity usage (United Nations, 2020). The residential sector consumes almost 30% of the planet's total energy, making it responsible for around 36% of CO_2 emissions, which is the primary agent causing climate change (Saleki & Bahramani, 2018). In the future, this percentage is projected to rise due to the rapid increase in population and urbanization. As a result, cities grow upwards due to the limited amount of land available to accommodate the growing population (Lima et al., 2019). In addition, urban growth will lead to alterations in the energy consumption pattern, with a particular focus on the increasing demand for residential construction in emerging economies. Governments are especially concerned about this issue. The provision of high-quality housing in urban regions has played a significant role in meeting the housing needs of the large influx of people migrating to rapidly growing cities. Moreover, as cities expand, energy consumption patterns will change, which is made worse by unpredictable weather conditions. (Shen et al., 2019). This emphasizes the importance of developing sustainable built space. Many studies conducted in the last few decades have concentrated on developing method to improve building sustainability, energy efficiency, and alternate energy source integration (Hong et al., 2019). By using early design strategies with a special focus on building envelope materials and local climate data, building energy performance can be enhanced. (Qian et al., 2019).

India is the world's third-largest producer and consumer of electricity with an installed capacity of 382 GW as of 31 March 2021. All India's per-capita electricity consumption has increased from 631.4 kWh (2005-2006) to 1161 kWh (2020-21) (Central Electricity Authority, 2022) as shown in Fig. 1.1. As a result, India has generated a total of 2279 million metric ton of CO_2 in 2021 which is 8% of world total emissions and third highest after China and USA (IEA, 2023). India has submitted its revised Intended National Determined Contribution (INDC) under the Paris Climate Agreement, pledging to cut its carbon emissions by one billion tonnes by 2030 and to lower its GDP's emission intensity by 45% from the level of 2005 by that same year. The overall energy conservation potential in India is about 23% (Chel and Kaushik, 2018).

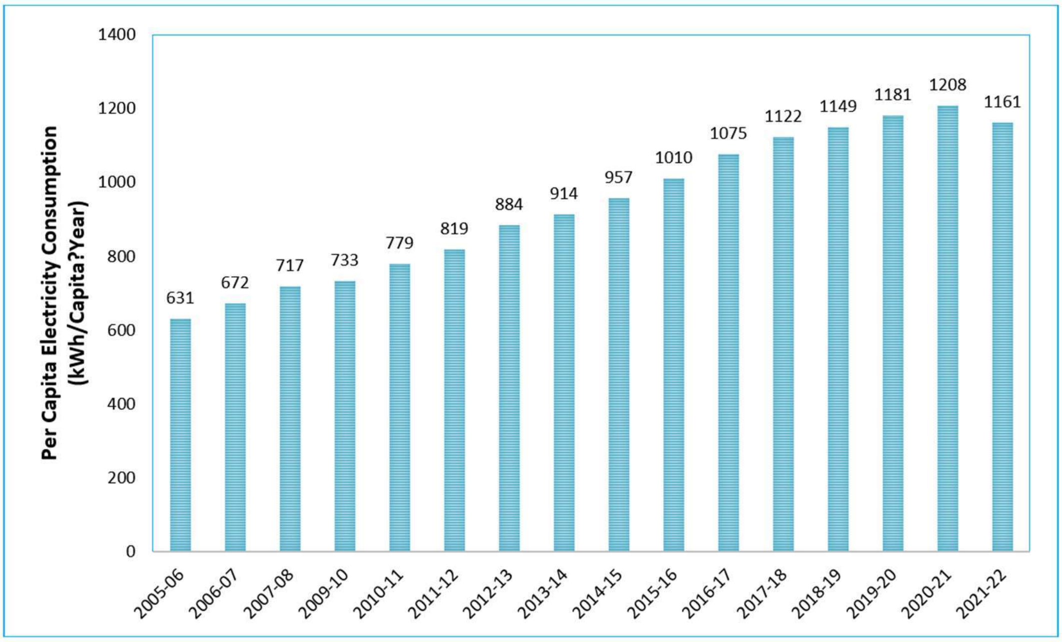


Figure 1.1: Growth of Per Capita Electricity Consumption in India from 2005-06 to 2021-22

[Source: CEA, 2022]

Therefore, improving the energy efficiency of all systems through cost-effective means is always a mutually beneficial choice, particularly for systems that consume a significant amount of energy. Given the rise in population and economic expansion, fast urbanization is unavoidable, particularly in developing nations. Big cities are experiencing an increase in high-rises, both residential and commercial, due to the combination of rising population density and limited land availability. The importance of energy efficiency in high-rise buildings has become increasingly significant. This study focuses on energy conservation building codes, envelope materials, air conditioners, embodied energy of different façade materials, and the energy efficiency ratio of air conditioners in the Indian context. It examines their influence on the energy efficiency of high-rise residential buildings.

1.1 Building Sector in India

India, the world's fifth-largest economy with 1.41 billion people, is currently experiencing rapid urbanization. Its housing demand has radically increased. India's household count was estimated to be 272 million in 2017 and is expected to rise to 328 million in 2027 and 386 million in 2037 (MoEF&CC, 2019). The entire population living in urban cities is expected to increase from approximately 470 million in 2019 to nearly 740 million by 2040, which means 46% urbanization (IEA, 2021b). This projected rise in urban population by 2040 would be the equivalent of adding thirteen Mumbai-sized cities to India. With a known fact that urban areas face congestion, necessitating more high-rise commercial and residential buildings. With better living conditions, the per capita residential built-up area in cities is expected to rise from 12.6 to 24.2 square meters. Due to high population density, increased trade activities, commerce, and urbanization, metro regions in India are experiencing a significant increase in housing costs. The scarcity and high cost of property and land have led to the need for vertical growth through towering buildings as a solution to accommodate more people, rather than expanding horizontally. The continual migration to metropolitans, limited space, and high population density in cities like Mumbai, Delhi, and Kolkata have led to congestion influx, making high-rise structures a vital requirement in today's society. Mumbai boasts the most high-rise buildings in India, with about 220 skyscrapers and 12,500 built high-rise structures (Nandgaonkar, 2023). Additionally, it is recognized for having the seventh most quantity of skyscrapers globally, as well as the greatest number of skyscrapers now being built. In India, structures that exceed a height of 75 feet or consist of more than 7-10 storeys are referred to as high-rises. Over the last ten years, several major cities in India have become centers for the construction of tall structures, with Mumbai taking the lead, followed by Hyderabad and Kolkata (Studio, 2021). The majority of these towering structures are used for residential purposes. India is the second most populous country globally, and this applies to all of its cities as well. To address the challenges posed by the nation's growing population and the scarcity and high cost of land, the most viable approach is to adopt vertical design and construction methods (Studio, 2021). Two-thirds of India's future residential housing units remain unbuilt, offering an opportunity to opt for energy-efficient design strategies, impacting operational energy consumption and CO_2 emissions for the next 60 to 80 years.

1.2 Building Classification

As per the National Building Code (NBC 2016), buildings in India are grouped into various categories residential, educational, institutional, assembly, business, mercantile, industrial, storage, and hazardous. The Energy Conservation Building Code (ECBC) 2017 (BEE, 2017) as applicable for commercial buildings also provides the classification of buildings based on their functional requirements. Based on this code these buildings can be named as hospitality, healthcare, assembly, business, educational, and shopping complex. Residential buildings can be further classified as lodging and rooming houses, one or two-family private dwellings, dormitories, multifamily apartment houses, and hotels where 50% of the floor space is used for dwelling. As per Eco-Niwas Samhita (ENS), Part-I (BEE, 2018), a residential building is any structure that offers sleeping quarters for standard residential use, whether or not it has a kitchen, dining area, or both. ENS, Part-II (BEE, 2021) further categorizes the building as low-rise, high-rise, affordable housing, and mixed-mode building. A low-rise building is four stories or less or is as tall as 15 meters without stilts and as tall as 17.5 meters with stilts. A high-rise building is defined as one that is four stories or higher, or as one that is 15 meters or higher without stilts and 17.5 meters or higher with stilts.

1.3 The Building Energy Scenario in India and Initiatives to Increase Energy Efficiency

India's increased building energy consumption will likely surge from 1.9 EJ in 2005 to around 8.12 EJ in 2030, a substantial 450% increase (GBPN, 2012). The residential building sector, which is 79.95% of the total housing stock, is the second highest energy-consuming sector after the industrial sector in India. Globally, 10% of world-delivered energy is consumed in residential buildings and the figure is increasing at a rate of 1.5% per year (Chandel et al. 2016). The residential building sector consumes substantial energy in modern urban cities of India both due to improved living standards and increasing population. Out of the total electricity consumed in the building sector, around 75% is used in residential buildings. From 55 TWh in 1996-97 to 260 TWh in 2016-17, the gross annual electricity consumption in residential buildings has been rising sharply by more than four times in a span of twenty years and future projections show that it will reach anywhere between 630-1100 TWh by 2032 (Central Electricity Authority 2017; NITI Ayyog).

The Indian government has implemented measures to enhance building energy efficiency. The Energy Conservation Act, implemented in 2001, resulted in the creation of the Bureau of Energy Efficiency (BEE) and the formulation of the Energy Conservation Building Code (ECBC). The ECBC, introduced in 2007 (BEE, 2007), holds the distinction of being India's inaugural building energy code. This regulation applies to newly constructed commercial structures that have a connected load exceeding 100 kWh or a contractual demand exceeding 120 kVA.

The ECBC offers three techniques for buildings to achieve compliance: prescription, basic trade-off, and whole-building performance. The basic trade-off method permits trade-offs between various elements of the building envelope, whereas the whole building performance approach provides flexibility throughout the entirety of the construction system, provided that the total energy performance is at least equal to or superior to that of ECBC compliance requirements. ECBC compliance is currently mandatory for all major national public buildings.

Aside from ECBC, there exist voluntary initiatives aimed at promoting the construction of energy-efficient and environmentally friendly buildings, including the Green Rating for Integrated Habitat Assessment (GRIHA), Indian Green Building Council (IGBC) rating system, Leadership in Energy and Environmental Design (LEED), BEE Star Rating and GEM sustainability (Green) Certification Rating. GRIHA, a construction rating scheme, is extensively adopted in India. This applies to newly constructed structures that have a total floor area exceeding 2,500 m^2. The eligible structures encompass offices, retail establishments, institutional edifices, hotels, medical centers, and multi-family skyscrapers. The rating system encompasses 34 elements that evaluate site strategy, the use of resources and conservation, building functioning, and innovative designs. GRIHA assesses the effectiveness of a building over its entire lifespan using energy and ecological concepts that are approved nationwide. Its objective is to reduce the environmental effect of buildings and encourage the development of sustainable construction. (GRIHA India, 2016a). The GRIHA Council, established by the Energy and Resources Academy with the backing of the Indian Ministry of New and Renewable Energy, executes the initiative (GRIHA India, 2016b). According to GRIHA, there are now 700 projects enrolled with the GRIHA system. To advance sustainable building methods in India, the Confederation of Indian Industry (CII) includes the Indian Green Building Council (IGBC). IGBC was founded in 2001 and works on creating green building rating systems, offering training, and promoting environmentally friendly building design. The Leadership in Energy and Environmental Design (LEED) India rating system, which is derived from the LEED rating system of the U.S. Green Building Council, is one of the most well-liked certification programs provided by IGBC. While the IGBC has been promoting the LEED India Rating since 2001, projects in India that want to receive a LEED rating can now register with the GBCI as of July 2014. Incentives for green projects certified by the Indian Green Building Council (IGBC) are provided by the central and state governments in twelve Indian states. At present, there are more than 3,480 operational building projects with an IGBC rating. The LEED accreditation assesses a construction's sustainability, water conservation, energy usage, resource management, interior environmental quality, and creativity. This evaluation takes into account the building's whole lifecycle, from design and construction to its upkeep and operation. LEED accreditation applies to several building types, including residential residences and commercial office structures. India has experienced a significant surge in the number of LEED-accredited structures in recent years. India was rated third on the compilation of nations with LEED building certification in 2023. The BEE Star Rating is a voluntary initiative designed to evaluate and classify the energy efficiency of pre-existing commercial structures. The constructions are evaluated using a 1 to 5-star rating system, which is determined by their operational energy use. This refers to the amount of energy consumed per floor-space unit annually. A 5-star rating indicates the highest level of energy efficiency for a structure. Presently, the BEE Star Rating scheme has assessed around 155 buildings (BEE, 2016). To encourage the design and construction of environmentally friendly buildings, ASSOCHAM has introduced the GEM Sustainability Certification Rating Programme. It incorporates recommendations from BEE ECBC 2017 and NBC 2016. Numerous urban developments, including hotels, restaurants, shops, institutions, and industries, are given Sustainability Certification Ratings by the program. Buildings that are new or old can both take part. Based on thirty sustainable development principles, the rating system employs a point scale with a range of 0 to 135 points. Based on the completion of requirements and the scores obtained, projects will be rated at one of five levels, from GEM 1. Green building initiatives and the Energy Conservation Building Code (ECBC) are two ways to improve building energy efficiency, but they work in different ways.

1.4 Major Drivers of Energy Consumption in Residential Buildings

Buildings contribute significantly to global energy use and the resulting emissions of CO_2. Key drivers, like population and income, can be analyzed to determine the primary factors influencing energy consumption. However, locating and obtaining other more precise indicators is challenging and less dependable, as they are challenging to quantify, particularly in developing nations (Ürge-Vorsatz et al., 2015). Some instances include urbanization, floor space, building numbers, occupant counts, equipment inventory, fuel costs, climatic indicators, and cultural and human behavioral factors. The primary factors often taken into account are population, affluence, efficiency, floor space, and climate (González-Torres et al., 2022).

1.4.1 Climate Zones of India

There are five primary climate groups identified by the Köppen Geiger classification (Kottek et al., 2006): tropical, dry, temperate, continental, and polar. India is classified as having a tropical climate. Bansal and Minke (1988) conducted comprehensive research in India and identified six distinct climate zones: hot and arid, warm and humid, mild, cold and overcast, cold and sunny, and mixed. The categorization criteria are outlined in Table 1.1. A location is classified into one of the initial five climatic zones if the specified conditions persist there for a duration exceeding six months. If none of the specified categories can be determined over six months or more, the climatic zone is designated as composite.

Table 1.1: Climate Zone Criteria

Climate Zones	Mean Monthly Temperature (C)	Relative Humidity (%)	Precipitation (mm)	Number of Clear Days
Hot & Dry	>30	<55	<5	>20
Warm & Humid	>30	>55	>5	<20
Moderate	25-30	<75	<5	>20
Cold & Cloudy	<25	>55	>5	<20
Cold & Sunny	<25	<55	<5	>20
Composite	When six months or more do not fall within any of the above categories			

[Source: Bansal & Minke, 1988]

India has been categorized into five primary climatic zones, as per the National Building Codes, 2005 (NBC, 2005). This alteration in classification is similar to the previous one, with the exception that the cold and overcast, and cold and sunny climates have now been categorized as cold climates. The term ‘moderate climate’ has been officially designated as ‘temperate climate’ (BIS, 2005). Figure 1.2 illustrates the distinct Indian climate zones.

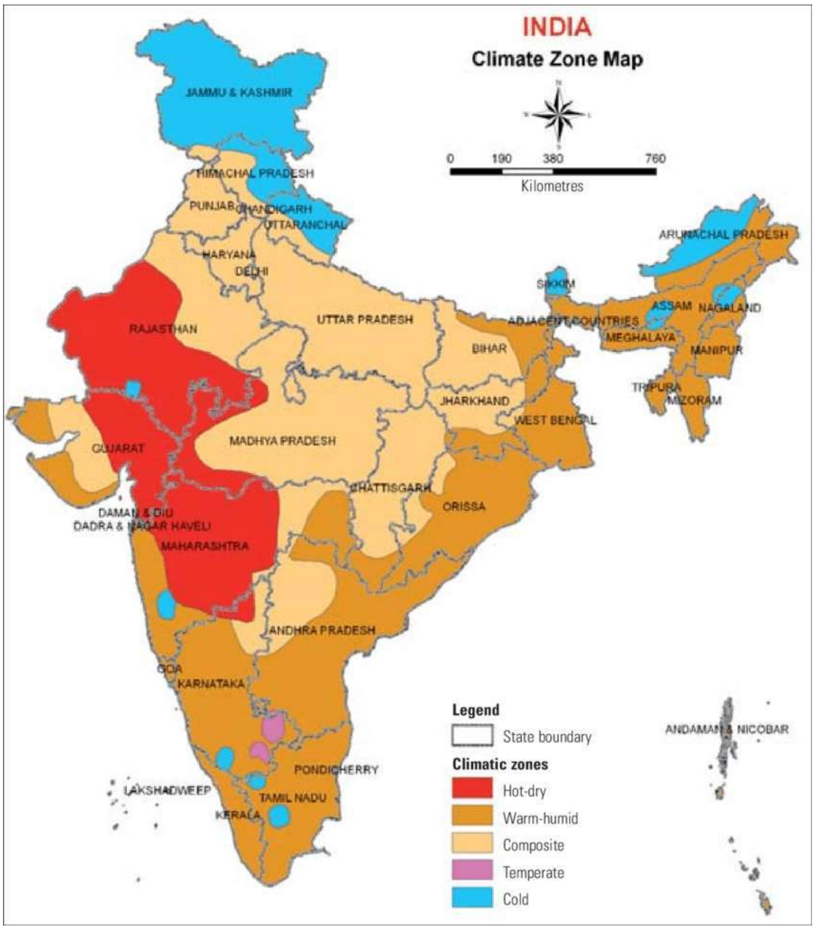


Figure 1.2: Map showing climatic zones in India

[Source: Singh et al., 2011]

In the Hot and dry climate, the diurnal temperature variations are high due to low relative humidity levels. Warm and humid climates are characterized by the presence of high relative humidity in the air with smaller diurnal temperature variations. Temperate or moderate climates are characterized by seasonal variations in heating and cooling demands that are not extreme. In cold climate conditions mean monthly temperature goes less than 25°C. In general, the composite climate is characterized by severe summers and winters as well as a unique monsoon season that brings with it a significant amount of rainfall.

Nevertheless, the NBC climatic zone classification solely considers outdoor circumstances and does not take into account factors such as inside temperature and RH, which are crucial for assessing building and occupant comfort. Globally, Cooling Degree Day (CDD) along with Heating Degree Day (HDD) have traditionally served as widely accepted measures of the cooling and heating demands resulting from outside temperature fluctuations. Based on the metrics of CCD, HDD, and yearly mean relative humidity, India has been classified into eight climate zones. (Bhatnagar et al., 2019).

1.4.2 Thermal Comfort and Cooling Demand

In tropical regions like India, it is crucial to take out heat from built space to ensure occupant thermal comfort. HVAC system play significant role in achieving occupant thermal comfort, but they consume a large amount of energy (Che et al., 2019). On the other hand, in such tropical temperatures, housing segments need to decrease their energy use to lower electricity demands (Kwong et al., 2014). This can lead to complications in balancing the need for thermal comfort as well as building energy efficiency, especially in a building that strives to minimize cooling energy consumption through various green initiatives. Thermal comfort has a direct impact on a building energy consumption because any discomfort felt by the occupants causes the cooling load to change. Correct climate characterization and the current definition of comfort boundary constraints are essential for building designers when designing and constructing projects (Belkhouane et al., 2017). The regulation of climatic conditions is a significant determinant of human existence, welfare, and physical well-being. The primary objective of building early-stage design is to optimize the utilization of favourable climate conditions at each project site by employing passive and bio-climatic design techniques. This approach aims to attain thermal comfort while minimizing reliance on active systems (Attia et al., 2019). Typically, it is impossible to achieve summer-time as well as winter-time comfort in buildings just by using passive and bio-climatic designing strategies. Hence, mechanical engineers employ active elements, like cooling and heating mechanisms and ventilation systems, to address the periods of cooling or heating needs. India is predicted to have approximately 1 billion air conditioners (or 1,144 million units) by 2050, up from about 36 million in 2018. (IEA, 2021). The India Cooling Action Plan (ICAP) estimates an 11-fold increase in cooling demand due to the growing built space of the building sector compared to baseline 2017-18 and hence targets a reduction of cooling demand across sectors by 20-25% by 2037-38 (MoEF&CC, 2019).

1.5 Driving Policies for Residential Building Energy Efficiency

The exponential increase in global energy consumption has already sparked fears over issues of availability, the loss of energy resources, and significant environmental consequences such as the loss of the ozone layer, global warming, and a changing climate. The proportion of energy use attributed to buildings, including residential as well as business sectors, has consistently risen on a global scale. The coming years will see a continued increase in energy demand due to factors such as growing populations, higher expectations for building services, improved comfort levels, and the tendency to spend more time indoors. Improving building energy efficiency has become a primary emphasis in energy policies at global, national, and local levels. It can be noted that 158 out of 196 countries mention buildings in their NDCs, according to the GlobalABC 2022 Global Status Report (GSR) (UNEP, 2022). Given that over 50% of India's total floor area remains undeveloped, implementing rules that specifically focus on enhancing energy efficiency in new constructions will have a significant and far-reaching effect. The National Mission for Enhanced Energy Efficiency was implemented by the government in 2009 as a component of the National Action Plan on Climate Change. The Mission initiated nationwide initiatives to enhance energy efficiency in many sectors and underscored the importance of building energy effectiveness and related legislation such as the ECBC. The ECBC establishes the minimal energy efficiency standards for new, sizable commercial structures. To attain the desired energy conservation, it is crucial to efficiently execute the ECBC (Yu et al., 2017).

Energy Conservation Building Code, also known as Eco-Niwas Samhita (ENS) Part I (Building Envelope), was introduced by the Bureau of Energy Efficiency in December 2018 in recognition of the significance of energy efficiency in residential buildings (BEE, 2018).

ENS Part-II was subsequently introduced in 2021, with a focus on electro-mechanical and renewable energy systems (BEE, 2021). Part I of the ENS has been prepared to establish minimum building envelope performance standards that will ensure proper natural ventilation and daylighting, while also limiting heat gains and losses in hot and cold climates. All residential buildings constructed on plots larger than or equal to 500 m^2 are covered by this. The ENS Part II code covers aspects of building service such as energy efficiency in electro-mechanical equipment for building operation, active thermal comfort requirements, and renewable energy generation. The BEE has developed an energy efficiency label for residential buildings to provide a benchmark to compare one house over the other on the energy efficiency standards. It is expected that 5-star rated homes will be 40% more energy efficient compared to 1-star rated homes.

1.6 Building Energy Environmental Impact

The building industry plays a crucial role in the energy system and is responsible for over 30% (with regional variations ranging from 21%-56%) of the world's final energy use (Li et al., 2019). The substantial consumption of building energy has posed significant problems to sustainable development, including the disruption of dependable energy supply, the escalation of GHG emissions, and the exacerbation of pollutants in the air (Varbanov et al., 2018). Hu (2023) carried out a detailed analysis of residential buildings in the United States by accounting for their associated embodied carbon emissions. Their finding highlighted the embodied carbon intensity of multifamily housing buildings, with an average of 144 kgCO2eq/m^2/yr. According to Shadram et al. (2016), embodied energy may make up as much as 60% of the total energy consumed by a building. According to Herztwich et al. (2020), the international resource panel has pointed out the potential for reducing greenhouse gas emissions from efficient material centric strategies applied throughout the building stock with a careful design approach. The urban heat island (UHI) generally refers to the phenomenon of local heating in city regions, where over 50% of the global population resides. The warming caused by this UHI is in addition to the climate change-induced warming and is responsible for relatively higher temperatures in urban areas. Studies have shown that UHI can result in higher building cooling energy consumption, having an overall impact on building energy usage (Salvati et al., 2017; Li et al., 2019). Building material manufacturing and CO2 emissions from building operations account for about 37% of global energy-related emissions. (IEA, 2021a). The building sector has a pivotal role in global decarbonization for net zero pathways.

1.7 Building Energy Modeling and Simulation

Due to the rising demand for operational energy in buildings, there is a growing interest in designing structures that are not only resource-efficient but also energy-efficient. To accomplish this, early design stage building modeling and energy simulation are widely used to assist developers in making optimal selections and opting for the most energy-efficient, cost-effective alternatives for design. Building energy simulations are becoming a more accepted tool for analysing building energy efficiency as well as occupant thermal comfort (Zerroug & Dzelzitis, 2015). Currently, there is a wide range of building simulation software available, each with its own user interface and simulation engine, that can be utilize to perform these studies depending on building functional requirements and modelling complexities. It is crucial to realise the limitations and complexity of building energy simulations due to the dynamic nature of external environments, the services used, and the significance of these simulation platforms.

The dependability of data transmission intuitive, user-friendly interfaces, and simulation run time are key factors in the practical application of these instruments. To achieve faster and more consistent execution of simulation tools, it is essential to have effective user input interchange and programming interfaces. This is particularly important due to the large volume of data that needs to be entered and the accessibility of advanced 3D geometry modeling engines (Crawley et al., 2008). The BEE-approved building energy modeling and simulation software named eQUEST is widely utilized by the building simulation group and Indian rating agencies, making it among the most widely used programs in this field. This simulation software is used in the present study.

1.8 Technoeconomic Features and Risk Associated with Building Energy Analysis

The implementation of technology-driven energy-conservation solutions in practical scenarios remains a challenge due to peoples' lack of awareness regarding their energy use and efficacy. As a result, they are incapable of implementing energy-saving measures as targeted. Furthermore, the initial expense of installing and implementing these measures for end-users remains a significant barrier. However, it is essential to perform a techno-economic evaluation (Himeur et al., 2022) when creating and marketing an innovative energy efficiency system. This assessment will determine the system's potential for success with user acceptance. Along with the technical review and validation, it is imperative to undertake a comprehensive analysis of the factors, drivers, obstacles, risks, potential, and possible options available in the energy-saving industry. Despite a surge in the growing number of energy-efficient constructions, the expansion of this in scale appears to be less robust than anticipated. In 2008, the US saw a mere 10% of non-residential building projects beginning with a focus on energy efficiency (Ashuri & Durmus-Pedini, 2010). One of the main obstacles in the growth of the energy-efficient construction industry is the risk associated with actual performance, which is compounded by challenges such as monetary feasibility, public knowledge of environmental issues, and governmental constraints. Performance risk denotes the gaps between the design phase's intended energy performance and the actual real-life energy performance once the building is occupied and becomes operational. This risk associated with energy-efficient built space developments are come from the uncertainties and fluctuations associated at various levels and components, such as early conceptualization, integrated engineering, building modeling, design assumptions, construction practice, erection, building service system equipment selection, installation, commissioning, and post occupancy uses. Additionally, other external factors like energy policy and energy supply costs also contribute to these risks (Sun et al., 2016). One of the biggest techno-commercial challenges in adopting evolving energy efficiency measures is addressing the uncertainties involved in estimating return on investment (ROI) and life cycle cost analysis.

1.9 Broad Research Area

The identified research areas cover a wide range of critical questions that are essential to the improvement of energy efficiency and sustainable building practices. Through exploring the context of residential buildings in urban areas such as Kolkata, the aim is to handle complex issues and customize energy efficiency solutions to meet local design requirements, ultimately promoting energy efficiency, sustainability, and affordability. Emphasizing the critical role of regulatory frameworks like the recently announced Eco-Niwas Samhita (ENS) Code, investigations aim to explore the practical impacts and efficacy of such landmark initiatives in promoting environmentally conscious, energy efficient building. Moreover, scrutinizing building envelopes external wall construction materials and assemblies, operational energy, embodied energy, environmental performance, and economic feasibility underscores the multidimensional nature of sustainable development. Additionally, critical analysis of residential energy conservation building codes serves as a foundation for refining regulatory mechanisms and guiding future code adoption, ensuring that built space sustainability remains a cornerstone of the construction industry’s trajectory. By means of multidisciplinary inquiry and empirical investigation, these research fields provide a path towards significant progress in the design and development of sustainable building, which will ultimately lead to a more resilient and energy efficient building.

1.10 Significance of the Study

Recognising the pressing need for sustainable practices in the fast-growing construction industry, particularly in the domain of urban residential buildings, the significance of this study resonates profoundly. At its core lies a careful examination of the Eco-Niwas Samhita Code, a milestone initiative poised to transform residential building energy conservation and mitigate built space greenhouse gas emissions. With an estimated 120 billion kWh of electricity savings and a resulting 100 million tonnes of CO2 emission reduction, this initiative is expected to have a significant impact from 2018 to 2030, which highlights its potential to influence future environmental policies and building codes. This energy conservation measure applies especially to residential buildings equipped with air conditioning as an active space cooling measure. If unconditional residential buildings meet the thermal transmittance value of the Eco-Niwas Samhita, internal thermal comfort conditions would be significantly improved (Bhanware et al., 2019). This study will provide significant inputs by way of critical influencing parameters, exterior wall assemblies, and impact analysis of new energy conservation building codes. The growing utilization of air conditioning in multi-storied residential group housing projects, along with the increasing use of façade materials that result in a larger building envelope and consequently higher energy consumption, could lead to a widening gap between rising power demand and diminishing supply. The study, therefore, suggests ways to reduce energy consumption by using combinations of wall and air conditioners and suitable façade materials for the best energy and economic performance - a goal towards achieving low carbon, yet a comfortable built environment.

Chapter 2

Literature Review

2.0 Introduction

A detailed literature review is carried out to explore the existing state-of-the-art knowledge and identify the potential research gap to assess and improve residential building energy performance. In this review, several aspects of energy-efficient design strategies related to residential buildings are explored and will be discussed in separate sections and subsections below. The review process includes four main phases. First, a literature search and screening using relevant keywords were performed. By setting the inclusion and exclusion criteria, a significant number of papers are shortlisted for detailed review. In the third step of segmentation, the extraction of relevant data related to residential buildings or having importance for this current research work was done. Later, analysis of results from the screened literature, synthesis, and summarization of the collected data and results were done. The framework for the literature review is presented in Fig. 2.1.

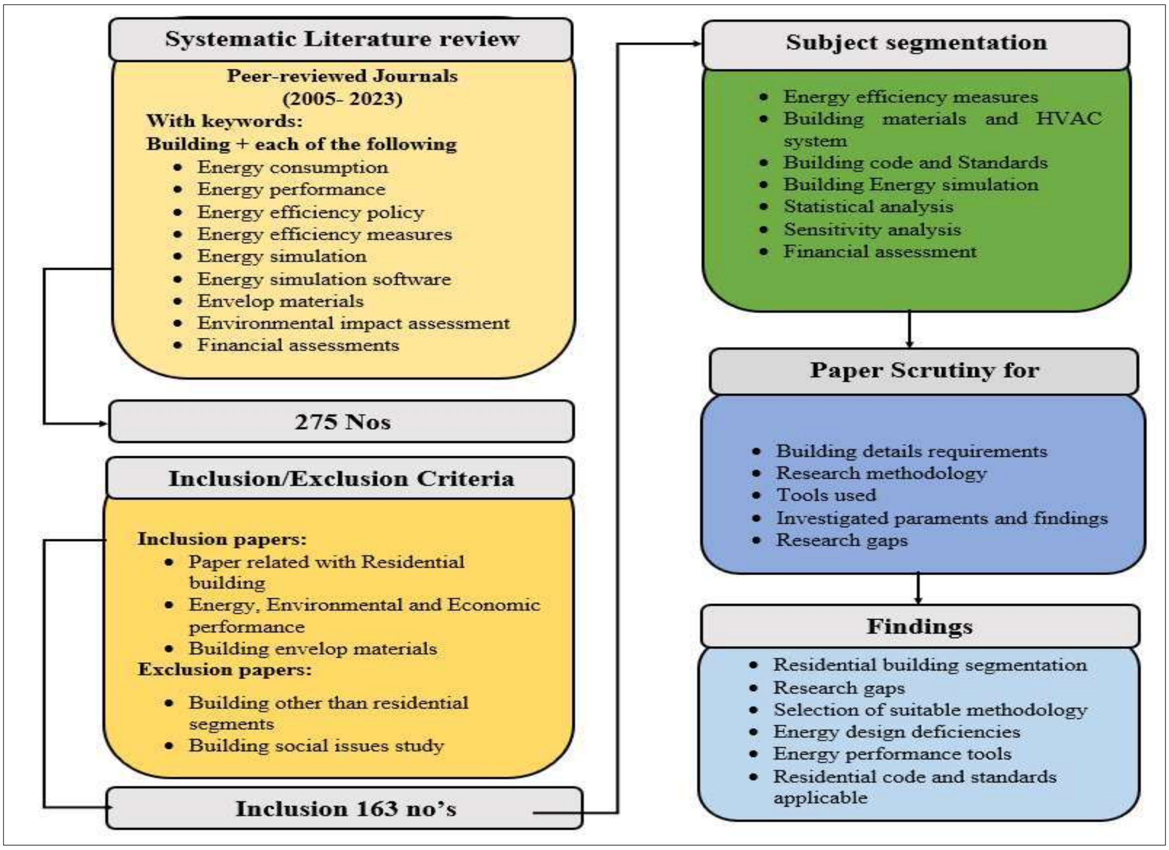


Figure 2.1: Literature Review Framework

2.1 Factors Influencing Residential Building Energy Consumption

The EBC-IEA report (Yoshino et al. 2017; Du et al. 2020) classified impacting factors on building energy consumption, as the local environment, technology, physical aspects, building attributes, and infrastructure for service, human-based, and social. Other factors driving energy consumption are internal and external illumination, household hot water, preparing food, ventilation, air conditioning, and heating, along with other devices in a residential building that consumes energy (Hu et al., 2017; Sakah et al., 2019). Human-based variables include building upkeep and operation, resident behaviour, and interior environment conditions. Usage of structural openings, illumination, and shading equipment, HVAC services (on-off state and setting point temperature), heated water, and electrical gadgets are essential resident activities. Energy consumption of gadgets can be categorized by their operating schedule and specifications, while plug-ins can be categorized by their type and count (Calì et al., 2016; Yao and Zhao 2017; Feng et al. 2016; Fan et al. 2015; Xie et al. 2016; Guo et al., 2018). Residents' habits may decide an area's occupancy pattern. The predicted mean vote (PMV) and interior temperature can assess interior environmental effectiveness. Social aspects comprise energy-related views and demography. Self-identified energy-saving activities can measure resident energy views (Fan et al., 2015; Azar and Al Ansari 2017). Additionally, occupiers' building system information affects their behaviour and domestic energy usage (Zhao et al., 2017). Family structure, earnings slab, and education are also factors (Sanquist et al., 2012; Fan et al., 2015; Huebner et al., 2015; Xie et al., 2016). Residential building energy research has become complex compared to other segments of buildings due to its diverse building stock, behavioural factors, ownership and tenure, upfront cost, occupant education, and awareness, and retrofit challenges during the building lifecycle. Excess variables make such research expensive and inaccurate to some extent. The major objectives used in the previous analysis are discussed in Table 2.1.

Table 2.1: Building Types and Objectives of Study

Authors (Year)	Building Types	Objective of the Study	Findings
Chen et al., 2024	Residential buildings	Carbon emission inequality analysis	Stress the importance of city-level emission mapping for customized indigenous solutions to cater to heterogeneity.
Ahmadi et al., 2024	Residential buildings	Energy Standard Compliance	The study demonstrated various scenarios for 2030–2050 energy consumption and reported a

			15.7%–38% CO_2 emission mitigation potential.
Agarwal et al., 2023	Residential buildings	Energy consumption feedback	The study reported 5 to 20% energy savings due to consumer feedback by narrating the significance of human behaviour.
Mujeebu et al., 2022	Residential buildings	Energy saving and cost for energy saving measures	A 63.5% EPI reduction was demonstrated with various energy efficiency measures with a payback period of 4.94 years.
Mostafavi et al., 2021	High Rise Residential buildings	Energy efficiency and emission	This review study demonstrated that envelope design enhancement has the highest energy-saving potential, up to 78.9%, and also points to the scope of embodied carbon along with operational emission reduction for high-rise development.
Economidou et al., 2020	Residential and non-residential buildings	Energy efficiency policies	This 50-year policy review concludes that building standards stringency and additional specific policies initiated by governing authorities yield a significant reduction in energy consumption and overall ecosystem upliftment for energy efficiency.
Li et al., 2019	Residential and non-residential buildings	Energy performance certification	Highlighted the importance of certification, awareness, and a strong data base to customise the solution for the energy performance of buildings.
Garg et al., 2019	Residential buildings	Energy efficiency	Discuss the various energy efficiency initiatives and associated barriers by highlighting the importance of national-level data collection and capacity building, including climate-specific research.
Graham et al., 2019	Residential and non-residential buildings	Potential of India Building sector	This study pointed to the continuous evaluation of energy standards, policies, and their adoption for low-carbon buildings at all levels.
Karunathilake et al., 2018	Residential buildings	Energy demand reduction	Reported the importance of seamless collection of all demand reduction strategies and effective communication with sustainable design communities.
Calero et al., 2018	Residential buildings	Building thermal system energy consumption reduction	The study reported that occupant awareness and renewable energy integration are key drivers for energy savings rather than replacing boilers.
Zou et al., 2018	Residential and non-residential buildings	Lifecycle approach for energy performance gap	The review work reported the gap between energy simulation and actual consumption in real life, with an open question for future research for performance validation and an interdisciplinary

			effort for building energy research investigations.
Berardi et al., 2017	Residential and non-residential buildings	Energy consumption comparison for cross country	Developing nation energy policy applicable to building is not sufficient to check their doubling energy demand and need for techno-economic analysis of the best possible design solution highlighted with all stakeholder awareness for any code and standard success.
Franco et al., 2017	NA	Energy consumption and emission due to urbanization	The consequences of urbanization were reviewed in this study, and the designed policy measures to reduce energy intensity and emissions were narrated.
Nejat et al., 2015	Residential buildings	Energy, emission, and policy status	An analysis of the top ten emission defaulter countries residential sector policy measures was investigated with actual performance status and pointed out that mandatory compliance yields a better outcome compared to voluntary adoption, as noted in the case of developing nations.
Fumo et al., 2014	Residential and non-residential buildings	Building model development for energy estimation	The significance of whole-building energy simulation as tools for accurate simulations of options to investigate their potential for reducing emissions and energy savings was described in this review paper.

2.2 Energy Conservation Building Codes

Different countries and organizations across the world have set building energy codes and standards to enhance energy conservation and efficiency in the built environment. Energy usage is high in emerging economies like India because of a stable economy and growing population. In the 1970s, India was anxious about energy conservation along with many countries due to a global oil crisis arising out of the 4th Arab-Israel war. Energy conservation was unimportant during the first fifteen years after independence (Verma & Jakhar, 2016). The Gazette of India released the "Energy Conservation Act, 2001" after the bill passed. In 2002, the Energy Management Bureau became the "Bureau of Energy Efficiency (BEE)", and the 2001 act made BEE an official entity under the Department of Power with regulatory authority to enforce act recommendations (Verma & Jakhar, 2016). In India, the process was initiated through the introduction of the Energy Conservation Building Code (ECBC) in 2007 by the

Bureau of Energy Efficiency (BEE), Government of India targeting commercial buildings. The code was recently revised and updated in the form of ECBC 2017.

The suitability and performance of building energy codes have been extensively studied worldwide. Different codes such as ISO 9164, EN 832, GB 50189 of China, TS 825 of Turkey, Code 19 of Iran, and German Regulations are compared by Fayaz and Kari (2009). Papadopoulos (2016) studied the achievements and challenges of regulating building envelope thermal performance in Europe over forty years. The implementation practice of building energy codes was studied across twenty-two countries (Evans et al., 2017) and the international implications of national and local coordination regarding the codes were further investigated for six different cities (Evans et al. 2018). A review of the building energy consumption, policies, rating schemes, and standards across different countries has been carried out by Lu and Lai (2019). A detailed review and comparison of different occupant-related aspects of twenty-three different building energy codes across the world has been done by O'Brien et al. (2020) to observe significant variations. Schwarz et al. (2020) identified innovative designs in building energy codes of Denmark, France, England, Switzerland, and Sweden for building decarbonization. The distributional consequences of building energy codes were evaluated by Bruegge et al. (2018) for home characteristics, energy use, and home value. Gaps are observed between actual, calculated and code-predicted building energy performances for California houses (Levinson, 2016) and Chinese households (Wang et al., 2019) maintaining energy efficiency standards. Annual energy savings of 12-21% from BIPV window and light dimming systems were evaluated for IECC code-compliant buildings in hot-humid climates (Do et al. 2017). Kalhor and Emaminezad (2020) carried out an optimization study with conventional thermal insulation materials following energy efficiency codes.

2.2.1 Energy Conservation Building Code for Commercial Buildings – ECBC 2017

Several studies have been carried out regarding the code provisions, strategies, and policies undertaken to increase building energy efficiency in different climate zones of India. The energy savings potentials through the implementation of the Energy Conservation Building Code have been investigated for six different commercial buildings (Tulsyan et al., 2013) and three categories of hotel buildings (Chedwal et al., 2015) in Jaipur, India. Chandel et al. (2016) carried out a detailed review of energy efficiency initiatives and regulations for residential buildings in India. A State-level analysis of building energy efficiency policies to improve building energy efficiency in India has been carried out by Yu et al. (2017). Bano and Sehgal

(2018) evaluated energy-efficient design strategies in terms of the thermal performance of high-rise and mid-rise office buildings in a composite climate. Bhatnagar et al. (2019) proposed a methodology for the development of reference building models in the Indian context by studying 230 low-rise and high-rise office buildings. Despite the current policy framework, India's energy demand is expected to double by 2040. Under this light early-stage design strategies for energy efficiency and its mass adoption in real life is a paramount concern.

2.2.2 Energy Conservation Building Code for Residential Buildings – Eco-Niwas Samhita 2018, Part-I

The residential sector floor space in India is expected to increase from 15.3 billion m^2 in 2017–18 to 21.9 billion m^2 in 2027, according to a study done by the Alliance for an Energy-Efficient Economy (AEEE) (Kumari et al., 2021). The residential building consumed 75% of India's electrical production in 2017–2018, according to BEE's yearly report. Realizing the importance, in 2018, BEE introduced the first part of the Energy Conservation Code for Residential Buildings (Eco-Niwas Samhita, 2018, Part-I). It fixed minimal building envelope parameters impacting (Eco-Niwas Samhita 2018, Part-I) heat gain/loss, natural ventilation, and illumination standards. Code assessment in real words Energy performance improvement is yet to be done, as hardly any studies have been reported. More details about this code are discussed in Chapter 4.

2.2.3 Star Labelling for Air Conditioners

Residential air conditioners must meet minimum energy performance standards set by various nations through their energy efficiency regulations. These standards encourage the market to develop benchmarks for energy-efficient products while also assisting households in reducing operational energy use. There is a significant opportunity for tropical countries to increase the effectiveness of their regulations through labelling, RAC ratings, etc. Andrade et al., 2021. Currently, about 85% of the global energy consumption for space cooling is governed by mandatory standards for air conditioners. More than 20 countries are developing additional standards, while Australia, Brazil, China, and India have recently strengthened their standards and star labelling (IEA, 2021; Abhyankar et al., 2017; BEE, 2018; Kumar et al., 2021; BEE; 2021). The star labelling program for room air conditioners (RACs) started as a voluntary initiative by the Bureau of Energy Efficiency (BEE) in India in 2006 and became subsequently mandatory in 2009. Every two years from 2009 to 2018, BEE updated energy performance thresholds for RACs. In 2015, BEE introduced voluntary labelling for inverter RACs, which became mandatory from January 2018 until December 2020. The improved rating methodology introduced in 2018 considered operating hours and temperature variations across India's climatic zones. The Indian seasonal energy efficiency ratio (ISEER) determines cooling energy consumption proportionally for different seasons. From July 2022 to December 2024, the updated RAC energy consumption standard has been effective with a revised value of ISEER (Abhyankar et al., 2017; BEE, 2018; Kumar et al., 2021; BEE; 2021). Investigation into its impact on building operational energy savings is crucial for more real-life adoption and future star labelling program improvement. A summary of previous literature analyzing this code and similar standards of various countries across the globe is given in Table 2.2.

Table 2.2: Reviewed Literature about Building Energy Codes and Standards

Authors (Year)	Country	Building Type	Findings
Allard et al., 2021	Finnish, Norwegian, Swedish, and Russian	Residential buildings	Nation specific standard has an important influence on building's specific energy use with expectation of more stringent code
O'Brien et al., 2020	23 countries like Australia, Austria, Belgium, Brazil, Denmark, England, France, Germany, India, Italy, New Zealand, Singapore, South Korea, Canada, USA, UAE, China etc. codes or standards were reviewed	Office building and other all type of buildings	Highlights the need of more research by accounting country specific occupant-related values, approaches, and system.
Wang et al., 2019	China	Residential buildings	Building Energy Efficiency Standards (BEES) compliance buildings achieved a 41% reduction in cooling and heating electricity usage.
Aydin & Brounen, 2019	Europe	Residential buildings	Household appliance leveling regulation results in a 0.24% annual electricity use reduction per capita.
Chandel et al., 2016	17 countries including India	All type of buildings	Effectiveness of code depends on availability of detailed technical methodology, regulatory structure, and enforcement effectiveness with scope to improve code though regular assessment.
Barkokebas et al., 2019	Canada	Residential buildings	Impact of code on energy consumption along with construction cost analyzed with finding that code compliance approach holds key.
Enker et al., 2017	Australia	Residential buildings	Study signifies the code importance and its practical application

2.3 Building Envelope Materials

Amongst different wall masonry materials, burnt clay bricks have been the most popular over the later part of human civilization, though possessing serious sustainability concerns owing to the consumption of non-renewable resources, greenhouse gas (GHG) emissions, and waste creation during production (Pacheco-Torgal et al., 2011). This resulted in the study and development of burnt bricks with different industrial wastes such as fly ash, oil wastes, marble waste mud, optical waste glass, organic wastes, granite powder, phosphor-gypsum, paper processing residues, river sediments etc, instead of virgin clay to make the product more sustainable (Lingling et al., 2005; Monteiro et al., 2005; Saboya et al., 2007; Lin et al., 2007; Demir et al., 2008; El-Mahllawy et al., 2008; Pinheiro et al., 2009; Ajam et al., 2009; Chiang et al., 2009; Sutcu et al., 2009; Samara et al., 2009). Researchers have also assessed and proposed sustainable and low embodied energy alternatives to burnt clay bricks such as mud concrete blocks, cement stabilized earthen blocks (CSEB), autoclaved aerated concrete (AACB) blocks, etc. (Udawattha et al., 2018; Gurupatham et al., 2021; Sadati et al., 2023). Studies regarding different material composites to replace traditional masonry walls from the sustainability viewpoint are also emerging, showing a significant reduction in energy consumption. Examples include recycled expanded polystyrene (EPS), foam concrete wall panels, multilayer hollow clay walls filled with insulation materials, optical fibre based translucent concrete (OFTC), etc. (Dissanayake et al., 2017; Chihab et al., 2022; Su et al., 2023. Different researchers have also explored the sustainability and energy savings potentials of Phase-Change Materials (PCM) and found encouraging results (Memon et al., 2014; Sinka et al., 2019; Abden et al., 2022).

The past decade saw space-cooling energy demand in residential buildings growing at over twice the rate of overall energy demand. A study by Randazzo et al. confirmed efficient air conditioner installations as a nationwide strategy against rising average temperatures due to climate change as each household with an AC uses 35% to 42% more electricity (Randazzo et al., 2020). Recent developments by room air conditioner (RAC) manufacturers show a significant increase in the efficiency of their several commercial products (Shah et al., 2017). Krarti and Howarth (2020) carried out a cost-benefit analysis of transitioning to high-efficiency ACs for residential buildings in Saudi Arabia and estimated an annual reduction of 33 TWh in electricity consumption and 24 million tons of CO_2 emission. Mujeebu and Bano (2022) assessed the energy-saving potential and cost-effectiveness of different active EEMs, including efficient ACs for a residential building in the warm humid climate of southern India, and estimated the possibility of 63% savings in EPI. Zhang et al. (2022) critically analyzed the impact of energy efficiency upgrades for air conditioners on residential electricity consumption in China and found that reduced AC-related energy consumption for individual households may eventually raise the total electricity consumption of the residential sector by increasing the AC purchase and use due to increased affordability. A study by Ali et al.(2022) estimated the potential energy savings of 11.6 TWh and CO_2 emissions reduction of 7.1 million MT over a 10-year cycle for Pakistani residential buildings through improvements in air conditioner energy efficiency. The scenario of the adoption of stricter energy efficiency standards for residential air conditioners in Guayaquil, Ecuador has been analyzed by Porras et al. The study found stricter MEPS can potentially reduce associated electricity demand and emissions between 5.7% and 31% respectively.

The use of masonry units began in the form of stone pieces and sun-dried mud bricks around 8000 BC in Mesopotamia (Torgal and Jalali, 2011), and by 4000 BC these were started being used to build palaces and temples there (Allen and Iano, 2019). Egyptians used stones as masonry units in building their temples and pyramids (Allen and Iano, 2019) while Harappans used dried and baked mud bricks extensively in the Indus Valley civilization around 3000 BC (New World Encyclopaedia). The evolution to fire-clay bricks also happened around the same time (Lynch, 1994). Since then, masonry units have seen many stages of evolution over the last five thousand years, the recent important ones being the machine quarried and worked stones and molded bricks during the Industrial Revolution, 19th Century invention of the hollow concrete blocks, early 19th Century introduction of brick cavity walls, still reinforced masonry of 20th Century and many more recent developments (Allen and Iano, 2019).

The environmental impact of fired-clay bricks, which dominated the history of masonry units lately, has always been of great concern because of non-renewable resource consumption, energy consumption, water consumption, greenhouse gas (GHG) emissions, and waste generation (Torgal and Jalali, 2011). The rising environmental concern has resulted in the study and development of fired-clay bricks with different industrial wastes such as fly ash (Lingling et al., 2005), oil wastes (Monteiro and Vieira, 2005; Pinheiro and Holanda, 2009), marble waste mud (Saboya et al., 2007), optical waste glass (Lin, 2007), organic wastes such as saw-dust, tobacco residues, grass (Demir, 2008) granite powder, kaolin, and blast furnace slag (El-Mahllawy, 2008), phosphor-gypsum (Ajam et al., 2009), rice husk (Chiang et al., 2009), paper processing residues (Sutcu and Akkurt, 2009), river sediments (Samara et al., 2009); all reducing the consumption of virgin clay to make the product more sustainable.

The concern for high energy consumption in producing fire-clay bricks also advanced the development of different low embodied energy non-fired bricks and blocks lately (Torgal and Jalali, 2011). Udawattha and Halwatura (2017) analyzed the life cycle cost of different walling materials such as brick, hollow cement blocks, and mud concrete blocks used for affordable housing in the tropics and found the latter as the most sustainable one. Gurupatham, et al. (2021) through a survey-based approach ranked cement stabilized mud blocks (CSEB) as more sustainable compared to burnt clay bricks and cement sand blocks, using eco-efficiency for tropical climatic conditions. Sadati et al. (2023) have studied the effect of wall materials like AAC block, LECA block, extruded polystyrene, etc. on the energy, environmental, and economic performance of an Iranian building and found reduction potential for annual heating and cooling loads as well as carbon dioxide emissions by up to 23.2 %, 26.4 %, and 18.5 %, respectively.

Some recent studies reviewed the ongoing developments in the field of sustainable wall options with a particular focus on energy and environmental perspectives (Torgal and Jalali, 2011; Mostafavi et al., 2021; Maier, 2022). Studies regarding different material composites to replace traditional masonry walls from the sustainability viewpoint are emerging. Dissanayake, et al. (2017) carried out a comparative embodied energy analysis of a house with recycled expanded polystyrene (EPS) based foam concrete wall panels along with traditional burnt clay bricks and cement sand blocks. The dynamic thermal performance of multilayer hollow clay walls filled with insulation materials in hot climates has been studied by Chihab et al. (2022). A total thermal load reduction of 28% was demonstrated by walls with 100% insulation-filled cavities compared to walls with air-filled cavities. Su et al. (2023) studied the effects of daylight on the energy performance of the combination of optical fibre-based translucent concrete (OFTC) walls and windows. They found that the combination of OFTC walls and windows can lower net electricity use by 32.07% and compared it to the combination of conventional concrete walls and windows.

Memon (2014), has conducted an extensive review of different studies regarding the use of Phase-Change Materials (PCM) in building walls. PCM could be incorporated into construction materials and elements by direct incorporation, immersion, encapsulation, shape stabilization, and form-stable composite PCM. The study discussed the differentiation between shape-stabilized and form-stable composite PCMs, the use of various construction materials as supports for form-stable composite PCMs, the test methods used to determine the chemical compatibility, thermal properties, thermal stability, and thermal conductivity of the PCMs, and integration of PCM in wallboards and concrete for building applications. Sinka et al. (2019), experimentally tested PCMs in a warm-summer humid continental climate and found that complex control systems are necessary to use the same with the highest efficiency. Abden et al. (2022) studied the combined use of PCM and thermal insulation to improve the energy efficiency of residential buildings in different climate zones of Australia and saw an improvement in their energy ratings by 3.5-4.8 stars with payback periods of renovation ranging between 2.2-7.5 years. In comparison to conventional bricks, a temperature drop of 4 °C to 9.5 °C is noted across single and dual PCM layer bricks (Saxena et al., 2020).

Many studies have examined how passive design could boost building energy performance in hot-humid climates. Natural ventilation is age-old best passive design method for improving thermal comfort within buildings in such climates (Chen et al., 2017; Zhang et al., 2022). Increased opening size along with ventilation pathways are key to improving natural ventilation in hot-humid climates (Chen & Yang, 2017). The shading situation and exterior wall U-values usually increase cooling energy usage (Kwok et al., 2017). Studies show that passive design solutions alone cannot provide household building cooling needs in hot-humid climates (Kwok et al., 2022). Both thermal comfort and AC electric bills are important for low/middle-income households. Hot to humid cities have contradictory design goals. In such climates, thermal comfort solutions may increase cooling energy use (Gao et al., 2024), discouraging financially constrained occupants.

2.4 Building Energy Simulation

Building operational energy estimation at the early design stage is key to deciding the various design strategies. This required the necessary tools, methods, and ways to represent the building virtually for the necessary analysis of various alternate options at the design stage itself. As programming has advanced, building simulation programs like BLAST, DOE2, eQUEST, EnergyPlus, and TRNSYS, which incorporate virtual building models representing actual buildings, have swiftly evolved into visualization tools featuring graphical user interfaces (Pan et al., 2023)). Due to its quick simulation capacity and easy user interface offered by eQUEST, high-rise residential modeling gives it an advantage compared to design-builder and EnergyPlus software. A summary of various literature that details different building energy simulation software is presented in Table 2.3.

Table 2.3: Reviewed Literature about Energy Simulation Software

Authors (Year)	Tools / Method Used	Objective / Advantage	Limitation / Findings
Shen et al., 2021	Green Design Studio	Physics-based data-driven tool with faster simulation time	Customized tool for green building design
Wang & Zhai, 2016	Advance in computational techniques	Review of Building simulation technique	Comparative details of various available energy simulation software options
Gui et al., 2018	Proposed Performance index through real-life data	Identification of Standard building	Building selection paraments information
Ahmad et al., 2018	Large-scale data-driven building energy estimation	Energy demand forecasting	Strengths and shortcomings of the various methods
Morrey & Ghosh, 2024	Building Component Library with Open Studio	Performance evaluation of gasochromic window	Required plugin of SketchUp Pro and EnergyPlus.
Singh et al., 2020	learning-based energy prediction	Reducing the computational time	Required plugin with EnergyPlus.

Table 2.4: Reviewed Literature about Critical Parameters and Their Identification

Authors (Year)	Building Types	Critical Parameters	Findings
Li et al., 2022	Residential and non-residential buildings	25 design factors covering all aspects of building	Highlighted the importance of building science research and real-life impact. This study also accounted for the various factors impacting energy demand, technical factors yielding energy savings, and potential challenges.
Islam et al., 2021	High Rise Residential buildings	23 Design deficiency parameters	Major design deficiencies impacting high-rise building operation and maintenance were identified, and a mitigation plan was also proposed through statistical analysis.
Mirrahimi et al., 2016	High Rise Residential buildings	Building envelope and thermal comfort parameters	The study reviewed the design parameters of high-rise buildings and noted that the envelope is the most influential parameter.
De et al., 2015	Multifamily Residential buildings	Envelope, window features, thickness of Insulation, and cooling system	This review work details the building research foundation by pointing out the complexity associated with the selection of buildings, dependent and independent variables, methodology framework, simulation software, and matrix of building performance.
Tian et al., 2013	Residential and non-residential buildings	Sensitivity Index	Global sensitivity analysis helps to identify key variables impacting building thermal performance.

2.5 Critical Parameters Identification

Sensitivity analysis is a widely used technique in the world of building energy efficiency to determine the impact of various critical influencing design parameters. (Hemsath and Bandhosseini 2015; Kristensen and Petersen 2016; Yang et al. 2016; O'Neil and Niu 2017; Liu et al. 2017; Tian et al. 2018; Li et al. 2018; Rivalin et al. 2018; Gagnon et al. 2018; Vivian et al. 2020). Vivian et al. (2020) performed an investigation of the energy flexibility of residential buildings for heating and cooling requirements through sensitivity analysis of thermal comfort sessional requirements. A summary of various literature that details building critical parameters identification and related tools is discussed in Table 2.4.

2.6 Importance of Techno-Economic Analysis of Energy Efficiency Measures (ECM)

To evaluate the viability and affordability of energy-efficient design interventions for high-rise residential buildings, many researchers performed techno-economic analyses to evaluate the potential benefits. These analyses typically involve the estimation of initial capital costs associated with implementing energy-efficient design measures, the estimation of payback periods, operation cost reduction, the return on investment (ROI), and the net present value (NPV) to determine economic viability. A brief review of the literature that performed Techno-economic analysis of energy efficiency measures is discussed in Table 2.5.

Table 2.5: Reviewed Literature about Techno-Economic Analysis of ECM

Authors (Year)	Objective	Economic Parameters	Findings
Mujeebu et al., 2022	Cost estimation of energy efficiency measures	Discounted payback period	various energy efficiency measures yielding a discounted payback period of 4.94 years.
Pallis et al., 2019	Cost-effectiveness and energy saving	life cycle cost	Life cycle cost is case-sensitive and depends on various factors like building type, climate condition, and energy efficiency measures adopted.
Singh et al., 2018	Cost-effectiveness of energy saving solution	life cycle cost	This study reported four and five-star BEE-rated appliances were found to have lower LCC and greater potential for electricity savings in this study.
Bansal et al., 2014	Estimation of Embodied energy and construction cost	Construction cost per m^2	With various material choices, affordable housing construction costs range from US \$62/m^2 to US \$91/m^2, with AAC block-based

			wall homes having the lowest construction costs.
Mekhilef et al., 2014	Energy saving and associated cost	Payback period and Life cycle cost	The study notices that cooling load reduction and window tinting offer a very viable economic solution for lowering heat gain with a quick payback period.

2.7 Importance of Environmental Impact of ECM

Determining appropriate design strategies targeted at reducing the overall energy consumption throughout the building's lifecycle requires evaluating the embodied energy (EE) and operational energy (OE) of buildings. A brief review of the literature that performed environmental impact analysis of energy efficiency measures is discussed in Table 2.6.

Table 2.6: Reviewed Literature for Environmental Impact of ECM

Authors (Year)	**Study Objective**	**Environmental Parameters**	**Findings**
Hu, M., 2023	Life cycle environmental impact	life cycle embodied carbon	Large multifamily have a high embodied carbon intensity
Bansal et al., 2021	embodied energy comparison for low and high-rise building	embodied energy	The embodied energy of high-rise development is 194% more than low rise development
Bansal et al., 2020	Embodied energy analysis of building components	Embodied energy	Building Components Embodied energy increases with an increase in the number of floors
Cherian et al., 2020	Comparative study of embodied energy for different construction materials	embodied energy	Gypsum-based glass fibre reinforcement materials help to reduce the embodied energy
Koezjakov, A et al., 2018	The operational and embodied energy ratio	Embodied energy	36-46% Embodied energy increase in an efficient home
Dixit, M. K., 2017	life cycle embodied energy estimation	embodied energy	Highlighted the importance of data quality and methodological uncertainty
Praseeda et al., 2016	Operational and embodied energy assessment	embodied energy	Construction material and Air conditioning extend the impact share of Operational and embodied energy in life cycle energy.

2.8 Research Gaps (RGs)

Research in the field of building energy performance has made significant strides, particularly in commercial buildings. However, a notable research gap exists in analyzing energy performance in residential buildings, specifically in the context of high-rise residential apartments. This gap is crucial, considering the increasing prominence of high-rise structures in urban landscapes and their unique energy consumption dynamics.

- **RG 1:** While existing literature has extensively explored the energy performance of commercial buildings, there is a notable gap in research focusing on residential buildings, particularly within the high-rise residential apartment category. This gap highlights the need for comprehensive studies that explore the unique energy dynamics and challenges faced by high-rise residential buildings.

- **RG 2:** The impact assessment of India's new energy conservation building codes, specifically Eco-Niwas Samhita, on the operational energy performance of buildings is an area that requires immediate investigation. This is crucial given that the code, introduced in 2018, specifically targets residential buildings, necessitating research to understand its effectiveness and implications on energy consumption and sustainability.

- **RG 3:** Although a limited number of studies have addressed the embodied energy associated with residential buildings, there is a significant dearth of such research on high-rise building energy efficiency measures, especially within warm and humid climate conditions. This research gap underscores the necessity for in-depth analyses that consider the environmental impact of energy-efficient measures in high-rise residential structures, particularly in regions prone to such climate challenges.

- **RG 4:** A comprehensive techno-economic analysis of various energy efficiency measures applicable to high-rise residential buildings is notably absent from existing literature. Bridging this gap is imperative to provide stakeholders with valuable insights into the feasibility, costs, and benefits of implementing different energy-efficient technologies and strategies in high-rise residential settings.

2.9 Research Questions (RQs)

Considering the identified research gaps, the following research questions were formulated to investigate key aspects of energy efficiency and environmental impact related to building design and construction. These questions not only aim to assess the impact of building regulations but also explore the intricate relationships between material choices, building design strategies, and operational energy consumption. By addressing these research questions, valuable insights can be gained to guide policymakers, architects, and developers toward more sustainable practices in the construction industry.

- **RQ 1:** To what extent do the updated energy conservation building codes in India enhance the energy efficiency of typical high-rise residential apartment buildings in the warm-humid climate of Kolkata, India, and what are the pivotal factors influencing this improvement?

- **RQ 2:** What is the influence of different exterior wall assembly materials on the embodied and operational energy performance and environmental sustainability of high-rise residential structures?

- **RQ 3:** How do variations in wall material compositions and air conditioning system specifications affect the overall energy usage and cost-effectiveness of high-rise residential buildings?

2.10 Research Objectives

Understanding the current state of energy performance in high-rise residential buildings is essential for sustainable urban development. In this context, addressing the research gap regarding the impact of building codes, specifically Eco-Niwas Samhita 2018 and ECBC, on operational energy performance becomes paramount. Following these considerations, the research objectives have been set for the present research work.

- To investigate the impact of building code (Eco-Niwas Samhita 2018 and ECBC) implementation on high-rise residential building operational energy performance and find the critical influencing parameters.

- To conduct a comparative analysis of energy and environmental performance of exterior wall assemblies for large apartments accounting for both embodied and operational energy.

- To perform a techno-economic analysis of various wall and air conditioner combinations for the best energy and economic performance for high-rise residential buildings.

By aligning these objectives with the broader goal of sustainable urban development, the present research seeks to contribute actionable knowledge that can inform policy-making and industry practices, ultimately fostering a more energy-efficient and environmentally conscious built environment.

2.11 Scope of the Research

The scope of the research encompasses a thorough investigation into the energy performance and sustainability aspects of high-rise residential apartment buildings, with a specific focus on addressing critical gaps in the existing literature. One primary area of inquiry revolves around analyzing the energy consumption patterns and efficiency measures tailored to high-rise residential structures, particularly in warm and humid climate conditions where energy demands and environmental impacts may vary significantly. Furthermore, the research will explore assessing the impact of India's Eco-Niwas Samhita code on building operational energy performance, considering the code's recent introduction and its implications for energy conservation in residential high-rises. Energy-efficient design strategies will be further investigated by drawing envelope design interference between residential and commercial energy performance codes. An integral component of the study involves evaluating the embodied energy associated with construction materials and processes specific to high-rise buildings, shedding light on the environmental footprint of these developments. Through a techno-economic analysis, various energy efficiency measures applicable to high-rise residential buildings will be scrutinized to ascertain their feasibility, cost-effectiveness, and potential for reducing energy consumption. The research outcomes aim to not only fill existing knowledge gaps but also provide actionable recommendations, guidelines, and policy insights for enhancing energy performance, reducing environmental impact, and promoting sustainability in the context of high-rise residential constructions. Moreover, by identifying future research directions and emerging technologies, the study intends to contribute to ongoing discourse and advancements in the field of sustainable building practices for high-rise residential developments. The scope of this research work can be summarized as follows:

- With a specific focus on high-rise residential apartment buildings in tropical climates, exploring the energy performance and sustainability aspects to address existing gaps in the literature.
- Analyzing the energy consumption patterns and efficiency measures, tailored to high-rise residential buildings.
- Assessing the impact of India's Eco-Niwas Samhita (ENS) code and energy conservation building codes (ECBC) on building operational energy performance.
- Evaluating the embodied energy associated with wall construction materials and processes to assess the environmental footprint.
- Techno-economic analysis of various energy efficiency measures and their feasibility and cost-effectiveness to assess their potential for reducing energy consumption.

Chapter 3

Methodology

3.0 Introduction

This chapter discusses the general methodology employed for performing the research work and provides details of the tools and techniques used. It covers the details of building location, climate analysis, collected building data, information about building simulation software, building modeling methods, and building performance simulation. It also introduces the statistical analysis and sensitivity analysis as considered in this study. This chapter further discusses the parameters to consider for environmental impact analysis and issues related to economic risk analysis.

3.1 Overview of Research Approach and Study Framework

The overview of the research methodology is shown in Fig. 3.1 with a step-by-step approach to the activity performed. It also highlights the various design variables and parameters that are considered for building energy performance analysis along with base case and energy efficient design case development.

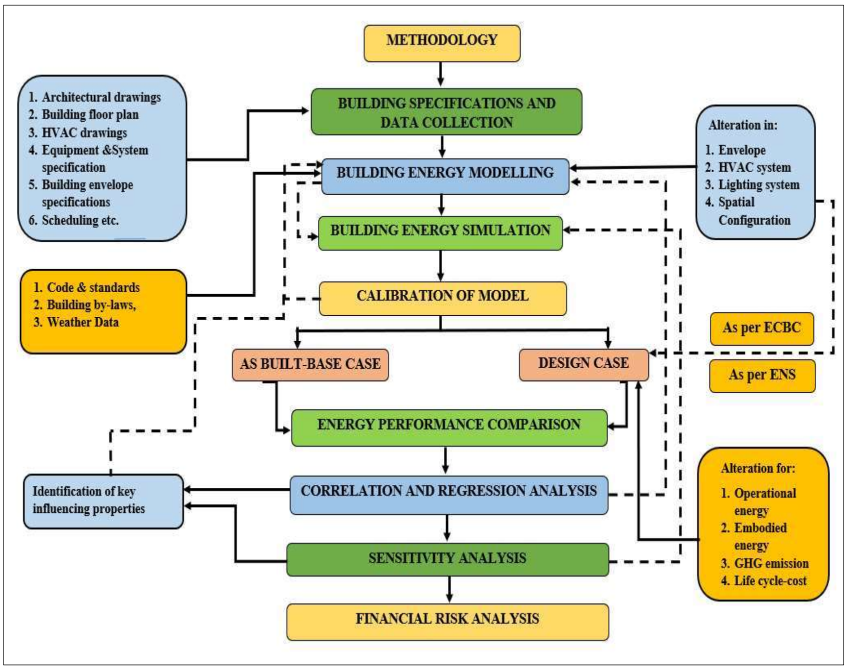


Figure 3.1: General Framework of the Study

3.2 Location of the study

Kolkata (22°34′N, 88°22′E), the state capital of West Bengal, India is chosen as the study area shown in Fig. 3.2(A). According to the climate zone map of India (ECBC, 2017), Kolkata has a warm-humid climate. According to the Köppen Geiger climate classification, Kolkata experiences tropical, savannah climate (Aw) as shown in Fig. 2(B) (Kottek et al., 2006).

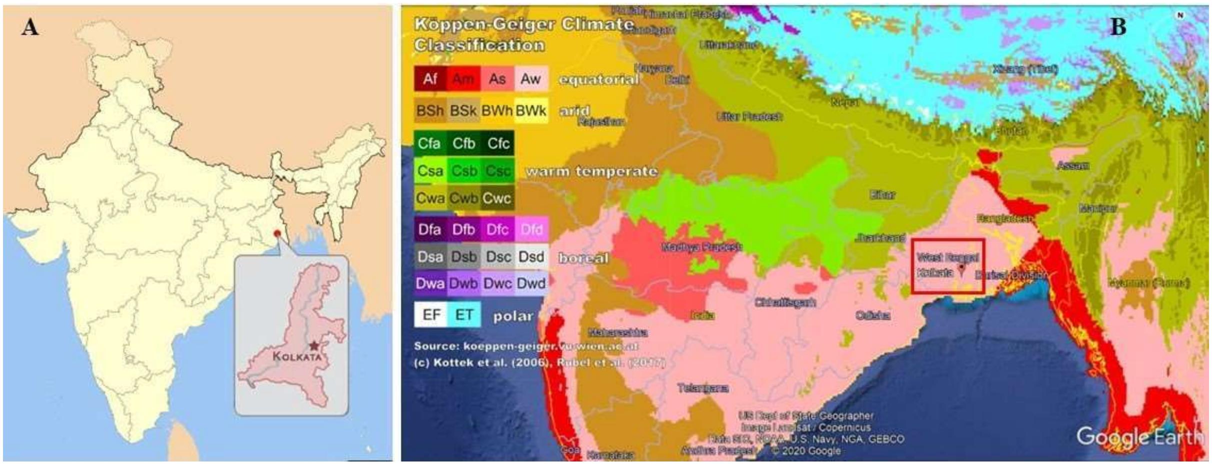


Figure 3.2: (A) Location of Kolkata in India (B) Climate of Kolkata as per Köppen Geiger Classification

[Source: Wikimedia Commons; Kottek et. Al., 2006 and Google Earth]

3.2.1 Climate Analysis

Climate analysis of Kolkata is performed by using the Climate Consultant 6.0 software. The city witnesses a high cooling degree of 3360 days. Maximum temperature reaches over 40°C in June and comes under 11°C in January as shown in Fig. 3.3. In Fig. 3.4, red represents the timings for all 12 months where temperature is higher than the comfort limits. The city experiences a lengthy rainy season (June-September) due to the southwest monsoon delivering a major part of the annual rainfall of about 1500 mm. These higher precipitation levels result in high humidity throughout the year. The discomfort during summer (March-June) and monsoon (June-September) gets worsened by the high relative humidity greater than 70%. The Wind-Rose diagram for Kolkata is shown in Fig. 3.5. The average wind speed in Kolkata is 2.6 m/s, with a maximum of about 10 m/s. The psychrometric analysis gives the annual discomfort hour as given in Table 3.1 is 4701 hours out of the annual 8760 hours. The city gets about 2,528 annual sunshine hours.

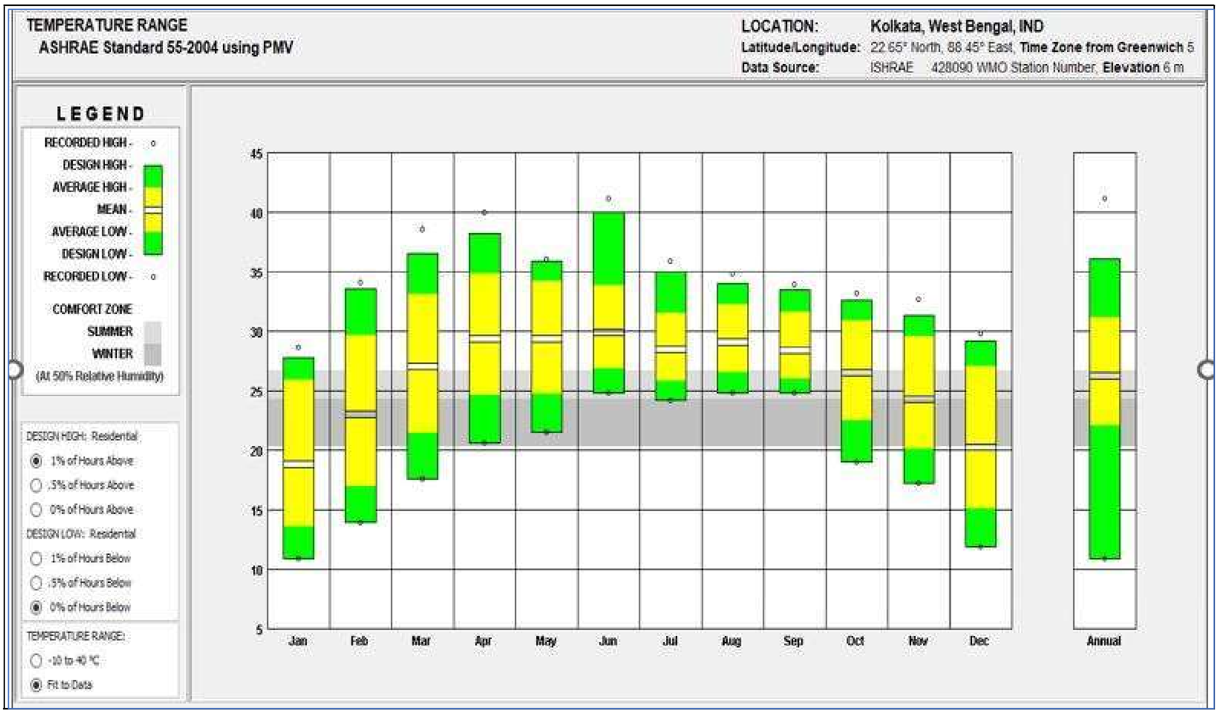


Figure 3.3: Annual Dry Bulb Temperature in Kolkata

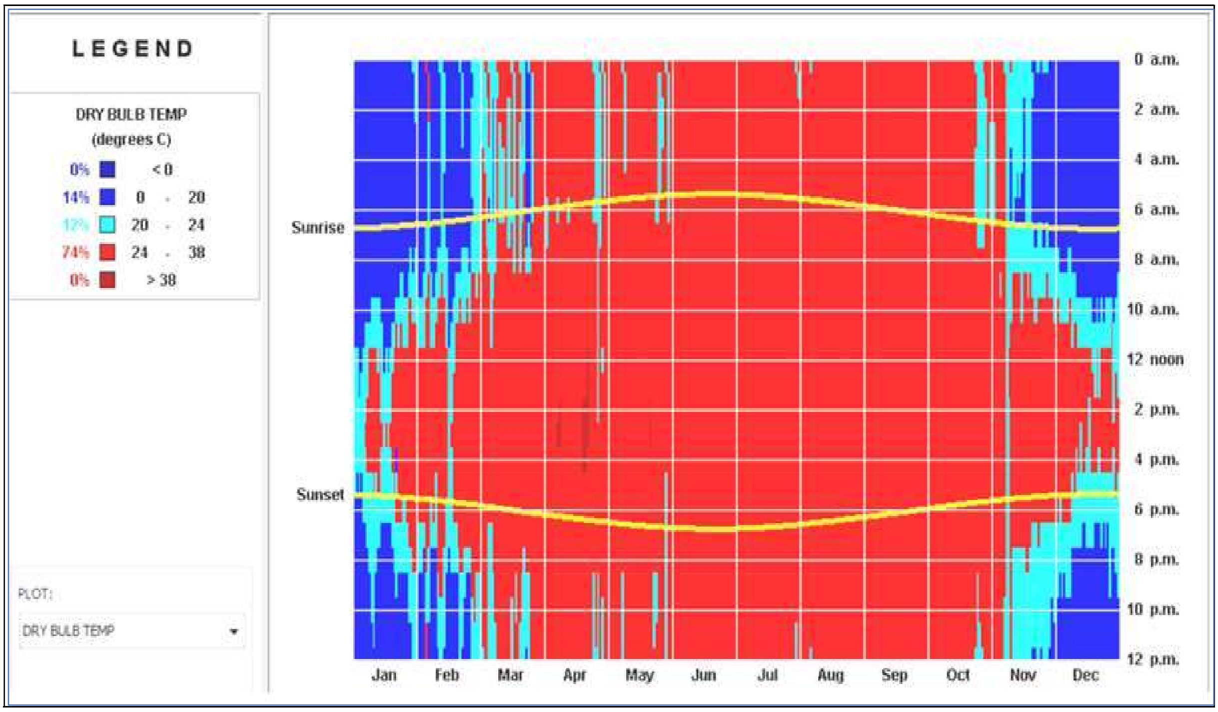


Figure 3.4: Time Table Plot of Dry Bulb Temperatures

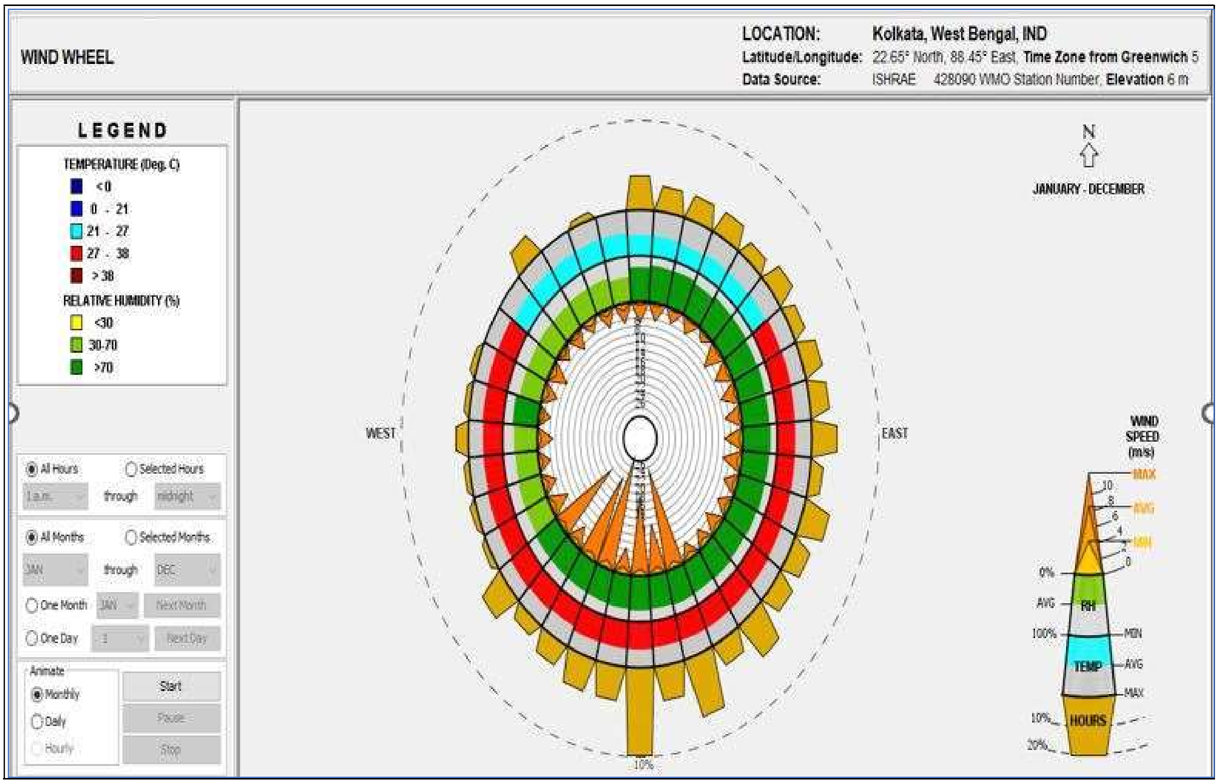


Figure 3.5: Wind-Rose Diagram for Kolkata

Table 3.1: Details of Annual Comfort and Discomfort Hours in Kolkata

Month	Comfortable Hours	Comfortable (%)	Discomfort (%)	Reason for Discomfort
January	186	25	75	Low dry bulb temperature
February	203	28	72	Low dry bulb temperature
March	341	46	54	Higher humidity and temperature levels
April	330	45	55	Much higher humidity level than March and continuous rise in dry bulb temperature
May	279	36	64	Temperatures are soaring high and humidity level also way above comfort levels
June	390	54	46	Humidity peaking higher than the previous months and temperatures are still at very high level
July	434	59	41	Humidity at the highest out of the given months and temperature crossing way beyond comfort threshold
August	434	59	41	Temperature has come down slightly but humidity levels still high
September	450	64	36	Not much different than the previous 2 months
October	465	61	39	Temperatures have further de-escalated but humidity still beyond comfort limits
November	330	44	56	Humidity levels have come down but temperature has dropped below comfort levels
December	217	28	72	Humidity is less and temperature is much below the comfort level

Table 3.2: Details of the Studied Buildings

Building	Storey	Azimuth of the Longer Axis	Height	Typical Floor to Floor Height	Built-Up Area	Conditioned Area	Envelope Area	Opaque Wall Area	Window (Non-Opaque) Area	Openable Window Area	Openable Window to Floor Area Ratio	Window Wall Ratio
Symbol		AZ	$H_{building}$	H_{floor}	$A_{built\text{-}up}$	$A_{conditioned}$	$A_{envelope}$	A_{opaque}	$A_{non\text{-}opaque}$	$A_{openable}$	WFR_{op}	WWR
Unit		Degrees	m	m	m^2	m^2	m^2	m^2	m^2	m^2	%	%
Building 1	G+16	31	55.10	3.00	9271.63	7454.45	9649.44	7492.85	2156.59	1437.73	19.29	22.35
Building 2	G+21	5	77.45	3.35	26404.62	15691.42	23709.22	19684.46	4024.76	2683.17	17.10	16.98
Building 3	G+14	356	49.38	3.00	9779.25	8005.46	6631.80	5535.56	1096.24	730.83	9.13	16.53
Building 4	G+9	343	30.20	2.90	3947.08	3469.93	4311.90	3461.59	850.31	566.87	16.34	19.72
Building 5	G+19	0	61.50	2.95	14409.54	12187.67	8128.93	5640.31	2488.62	1659.08	13.61	30.61
Building 6	G+16	0	54.60	3.00	9085.17	6694.97	8510.40	6602.88	1907.52	1271.68	18.99	22.41
Building 7	G+24	8	80.20	3.15	33645.76	26700.61	22440.35	19151.39	3288.96	2192.64	8.21	14.66
Building 8	G+19	30	59.60	2.95	11587.15	9633.58	10943.76	8946.05	1997.71	1331.81	13.82	18.25
Building 9	G+18	14	56.40	2.90	10516.90	8726.10	8571.29	6769.85	1801.44	1200.96	13.76	21.02
Building 10	G+24	31	88.20	3.49	16898.23	13308.82	13179.64	11381.50	1798.14	1198.76	9.01	13.64

3.3 Details of the Studied Buildings

Ten under-construction high-rise (ten to twenty-five stories high) residential apartment buildings from different locations in Kolkata were considered for the present research. Factors like building height, built-up area, floor geometry, and opaque and non-opaque envelope areas were varied across the chosen buildings. Table 3.2 presents detailed information for the considered buildings. In terms of data volume and diversity, the ten studied buildings represent G+9 Storey to G+24 Storey buildings, 1280 dwelling units (2BHK to 4BHK with 500 to 2900 Sq.ft. area) with a total of 15.66 lakh Sq.ft. of built-up space.

The built-up area is the total area of all floors within a building, excluding the roof, as well as the areas occupied by external walls and parapets on those floors. The carpet area refers to the clear space measured from the outer edges of external walls to the inner surfaces of walls, excluding the thickness of internal or partition walls. The envelope area is the gross external wall area including the opening of the building envelope.

3.4 Estimation of the Building Operational Energy Performance through Energy Simulation

Building energy modeling and simulation closely mimic the actual building under consideration at the design stage itself and evaluate the building performance before going for construction at the site. At an early stage, it helps to optimize the design of different systems and helps select the most efficient building materials, equipment, appliances, and schedules. It simultaneously serves the interests of the occupant, the building owner, and as a whole, the environment. Simulation input parameters deal with thermal comfort, visual comfort, and indoor air quality to enhance occupant's productivity. It becomes easier for the designers to choose efficient equipment and materials and to go for climate-responsive strategies. The optimal building energy performance and lower operational cost serve the interest of the building owner. The environmental impact gets reduced by the energy saving achieved at the end. The whole building performance method is widely used for building operational energy performance assessment through energy modeling and simulation. In this section, the general procedure followed during the energy simulation is described. The specific methodologies in this regard followed during various stages of the present research are elaborated in detail in relevant sections of Chapter 4, Chapter 5, and Chapter 6.

3.4.1 Description of the Energy Modeling Software

A building following the ECBC code shall need to show compliance through whole building energy simulation software that has been approved by BEE. eQUEST is amongst the BEE-recommended tools for building energy simulation based on the DOE 2.2 platform. It is a widely used and well-accepted building energy simulation tool. Since its introduction, various versions of eQUEST have appeared. The latest version, eQUEST 3.65, was published by the US Department of Energy in October 2018. Its widespread use stems from its free availability and availability at all stages of building development from initial design to finalization. eQUEST has three unique input wizards: Schematic Design Wizard, Design Development Wizard, and Energy Efficiency Wizard. Each corresponds to a different stage of the design process. The schematic design wizard is used in the early stages of design and requires minimal input from the user. This is especially useful when there is little information about building parameters. Design development wizards, on the other hand, require increasingly specific information as the design progresses. Energy Efficiency Wizard allows you to analyze various situations and enter the necessary data to evaluate energy performance.

eQUEST simulations are designed for buildings with simple seasonal patterns, easy building envelope design, limited window and door types, one HVAC system per zone, and accurate weather data (.bin format) available. Due to software limitations, roof and wall structures can have up to six layers, which effectively simulate exteriors with fewer layers. eQUEST effectively manages the modeling of simple roof designs, whether flat or pitched. Although there is a wide range of window and door options, eQUEST limits someone to specifying only three types for each shell. Furthermore, it is possible to efficiently represent many shielding techniques, such as overhangs, fins, and drapes. Multiple glazing options are available. Double or triple-pane windows may include insulation such as air or argon. eQUEST can efficiently model structures using a limited number of windows and doors, includes basic frame options, and uses inert gas insulation. eQUEST allows you to accurately model a variety of HVAC designs, including direct expansion (DX) coils, chilled water coils, evaporative coolers, furnaces, electrical resistance heating, and hot water coils. However, eQUEST is most suitable for buildings with one HVAC system serving each zone at maximum capacity. Operations can be scheduled appropriately and efficiently. Multiple preconditioning and preheating scenarios can be accurately represented. The model can incorporate counterflow, crossflow, parallel flow, and mixed flow energy recovery wheels.

eQUEST performs best when equipment, occupancy, and HVAC schedules maintain a consistent hourly pattern. The timetable of various electrical loads can have a significant impact on the energy efficiency of a facility. Therefore, the accuracy with which you simulate a timetable is directly affected by the accuracy with which you model the actual schedule. eQUEST works best when equipment, occupancy, and HVAC schedules are followed consistently on an hourly basis. The placement of various electrical loads has a significant impact on the energy efficiency of a building. Therefore, the accuracy of reproducing the schedule is directly dependent on the accurate representation of the actual timetable.

eQUEST cannot model advanced lighting systems such as LED lights or occupancy sensors. However, it is possible to include the energy efficiency benefits of these technologies in the load profile by manually changing the lighting load in each area. Additionally, eQUEST lacks specific functionality to model balconies. However, the shading effect that a balcony has on the windows and doors below can be recreated by simulating an overhang. This solution allows the program to take into account the shade of the balcony. Also, eQUEST cannot effectively simulate sub-hourly load calculations or assess occupant thermal and optical comfort levels. Furthermore, its effectiveness decreases when dealing with buildings with complex structures, such as those featuring conical or dome-shaped roofs. eQUEST performs load calculations every hour. Additionally, eQUEST cannot accurately model situations where one zone is served by multiple HVAC systems. It's also not enough for a structure with over 400 zones, each with its zone controls. The accuracy of eQUEST simulations depends on the ability to depict these factors accurately. The accuracy of the results produced by building energy modeling techniques like eQUEST depends on the accuracy of the input data. Even for experienced energy modelers, all energy modeling software has inherent limitations and cannot produce results that fully correspond to real-world results. This study chose to use eQUEST for building energy modeling because of its strengths, known weaknesses having no impact on this segments of building, rapid simulation capabilities, user-friendly interface, and recognition by the Building Regulatory Authority of India.

3.4.2 Energy Model Development

Building energy modeling is the practice of constructing a digital replica of an existing or new building by using customized computer software to simulate its operational energy performance. This process involves inputting various building parameters and features, as summarized in Table 3.3, such as its dimensions, architectural design, construction materials details (wall, roof, glass and partition wall, floor), HVAC systems, internal loads, fenestration properties, insulation levels, utility rates, weather data, geographical location, occupancy patterns, lighting, and equipment schedules. Through sophisticated algorithms, the software can analyze these inputs to simulate thermal dynamics by using building physics and estimate the building's energy usage accurately.

Table 3.3: Building Energy Model Input Categories

Building Project Level	Form	Envelope	Equipment	System
Location	Orientation	Walls	Lighting	HVAC System
Building type	Aspect ratio	Roof	Equipment	Thermostats set points
Total Built-up	Floor height	Floor	Control	Components efficiency
Total floor	Window location and size	Internal partition	Daylight zone	HVAC operation schedules
Weather data	Window to wall ratio	Window	Operating schedules	Economizer setting
Utility rates	Shading	Infiltration	-	-

3.4.2.1 Geometry of the Buildings

Geometry of buildings includes information regarding building orientation, aspect ratio, window size, window-to-wall ratio, floor-to-floor height, and number of floors. Figures 3.6 and 3.7 show modeling screenshots from the software wizard.

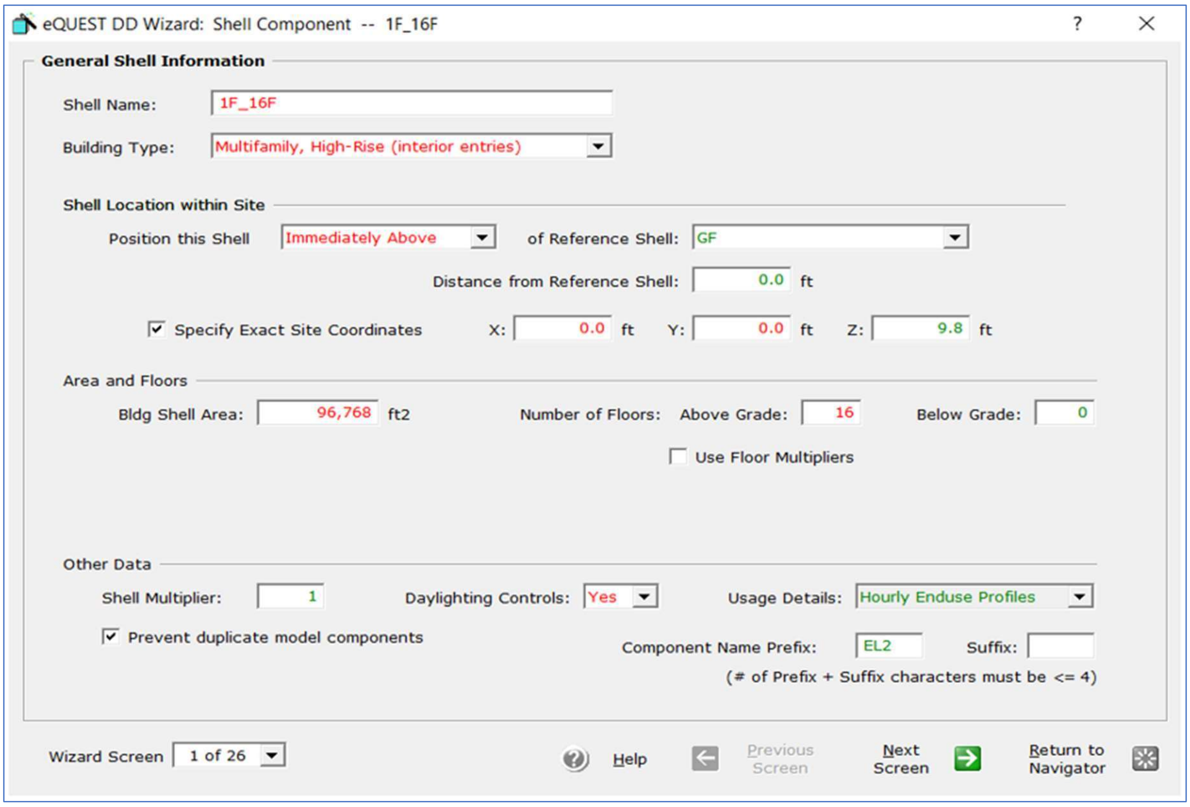


Figure 3.6: Building Modeling

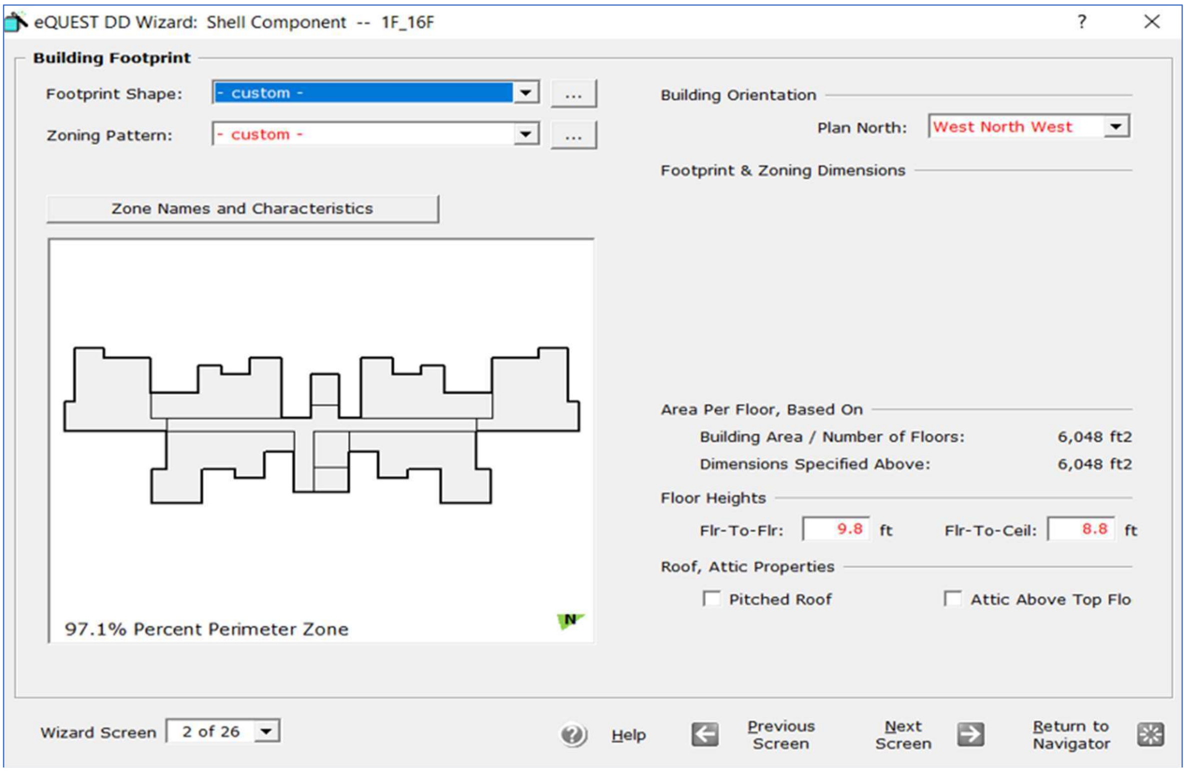


Figure 3.7: Building Floor Geometry Modeling

3.4.2.2 Envelop Materials and Construction Details

The envelope parameters describe the thermal properties of various envelope components i.e. walls, roof, internal partitions, floors, windows, and glazing. The construction layer of materials impacts the thermal transmittance value of the wall and roof and hence it required modeling for each target analysis. Figures 3.8 and 3.9 show modeling screenshots.

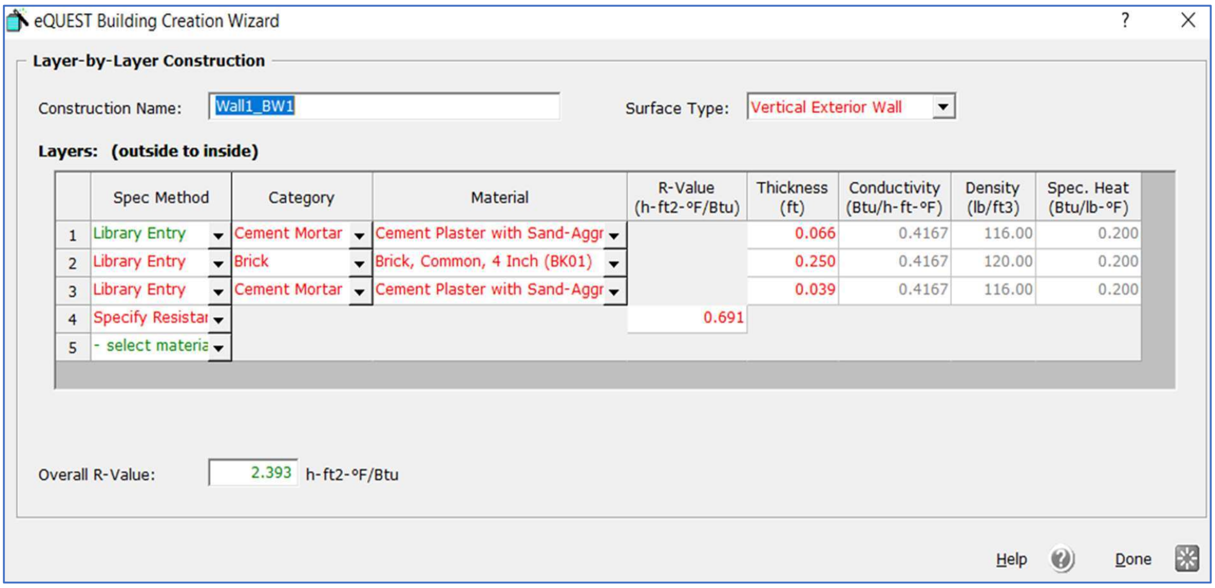


Figure 3.8: Building Wall Construction Modeling

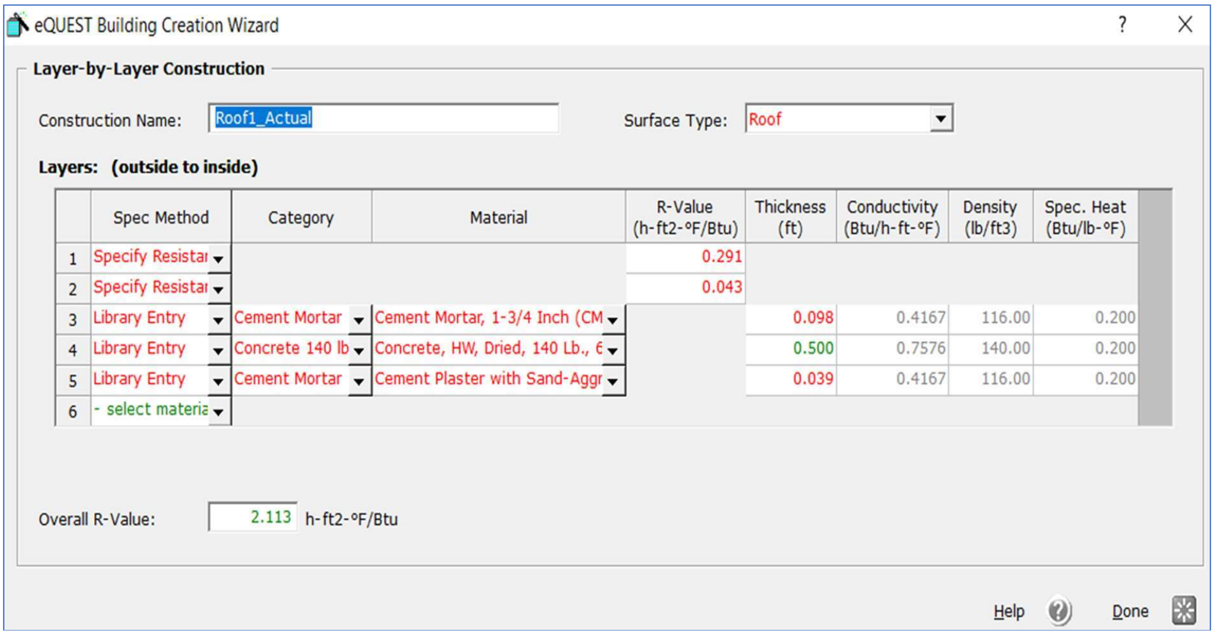


Figure 3.9: Building Wall Construction Modeling

3.4.2.3 Lighting and Other Controls

Since all ten buildings under consideration in this study are in varying stages of design, development, and construction, precise data regarding lighting power and control could not be found. ANSI/ASHRAE/IES 90.1-2016 (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2016) recommended values are considered for the interior lighting power density (*LPD*). A daylight control measure was turned on during energy simulation in every design scenario to estimate the ensuing impact of daylight use on energy performance.

3.4.2.4 HVAC System Details

Split air conditioners are typically used as active cooling measures for the conditioned spaces in typical high-rise apartment buildings in Kolkata, and hence this is considered in all design situations. ECBC 2017 and ENS Part-II specified HVAC system requirements are followed along with BEE star labeling for higher energy efficiency. A typical modeling screenshot is shown in Fig. 3.10.

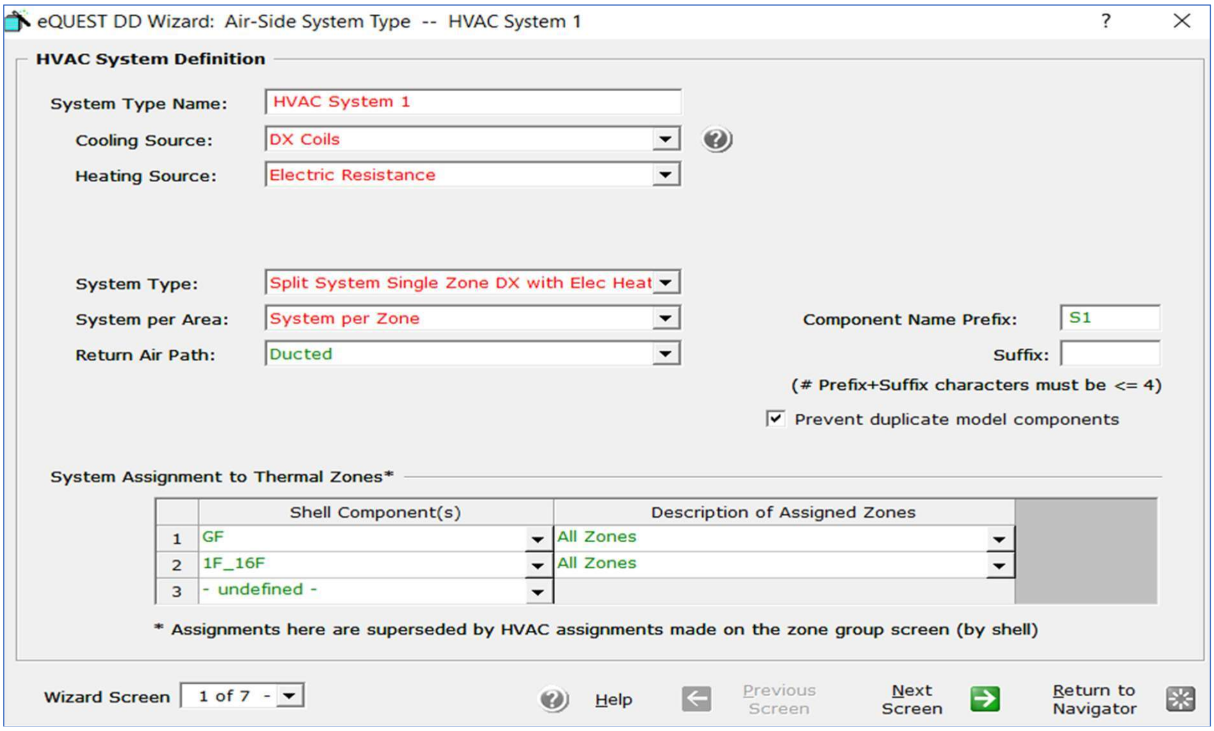


Figure 3.10: Building HVAC System Modeling

3.4.2.5 Weather File and Electricity Tariff Used for the Simulations

ISHRAE Weather files were created by exploring weather data from various sources like the National Center for Environmental Data (NCEL), the Indian Bureau of Meteorology, and satellite-driven solar radiation data developed by the National Renewable Energy Laboratory (NREL). Using the eQUEST weather processor, the collected energy Plus weather file for Kolkata (IND_Kolkata.428090_ISHRAE.epw) is converted to eQUEST usable format while running the energy simulations.

Calcutta Electric Supply Corporation (CESC) is the electricity provider in Kolkata City, and the electricity tariffs provided by them are used to prepare the electricity rate file used in the energy simulations.

3.4.2.6 Various Schedules

The occupancy, internal lighting, and equipment schedules are chosen as typical for daytime unoccupied (on weekdays) residential buildings as shown in Fig. 3.11.

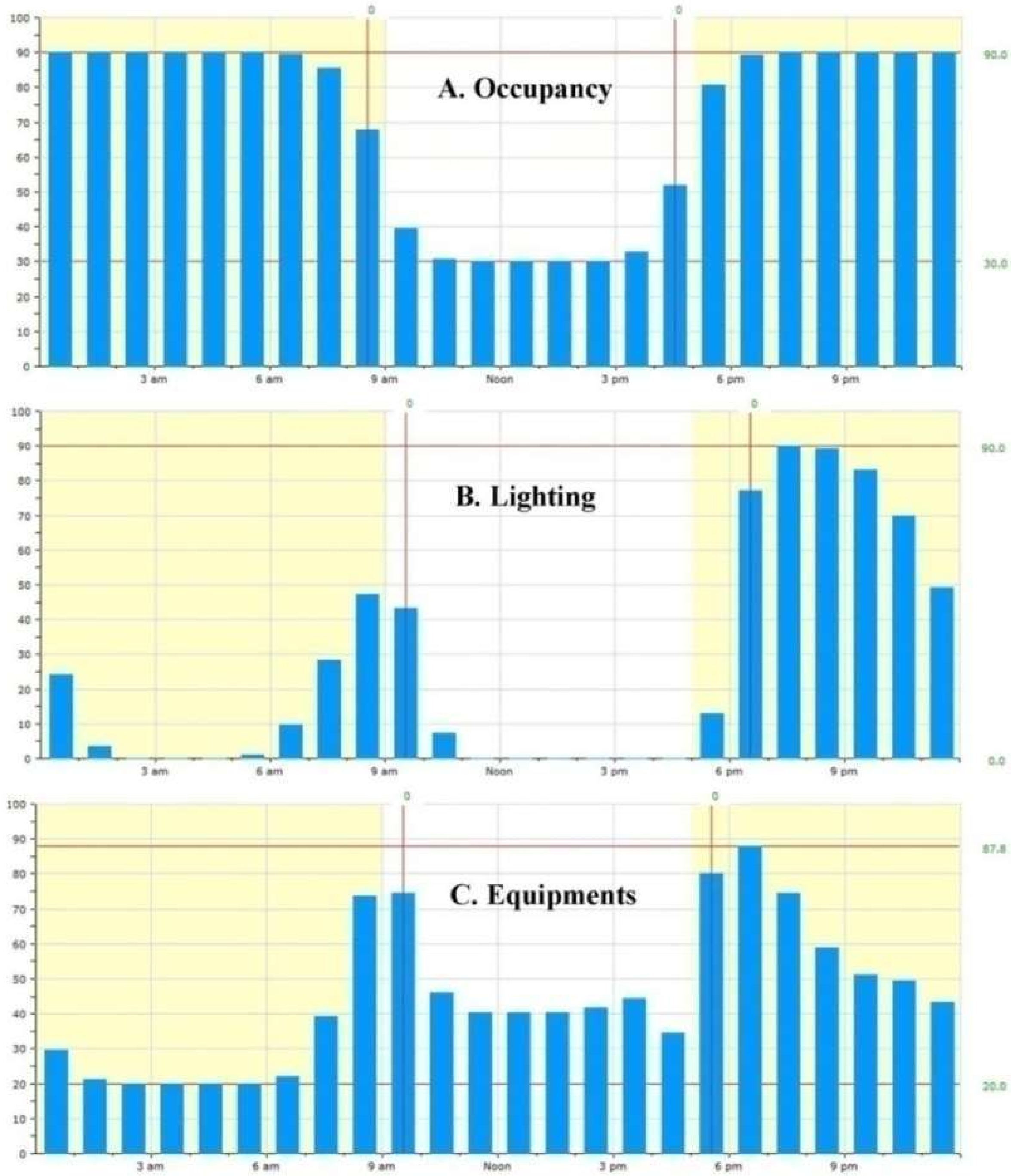


Figure 3.11: Typical Weekday Schedules for (A) Occupancy, (B) Internal Lighting, and (C) Equipment

3.4.2.7 Model Validation

The buildings considered in the present study are at the design and construction stages. Therefore, actual electricity bills are not available for directly validating the simulation outputs. The envelope construction with finishing is complete for three buildings viz. Building-1, Buiding-4, and Building-9. These buildings are chosen for validation, by comparing the simulated indoor temperatures with the measured indoor temperatures at the apartments on typical floors. The zone temperature of different indoor spaces and the associated heating-cooling energy performance of the same is directly affected by the envelope performance. Therefore, a comparison of measured ($T_{measured}$) and simulated temperature ($T_{simulated}$) is used validating the simulation models. The process is described in detail in Section 4.3.1.2.1 of Chapter 4.

3.4.3 Energy Simulation

The 'Whole Building Performance Method' as described in ECBC, 2017 is used as a guideline to run the whole building energy simulation to determine the operational energy performance of the studied buildings. Once the energy simulation models were framed the simulations were run to assess the annual operational energy consumption (for 8760 hours) under different heads.

In Chapter 4, the simulation is run for five different design cases to compare the energy performance of different ECBC-prescribed performance levels with the typically practiced baseline. In Chapter 5, the operational energy performance of nine different exterior wall alternatives is studied and compared through energy simulation. In Chapter 6, the nine exterior wall alternatives are combined with five different room air conditioners to yield forty-five different wall-AC combinations. The operational energy performance of these combinations is assessed and compared through energy simulation.

3.5 Estimation of the Building Embodied Energy Performance

The embodied energy is defined as the total amount of energy consumed during the excavation, manufacturing, transportation, fabrication, and assembly of construction materials. In Chapter 5, the embodied energy associated with nine different façade variations considered as energy efficiency measures are estimated. The masonry work quantity for each case is estimated for all ten buildings using the standard center line method (Chakraborti, 1987). Once the volume of the masonry units, cement mortar, and cement plasters are found out, the mass quantities for each are estimated using the material densities. The mass quantities of the masonry items are then multiplied by respective embodied energy coefficients and are cumulated to find out the embodied energy for the exterior walls of a building for a particular façade option. The process is described in detail in Chapter 5.

3.6 Estimation of the Environmental Impact of Different Façade Variations

Every energy efficiency measure incorporated in the building design features has its environmental impact. The environmental performances of the major energy efficiency measures in terms of nine alternative exterior wall assemblies are investigated in terms of their operational, embodied, and cumulative GHG emission potentials.

The greenhouse gas (GHG) emissions resulting from the building's operational energy consumption throughout its lifespan are determined by multiplying the lifetime (fifty years) operational energy consumption by the average GHG emission factor of the Indian electricity grid. To find out the embodied GHG emission, the mass quantities of the masonry items for a façade alternative are multiplied by respective Global Warming Potentials. The cumulative GHG emission is given by adding the operational and embodied components. The process is described in detail in relevant sections of Chapter 5.

3.7 Estimation of the Economic Impact of Different Wall-AC Combinations

At present, there is a lack of comprehensive and accurate economic understanding among various stakeholders regarding energy-efficient high-rise buildings. There is a general perception that energy-efficient buildings require substantial investment and cost, leading to reluctance in their development or purchase. Hence, Techno-economic analysis of any proposed energy efficiency measures holds the key to user acceptance. Along with the initial capital investment of the forty-five different wall-AC combinations as proposed energy efficiency measures, a life cycle cost analysis is performed. With needful quantity estimation, the individual cost of the proposed options is estimated and averaged out for all the buildings. These averaged capital costs were added to estimate the average initial capital investments required for different wall-AC combinations considered in the study and presented in terms of combined capital cost by adding each one for that specific case. The energy simulation input for the utility rate incorporated the latest urban commercial tariff rate supplied by the CESC for the calculation of electricity tariffs. The annual cost of operational energy consumption for every simulation case was taken out of the simulation reports and reported using the annual operational energy costs.

The annual inflation rate (r) of electricity was taken into account when calculating the future annual expenses for paying electricity bills to estimate the life cycle cost. The relevant discount factor (i) was applied to each case's future cash flow to convert it to its present value. To estimate the present value of the total expenditure the present value of the cash flow for fifteen years is added to the combined capital cost for each of the considered combinations. The process is described in detail in Section 6.2.2 of Chapter 6.

3.8 Statistical Analysis

The statistical method is adopted for the building design variable impact association analysis. Correlation and linear regression are the two most widely used methods when analyzing the association between quantitative variables. In Chapter 4 both of these analyses are carried out to study the association between building operational energy performance and different variables influencing it using 'SPSS Statistics' software (version 23).

In a multivariate scenario, the multiple correlation analysis assesses the statistical association among different variables. The analysis is performed for both *EPI* and *RETV* to identify their association with different influencing variables using 'SPSS Statistics' software (version 23). Both Pearson Correlation Coefficients (r) and Spearman's Rank Correlation Coefficients (r_s) are calculated. The coefficients showing significance at 0.01 level and 0.05 are reported and highlighted.

On the other hand, to develop a mathematical relationship between the energy performance indices with the different influencing variables multivariate regression analyses are run and regression equations are generated. These equations are subsequently used in 'sensitivity analysis' for critical influencing variable identification.

3.9 Sensitivity Analysis

To analyze the effects of the uncertainty in the input variables sensitivity analysis is widely used by researchers. The 'What If' kind of sensitivity analysis, as carried out in Chapter 4 (Section 4.3.3), typically identifies the critical parameter dependence of the solution (operational energy performance in the present study) and helps in decision-making. The 'TopRank' software (version 5.5) of Palisade Decision Tools Suite (2009) is used to comparatively assess the influence of different input variables on the operational energy performance of the studied buildings and to point out the most critical ones demanding attention. The critical influencing parameters identified in the process are chosen for further analyses carried out in Chapter 5 and Chapter 6.

3.10 Risk Analysis through Monte Carlo Simulation

Risk analysis, a core concept in financial theory, involves assessing uncertainties in economic estimation. Monte Carlo Simulation (MCS), a widely used method based on probability distributions, reliably forecasts economic conditions with stability. The MCS model of the '@Risk' software (version 5.5) from Palisade Decision Tools Suite (2009) is used for economic risk analysis by using probability distributions of input variables. Using mean (μ) and standard deviation (σ) parameters, this process produced probability distributions for the present value of total expenditure for different wall-AC combinations considered in Chapter 6. The process is detailed in Section 6.2.3.1.

3.11 Assumptions and Study Scope Limitation

The scope of the study is limited to only high-rise residential apartment buildings in Kolkata that represent a warm and humid climate. The building's occupants use it year-round to the intended design and predefined user guidelines. Based on the building model, all predefined parameters are followed and applied. However, these parameters are subject to change on occasion based on evolving needs and conditions. The home appliances and equipment function in compliance with a predefined schedule and the manufacturer's specifications. Architectural energy efficiency measures and social constraints of high-rise occupants were not considered in this study.

Chapter 4

Assessment of Building Energy Performance and Identification of the Critical Influencing Parameters

---

4.0 Introduction

Buildings currently consume about 33% of India's total final energy consumption (Yu et al., 2017). It is still increasing at around 8% annually (Dhaka et al., 2012). The residential building sector, which is about 80% of the total housing stock, is the second highest energy-consuming sector after the industrial sector in India. The residential building sector consumes substantial energy in modern urban cities of India both due to improved living standards and increasing population. Out of the total electricity consumed in the building sector, around 75% is used in residential buildings. From 55 TWh in 1996-97 to 260 TWh in 2016-17, the gross annual electricity consumption in residential buildings has been rising sharply by more than four times in a span of twenty years and future projections show that it is expected to reach anywhere between 630-1100 TWh by 2032 (Central Electricity Authority 2017; NITI Ayyog). The situation as of now demands the implementation of urgent measures to optimize building energy demand in the residential building sector alongside others by increasing building energy efficiency. Regulatory measures implemented through building energy codes have been proven effective worldwide in this regard. Energy Conservation Building Codes (ECBC) for commercial and residential buildings in India are already introduced by the Bureau of Energy Efficiency (BEE). In the present chapter, the influence of different envelope parameters as specified in the ECBC for residential buildings (Eco-Niwas Samhita, 2018, Part-1) on the energy performance of typical high-rise residential apartments in the warm-humid climate of Kolkata, is studied in detail. Statistical association of the energy performance with different variables regarding building geometry and envelope material properties is also investigated. The effects of uncertainties in the variables on the building energy performance are explored through sensitivity analyses. The most critical variables influencing the building energy performance are thus identified through this sensitivity analysis.

4.1 Energy Conservation Building Codes (ECBC) for Residential Buildings

With an anticipated rapid growth in the residential building stock across India, BEE introduced Eco-Niwas Samhita, 2018, Part-1, the ECBC for residential buildings, which sets minimum performance standards for four building envelope compliance parameters viz. Window (possible to open) to Floor Area Ratio (WFR_{op}), Visible Light Transmittance (*VLT*), Roof Thermal Transmittance (U_{roof}), and Residential Envelope Transmittance Value (*RETV*) to ensure energy efficiency. The code applies to residential buildings or residential parts of the 'mixed land-use building projects' built on a plot area ≥ 500 m^2.

Eco-Niwas Samhita, 2018 (Part-1) specifies minimum requirements for WFR_{op} i.e. the ratio of areas that can be opened to the atmosphere to the carpet area of the dwelling units, based on the climate zone of the building. It ensures sufficient external air ventilation to improve thermal comfort and energy efficiency as per the recommendations of the National Building Code (NBC, 2016).

The potential for daylight use is ensured by the optimum choice of glasses with sufficient *VLT*. Eco-Niwas Samhita, 2018 specifies the minimum *VLT* requirement based on window wall ratio (*WWR*) i.e. the ratio of the area of non-opaque building envelope components to the envelope area (excluding roof) of the buildings.

Transmittance or U-value is the heat flow density (W/m^2) through a physical body with a 1K temperature difference (ΔT) between the air inside and air outside of it, in units of W/m^{2}K (Szokolay 2004). Eco-Niwas Samhita, 2018 helps to reduce heat gain or loss through the roof by setting a maximum limit to U_{roof}.

$$RETV = \frac{1}{A_{envelope}} \left[\begin{array}{l} \left\{ a \times \sum_{i=1}^{n} \left(A_{opaque_i} \times U_{opaque_i} \times \omega_i \right) \right\} + \\ \left\{ b \times \sum_{i=1}^{n} \left(A_{non-opaque_i} \times U_{non-opaque_i} \times \omega_i \right) \right\} + \\ \left\{ c \times \sum_{i=1}^{n} \left(A_{non-opaque_i} \times SHGC_{equivalent_i} \times \omega_i \right) \right\} \end{array} \right] \qquad \text{Equation (4.1)}$$

Eco-Niwas Samhita, 2018 uses a single parameter named *RETV* to characterize the thermal performance of the building envelope except the roof. *RETV* represents the net heat gain rate through the building envelope components (excluding roof) per unit building envelope area (excluding roof). RETV takes into account the conductive heat gain through opaque (e.g. wall) and non-opaque (e.g. window glazing) envelops along with solar radiation heat gain through the latter as expressed in Eqn. (4.1). Limiting *RETV* helps reduce heat gain and improve building energy performance.

In the above equation, $A_{opaquei}$ represents the area of different opaque building components (external brick wall) in all four cardinal directions of the building façade. $A_{non\text{-}opaquei}$ represents the same for non-opaque building components (window glazing). Thermal transmittance of the external wall ($U_{opaquei}$ or U_{wall}), same for window glazing ($U_{non\text{-}opaquei}$), and solar heat gain coefficient ($SHGC_{equivalenti}$) for the window glazing represent the thermal properties of the building envelope components. The orientation factors (ω_i), taking care of direct and diffused solar radiation received on the vertical building surface in a specific orientation are available in Annexure-6 of Eco-Niwas Samhita, 2018 along with the values of the coefficients a, b, c.

The revised energy conservation building code for commercial buildings (ECBC, 2017) through its mandatory and prescriptive energy efficiency measures (EEM) for envelope, HVAC and comfort systems, electro-mechanical systems, lighting, etc., encourages energy efficient design of buildings through the Integrated Building Design approach. For residential building codes, Eco-Niwas Samhita, 2018, Part-1, dealing with the envelope parameters is explored in the present chapter. Eco-Niwas Samhita, 2021, Part-2, dealing with the electro-mechanical systems is explored in the Chapter-6 of the thesis.

4.2 Objectives and Framework of the Study

The study in the present chapter is focused on the following objectives as detailed below. The different stages involved in the study framework are presented in Fig. 4.1.

- To study the influence of different envelope parameters as specified in the ECBC for residential buildings (Eco-Niwas Samhita, 2018, Part-1) on the energy performance of typical high-rise residential apartments in the warm-humid climate of Kolkata.
- To study the statistical association of building energy performance with different variables regarding building geometry and envelope material properties.
- To probe into the uncertainty in the variables through sensitivity analyses and identify the critical factors influencing the building energy performance.

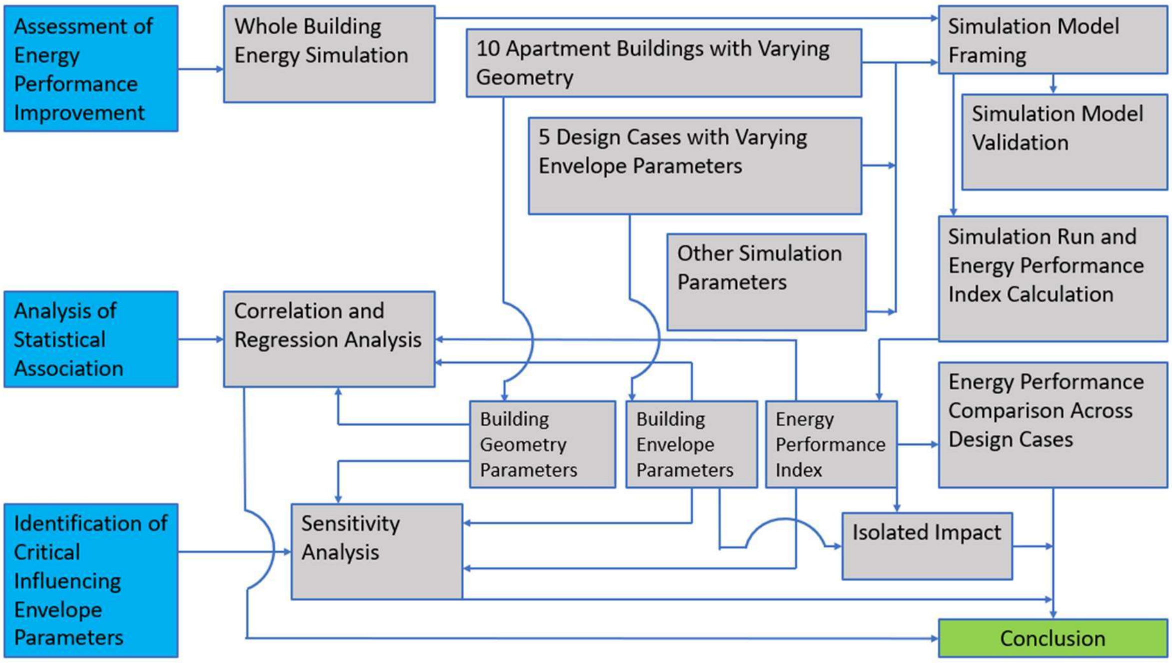


Figure 4.1: Framework of the Study

4.3 Methodology

4.3.1 Assessment of Energy Performance

4.3.1.1 Framing Energy Simulation Models

A total of ten high-rise residential apartment buildings in the warm-humid climate of Kolkata are chosen as the test subjects for the present study. The details of the buildings are provided in Chapter 3. The energy performance for each of the buildings is assessed through whole building energy simulation by eQUEST 3.65. For each of the buildings, five design cases were considered in framing the energy simulation models using the 'Design Development Wizard' of the software. Models for Case-1 followed the actual design available from the drawing and design documents and typical construction practices followed in Kolkata. Required parameters are changed for Case-2 models to comply with the specifications of Eco-Niwas Samhita, 2018 (Part-1). Models for the remaining three cases viz. Case-3 (ECBC 2017 Baseline design), Case-4 (ECBC 2017 Plus design), and Case-5 (ECBC 2017 Super design) followed the Energy Conservation Building Code (ECBC, 2017) specifications for the considered parameters. The basic building geometry and orientation (parameters as described in Table 3.2 apart from A_{opaque}, $A_{non\text{-}opaque}$ and $A_{openable}$) were kept the same as the actual one over all the design cases for a particular building. Typical floor plans and views of the energy simulation models are shown in Fig. 4.2.

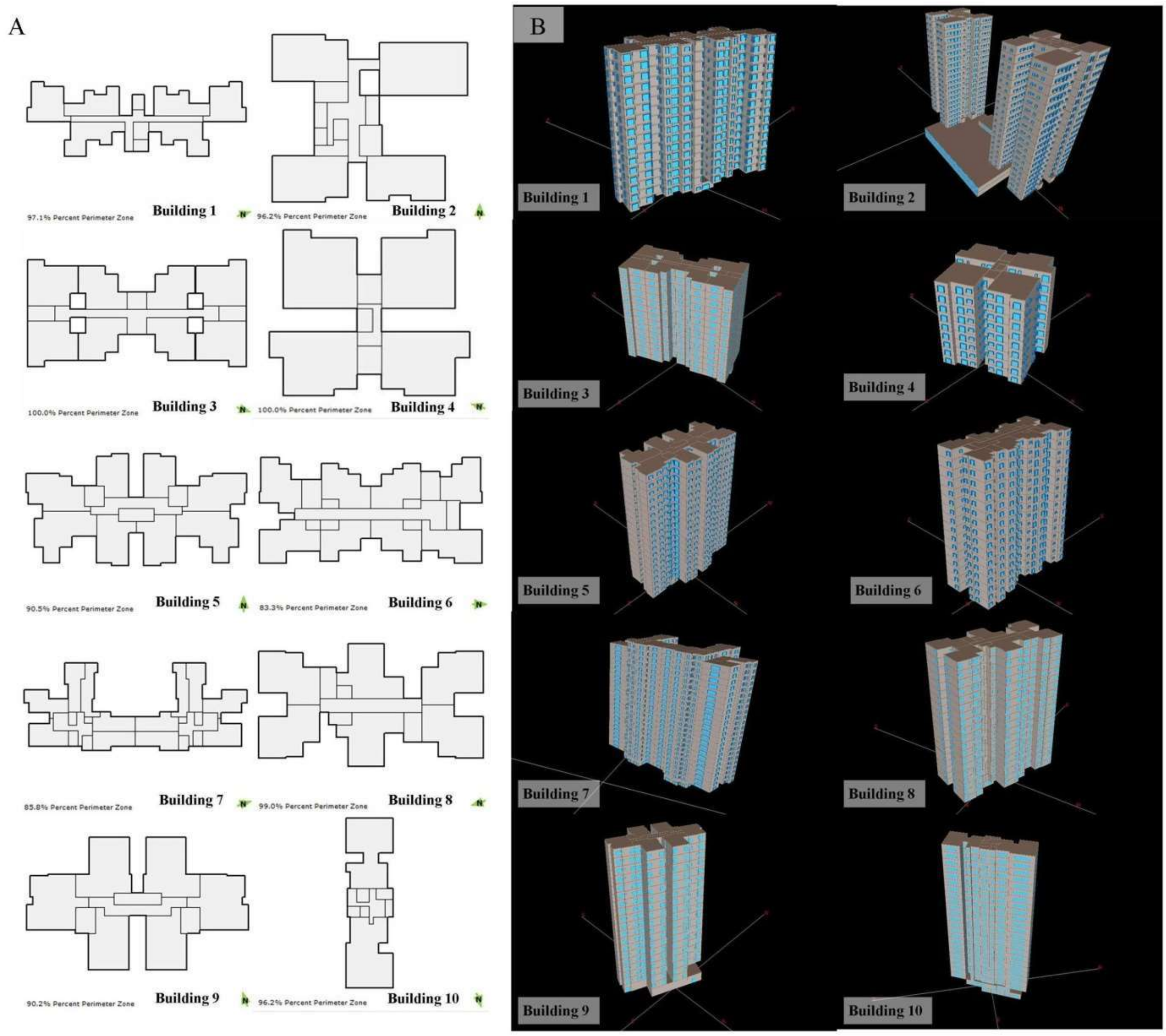


Figure 4.2: The Studied Buildings (A) Typical Floor Plans (B) 3D View of the Energy Simulation Models

4.3.1.1.1 Compliance with 'Openable' Window to Floor Area Ratio (WFR_{op}) Specifications

For Case-1 models the actual value of WFR_{op} is calculated for all ten buildings. The openable window area is 2/3rd of the overall window area as three-panel sliding doors and windows are typically considered in Kolkata's apartments. For the warm-humid climate of Kolkata, the minimum code specified value for WFR_{op} is 16.66%. To comply, wherever required, the overall *WWR* values for these buildings are increased till the WFR_{op} values cross the requisite percentage. *WWR* values for the buildings which have already complied are kept unchanged. The actual and modified values are presented in Table 4.1.

Table 4.1: Actual and Modified WFR_{op} and WWR Values

Building	Actual Values*		Modified Values**		Change in Opaque Wall Area and Window Area
	Openable Window to Floor Area Ratio	Window Wall Ratio	Openable Window to Floor Area Ratio	Window Wall Ratio	
Symbol	WFR_{op}	WWR	WFR_{op}	WWR	
Unit	%	%	%	%	m^2
Building 1	19.29	22.35	19.29	22.35	0
Building 2	17.1	16.98	17.1	16.98	0
Building 3	9.13	16.53	16.66	30.17	904.57
Building 4	16.34	19.72	16.67	20.12	17.24
Building 5	13.61	30.61	16.66	37.47	557.29
Building 6	18.99	22.41	18.99	22.41	0
Building 7	8.21	14.66	16.66	29.74	3384.8
Building 8	13.82	18.25	16.66	22	409.92
Building 9	13.76	21.02	16.67	25.45	379.95
Building 10	9.01	13.64	16.66	25.24	1528.4

* Used for Case-1; ** Used for Case-2, Case-3, Case-4 and Case-5

4.3.1.1.2 Compliance with Visible Light Transmittance (*VLT*) Specifications

For residential apartments in Kolkata, single-glazed units (SGU) made of clear float glasses are typically considered. Therefore, clear float glass properties for the products of three leading glass manufacturers viz. Saint Gobain Glass (SGG), Pilkington, and Asahi India Glass Limited (AIS) as presented in Table 4.2 are considered as available options. An average *VLT* of 87.87% is considered for Case-1 models. For the remaining cases, corresponding code-specified values as described in Table 4.3 are maintained considering the market available options. Along with the *VLT*, the thermal properties (U_{glass} and *SHGC*) of the glass products played an important role in their choice.

Table 4.2: Properties of Market-Available Glass Products Considered in the Study

Manufacturer	Product	Type	Glass Properties		
			Transmittance	Visual Light Transmittance	Solar Heat Gain Coefficient
Symbol			U_{glass}	VLT	$SHGC$
Unit			W/m^2°K	%	
Saint Gobain Glass	PLANILUX	6 mm Clear Float Glass	5.7	89	0.82
Pilkington	OPTIFLOAT		5.7	88	0.81
AIS	CLEAR FLOAT		5.68	86.6	0.81
Average			**5.69±0.01***	**87.87±1.21***	**0.81±0.01***
Saint Gobain Glass	EVO CLEAR COSMOS	6 mm Clear SGU	3.8	28	0.29
AIS	ECOSENSE EDGE NATURA		3.7	28	0.3
Average			**3.750±0.071****	**28.0±0.000****	**0.295±0.007****

* Used for Case-1; ** Used for Case-2

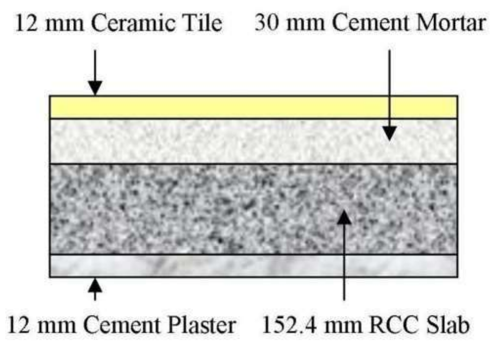
Table 4.3: The Envelope Material Parameters Considered for the Design Cases

Description	Symbol	Unit	Design Cases				
			Actual Design	Compliance Threshold	ECBC Baseline	ECBC +	ECBC Super
			Case-1	Case-2	Case-3	Case-4	Case-5
Roof U-value	U_{roof}	W/m^2°K	2.69	1.20**	0.33**	0.20**	0.20**
Wall U-value	U_{wall}	W/m^2°K	2.05	2.05	0.40**	0.34**	0.22**
Glazing Visual Light Transmittanmce	VLT	%	87.87	28 (27.00*)	27.00*	27.00*	27.00*
Glazing U-value	U_{glass}	W/m^2°K	5.69	3.75	3.0**	2.2**	2.2**
Glazing SHGC (North)	$SHGC_{north}$		0.81	0.295	0.50**	0.50**	0.50**
Glazing SHGC (Non-North)	$SHGC_{non\text{-}north}$		0.81	0.295	0.27**	0.25**	0.25**
Residential Envelope Transmittance Value	$RETV$	W/m^2	20.37±2.24	13.98±0.80 (15.00**)	7.57±1.24	6.79±1.14	6.33±1.18
Window Shading			Yes	Yes	Yes	Yes	Yes

* Minimum Required Values, ** Maximum Allowable Values

4.3.1.1.3 Compliance with the Roof Thermal Transmittance (U_{roof}) Specifications

The typical roof construction practiced in Kolkata, as shown in Fig. 4.3, is considered for Case-1 models. As a building roof typically consists of multiple material layers, the methodology of calculation of thermal transmittance of roof and wall as specified in Annexure-5 of Eco-Niwas Samhita, 2018 is followed. Thickness of the material layer (t_i) is taken from the typical construction practiced in Kolkata. The material thermal conductivity (k_i) and the interior and exterior surface film thermal resistance (R_{si} and R_{se}) are taken from material specifications provided in Eco-Niwas Samhita, 2018 as well as ECBC, 2017. For the remaining cases, U_{wall} values are kept at maximum allowable limits as described in Table 4.3.

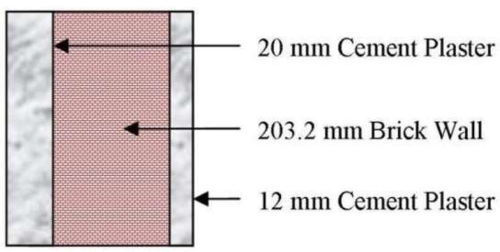


Material Layer	Thickness	Conductivity	Resistance
Symbol	t_i	k_i	R_i
Unit	mm	W/mK	m^{2}K/W
Ceramic Tile	12.0	1.5996	0.0075
Cement Mortar	30.0	0.7190	0.0417
RCC Slab	152.4	1.5800	0.0965
Cement Plaster	12.0	0.7210	0.0166
Interior Surface Film Thermal Resistance (R_{si})			0.1700
Exterior Surface Film Thermal Resistance (R_{se})			0.0400
Total Thermal Resistance (R_T)			0.3723
Roof Thermal Transmittance (U_{roof}) = 2.6860 W/m^2°K			

Figure 4.3: Typical Roof Construction as Practiced in Kolkata

4.3.1.1.4 Compliance with the Residential Envelope Transmittance Value (*RETV*) Specifications

Thermal transmittance of the external wall ($U_{opaquei}$ or U_{wall}), same for window glazing ($U_{non\text{-}opaquei}$), and solar heat gain coefficient ($SHGC_{equivalenti}$) for the window glazing represent the thermal properties of the building envelope components required for RETV calculation using Eqn. (4.1). For the calculation of thermal transmittance of the external opaque wall (U_{wall}), the same methodology as specified in Annexure-5 of Eco-Niwas Samhita, 2018 is followed. The typical external brick wall construction practiced in Kolkata, as shown in Fig. 4.4, is considered for Case-1 models. Also for Case-2, the wall construction is kept unaltered. For the remaining three cases of ECBC, 2017 compliant designs the U_{wall} values are kept at maximum allowable limits as described in Table 4.3.



Material Layer	Thickness	Conductivity	Resistance
Symbol	t_i	k_i	R_i
Unit	mm	W/mK	m^{2}K/W
Cement Plaster	20.0	0.7210	0.0277
Solid Burn Clay Brick	203.2	0.7400	0.2746
Cement Plaster	12.0	0.7210	0.0166
Interior Surface Film Thermal Resistance (R_{si})			0.1300
Exterior Surface Film Thermal Resistance (R_{se})			0.0400
Total Thermal Resistance (R_T)			0.4889
Wall Thermal Transmittance (U_{wall}) = 2.0454 W/m^2°K			

Figure 4.4: Typical Wall Construction as Practiced in Kolkata

As already discussed, residential apartments in Kolkata typically use single-glazed units (SGU) made of clear float glasses for non-opaque building envelope components like window glazing. Properties for market available options for the same are described in Table 4.2. An average U_{glass} value and *SHGC* of 5.69 W/m^2°K and 0.81 respectively are considered for Case-1 models. For Case-2 models, Eco-Niwas Samhita, 2018 specified that *RETV* of 15 W/m^2 is achieved by altering window glass thermal properties while keeping the U_{wall} unaltered. For the remaining three cases, the glass thermal properties are considered as per the ECBC, 2017 recommendations as described in Table 4.3. The resultant *RETV* values for all the design cases are also presented.

4.3.1.1.5 Heating, Ventilation and Air Conditioning (HVAC), Lighting and Equipment, Occupancy and Schedule

For typical apartment buildings of Kolkata unitary split air conditioners are generally used for the conditioned spaces and the same is considered across all the cases. ECBC, 2017 specified HVAC system requirements are followed in Case-3, Case-4, and Case-5 models. For actual design in Case-1 and Eco-Niwas Samhita, 2018 (which sets and recommends provisions for building envelope parameters only) compliant design in Case-2, HVAC system efficiency and other parameters are kept the same as Case-3 design. For all the simulation runs the cooling systems are sized by the 'Auto-Size' capability of eQUEST 3.65.

As all the ten buildings considered in the present study are either at the design stage or are under construction, actual information about lighting power and control could not be obtained. The interior lighting power density (*LPD*) is chosen as per the recommendation of ANSI/ASHRAE/IES 90.1-2016 (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2016). No consideration is made for exterior lighting either in any of the design cases. To estimate the consequent impact of daylight use (by providing minimum VLT as discussed in Seion-3.3.2) on energy performance, a daylight control measure was activated during energy simulation for all cases.

The buildings are considered typical daytime unoccupied (on weekdays) residential ones and the occupancy, internal lighting, and equipment schedules are chosen accordingly as shown in Fig. 4.5. 5 kW intermittently operating elevators are assigned to the buildings as per the building drawings. The HVAC system information as well as the information for lighting, equipment, occupancy, and schedules is summarized in Table 4.4.

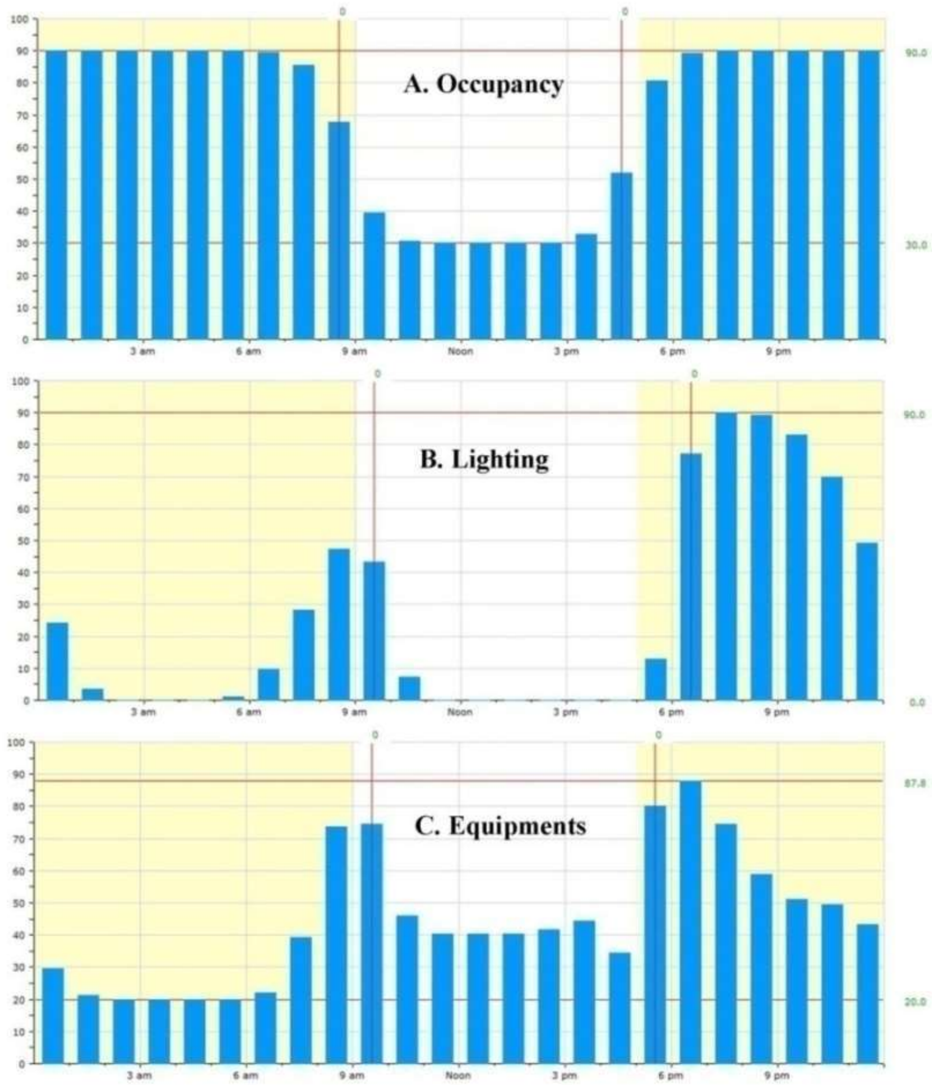


Figure 4.5: Typical Weekday Schedules for (A) Occupancy, (B) Internal Lighting and (C) Equipment

Table 4.4: HVAC, Lighting, Equipment, and Other Parameters for all the Design Cases

	Description	Symbol	Unit	**Design Cases**				
				Actual Design	**Compliance Threshold**	**ECBC Baseline**	**ECBC +**	**ECBC Super**
				Case-1	**Case-2**	**Case-3**	**Case-4**	**Case-5**
HVAC	HVAC System Type			Split System, Single Zone DX				
	BEE Star Rating			3 Star	3 Star	3 Star*	4 Star*	5 Star*
	Cooling Energy Efficiency Ratio	*EER*	W/W	3.1	3.1	3.1*	3.3*	3.5*
	Zone Cooling set point		deg F	78	78	78	78	78
	Zone Heating set point		deg F	68	68	68	68	68
Lighting	Lighting Power Density	*LPD*	W/ ft^2	0.70 (as per ANSI, ASHRAE, IES 90.1- 2016)				
	Daylight Control			30% light power dimming during daylight hours in the daylit areas				
Equipment Power Density		*EPD*	W/ ft^2	0.30 (Software Default)				
Elevator Power			kW	5 kW/Elevator (number of elevators is as per the actual drawing)				
Occupancy			m^2/Person	12.50 (as per National Building Code, 2016)				

* Minimum Required Values, ** Maximum Allowable Values

4.3.1.2 The Energy Simulation

The 'Whole Building Performance Method' as described in ECBC, 2017 is used as a guideline to run the whole building energy simulation to determine the energy performance of the studied buildings for five considered design cases. eQUEST 3.65, a front-end to the DOE-2.2 engine, has been used as the simulation tool. Energy Plus weather file for Kolkata (IND_Kolkata.428090_ISHRAE.epw) is collected and converted to eQUEST usable format by eQUEST weather processor which is used during the energy simulations. Calcutta Electric Supply Corporation (CESC) is the electricity provider in Kolkata City, and their latest tariff under effect from 4th July 2018 (CESC, 2018) is used to prepare the electricity rate file used in the energy simulations.

The simulations were run after framing the models and the annual operational energy consumption under different heads was assessed. To normalize the annual energy consumption the Energy Performance Index (*EPI*) as expressed in Eqn. (4.2) was calculated for each building.

The *EPI* for cooling energy ($EPI_{cooling}$) and internal lighting energy ($EPI_{lighting}$) are also calculated along with the overall *EPI* and are used for further analyses.

$$EPI = \frac{annual\_energy\_consumption}{A_{built-up}} \quad \text{Equation (4.2)}$$

4.3.1.2.1 Validation of the Simulation Models

The buildings considered in the present study are at the design and construction stages. Therefore, actual electricity bills are not available for directly validating the simulation outputs. The envelope construction with finishing is complete for three buildings viz. Building-1, Buiding-4, and Building-9. These buildings are chosen for validation, by comparing the simulated indoor temperatures with the measured indoor temperatures at the apartments on typical floors. The zone temperature of different indoor spaces and the associated heating-cooling energy performance of the same is directly affected by the envelope performance. Therefore, a comparison of measured ($T_{measured}$) and simulated temperature ($T_{simulated}$) is used validating the simulation models.

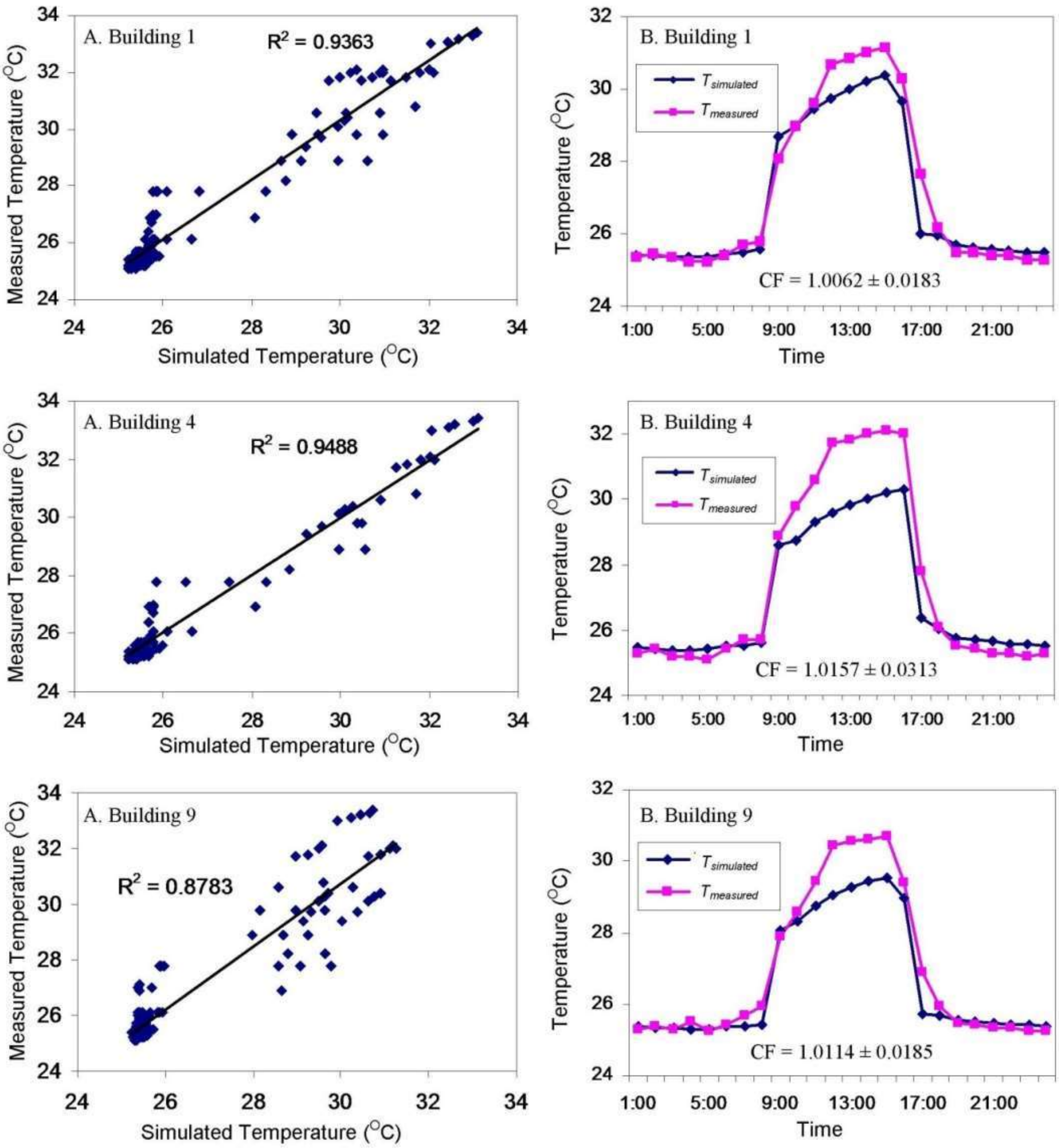


Figure 4.6: Measured and Simulated Indoor Temperature Comparison (A) Scatter Plots (B) Diurnal Temperature Variation Pattern

In July 2019, automatic ambient temperature loggers (Make: HTC, Model: Easy Log, Resolution: 0.1°C) were placed in the living rooms of the apartments of the selected buildings, and ambient temperatures ($T_{measured}$) were recorded for a whole day. Six apartments for Building-1, four apartments for Building-4, and six apartments for Building-9 were chosen for monitoring. The 'hourly reports' for the 'zone temperatures' provide the simulated temperatures ($T_{simulated}$) for the same spaces. Scatter plots with $T_{measured}$ and $T_{simulated}$ are drawn for all three buildings and the respective coefficient of determination (R^2) is checked. A calibration coefficient (CF), represented by the ratio of the $T_{measured}$ and $T_{simulated}$, is also calculated for each hour for each of the considered apartments, and the daily average is calculated. The scatter plots and time series graphs for the considered three buildings are shown in Fig. 4.6. Both R^2 value and *CF* values being close to '1' show a good association between measured and simulated temperature and high simulation efficiency. Similar observations were made earlier by Pellegrino et al. (2011), Biswas et al. (2013), and Pellegrino et al. (2016) regarding hourly variations of indoor temperature for Kolkata buildings.

4.3.2 Statistical Association Analysis

4.3.2.1 The Correlation Analysis

In a multivariate scenario, the multiple correlation analysis assesses the statistical association among different variables. The analysis is performed for both *EPI* and *RETV* to identify their association with different influencing variables using 'SPSS Statistics' software (version 23). Both Pearson Correlation Coefficients (r) and Spearman's Rank Correlation Coefficients (r_s) are calculated. The coefficients showing significance at 0.01 level and 0.05 are reported and highlighted. Strong ($\pm0.5 < r < \pm1.0$) to moderate ($\pm0.3 < r < \pm0.5$) correlations are identified and necessary discussions are made.

4.3.2.2 The Regression Analysis

Multivariate regression analyses were run using 'SPSS Statistics' software (version 23) to generate regression equations, as described in Table 4.8, showing the mathematical relationship of the three energy performance indices viz. EPI, $EPI_{cooling}$, and $EPI_{lighting}$ with different influencing variables. All sixteen variables were taken into account for the regression analysis regarding overall *EPI*. For $EPI_{cooling}$, *VLT* was omitted as it will not influence the cooling energy consumption. The *EER*, U_{roof}, and *RETV* are not taken into account during the regression analysis for $EPI_{lighting}$ for the same reason.

4.3.3 Sensitivity Analysis for Identification of Critical Parameters Influencing the Building Energy Performance

To analyze the effects of the uncertainty in the input variables sensitivity analysis is widely used by researchers. Existing literature shows the use of sensitivity analysis in identifying the influence of building materials, geometry, design, meteorological, and occupant behavior parameters on building energy performance (Hemsath and Bandhosseini 2015; Kristensen and Petersen 2016; Yang et al. 2016; O'Neil and Niu 2017; Liu et al. 2017; Tian et al. 2018; Li et al. 2018; Rivalin et al. 2018; Gagnon et al. 2018; Vivian et al. 2020). Similar studies have been performed in the Indian context also. Singh et.al (2016) carried out sensitivity analyses of energy and daylight performances for an office building using external Venetian blind shading in Jodhpur and identified WWR, glazing type, blind orientation, and slat angle as the influencing factors. Gokarakonda et.al (2019) identified the cooling set-point temperature, building size, window SHGC, and exterior surface properties as influencing parameters when cooling energy consumption, thermal comfort conditions, and natural ventilation hours are considered for mixed-mode buildings in India.

The 'What If' kind of sensitivity analysis, through its iterative approach, typically identifies the critical parameter dependence of the solution and helps in decision-making. In the present study, this technique is adopted while assessing the influence of different input variables on *RETV* and *EPI* and the most critical ones demanding attention are identified. The 'TopRank' software (version 5.5) of Palisade Decision Tools Suite (2009) was used. The variables in the generated regression equation (as described in Table 4.10) were used for *EPI*, and for *RETV*, variables in the Eqn. (4.1) were used. These variables were varied in an iterative way and standard 'Tornado Diagrams' and 'Spider Diagrams' were generated for each case. Discussions are made regarding the critical influencing parameters thus identified.

4.4 Results and Discussion

In this study, ten different buildings were considered to understand the dependency of the *EPI* on building geometry parameters. Further, the dependence of *EPI* on different building envelope parameters was verified by varying them for all the buildings over five proposed design cases. The effect of these variations on operational energy performance, using the results of the energy simulations, is analyzed and presented. The association of the energy performance with the geometry and envelopn varying input parameters is assessed through correlation and regression analysis. The effect of these input parameters on energy performance is assessed through sensitivity analysis. In all the performed analyses cooling and lighting energy performance ($EPI_{cooling}$ and $EPI_{lighting}$) is considered along with the overall operational energy performance expressed in terms of *EPI*.

In Part I of the Eco-Niwas Samhita, 2018 code, RETV is defined as a single parameter that characterises the building envelope's thermal performance, considering walls and glass with the exception of the roof. Its variation is also noted for each of the ten buildings and the five suggested design scenarios. Additionally, the relation and sensitivity of *RETV* with the input parameters are also analyzed and reported.

4.4.1 Variation of *EPI* and *RETV* over Considered Design Cases

Variation of energy performance over the five proposed design cases expressed in terms of three energy performance indices viz. *EPI*, $EPI_{cooling}$, and $EPI_{lighting}$ are given in Table 4.5. The values are averaged for the ten considered buildings and the average percentage improvement of these indices for the considered design cases over the actual design in Case-1 are calculated and shown in Fig. 4.7 (A).

The overall *EPI*, the Eco-Niwas Samhita, 2018 compliant design (Case-2) demonstrate an improvement of 7.88% over the actual design (Case-1). The improvement is further increased to 17.14%, 21.37%, and 25.57% respectively for Case-3, Case-4, and Case-5 (ECBC, 2017 compliant levels). Earlier research regarding institutional and commercial buildings implementing ECBC specified and other energy efficiency measures have shown percentage energy savings in the order of 3.18-5.40% (Dutta and Neogi, 2013), 17-42% (Tulsyan et al. 2013), 18.42-37.20% (Chedwal et al. 2015), 37-75% (Bano and Sehgal, 2018) in various climatic zones of India.

In the current study, the principal focus of input variation is set on the envelope parameters that are expected to impact the $EPI_{cooling}$ most. As expected, the corresponding percentage improvements over the actual basecase design are more prominent (11.35%, 24.02%, 30.28%, and 36.34% respectively) for $EPI_{cooling}$. Pellegrino et al. (2016) reported that HVAC energy savings of 35-76% for residential buildings in Kolkata employing different low-cost energy efficiency measures.

Table 4.5: Energy Performance Improvement Observed for the Considered Design Cases

Building		**Design Cases**								
		Actual Design	**Eco-Niwas Samhita**		**ECBC (2017)**		**ECBC (2017) +**		**ECBC (2017) Super**	
		Case 1	**Case 2**		**Case 3**		**Case 4**		**Case 5**	
Parameters		**Energy Performance Index**	**Energy Performance Index**	**Percent Improvement over Actual**	**Energy Performance Index**	**Percent Improvement over Actual**	**Energy Performance Index**	**Percent Improvement over Actual**	**Energy Performance Index**	**Percent Improvement over Actual**
Symbol		*EPI*	*EPI*	I_{EPI}	*EPI*	I_{EPI}	*EPI*	I_{EPI}	*EPI*	I_{EPI}
Unit		kWh/m^2	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Overall (*EPI*)	Building 1	120.03	104.5	12.94	99.14	17.4	94.72	21.09	89.76	25.22
	Building 2	88.95	85.29	4.11	75.65	14.95	72.19	18.84	68.64	22.83
	Building 3	110.59	101.85	7.91	90.28	18.37	85.21	22.95	80.84	26.9
	Building 4	121.99	109.82	9.98	100.5	17.62	95.4	21.8	89.24	26.85
	Building 5	110.36	104.69	5.14	92.3	16.36	87.4	20.8	82.63	25.13
	Building 6	114.73	103.11	10.12	93.4	18.59	88.56	22.81	83.72	27.02
	Building 7	103.66	96.7	6.71	86.96	16.11	82.4	20.51	78.21	24.55
	Building 8	113.45	105.96	6.6	93.53	17.56	88.65	21.86	83.7	26.23
	Building 9	80.58	75.36	6.48	69.42	13.85	66.08	17.99	62.92	21.92
	Building 10	117.28	106.93	8.82	93.12	20.6	87.91	25.04	83.19	29.07
	Average	**108.16**	**99.42**	**7.88**	**89.43**	**17.14**	**84.85**	**21.37**	**80.28**	**25.57**
		±13.53	**±10.89**	**±2.64**	**±9.82**	**±1.93**	**±9.26**	**±2.04**	**±8.49**	**±2.12**
Cooling ($EPI_{cooling}$)		**73.72**	**65.19**	**11.35**	**55.9**	**24.02**	**51.32**	**30.28**	**46.85**	**36.34**
		±11.67	**±9.35**	**±2.92**	**±8.26**	**±1.47**	**±7.75**	**±1.44**	**±7.03**	**±1.43**
Internal Lighting ($EPI_{lighting}$)		**16.85**	**17.62**	**-4.7**	**17.68**	**-5.02**	**17.68**	**-5.02**	**17.68**	**-5.02**
		±1.57	**±1.55**	**±3.97**	**±1.56**	**±4.09**	**±1.56**	**±4.09**	**±1.56**	**±4.09**

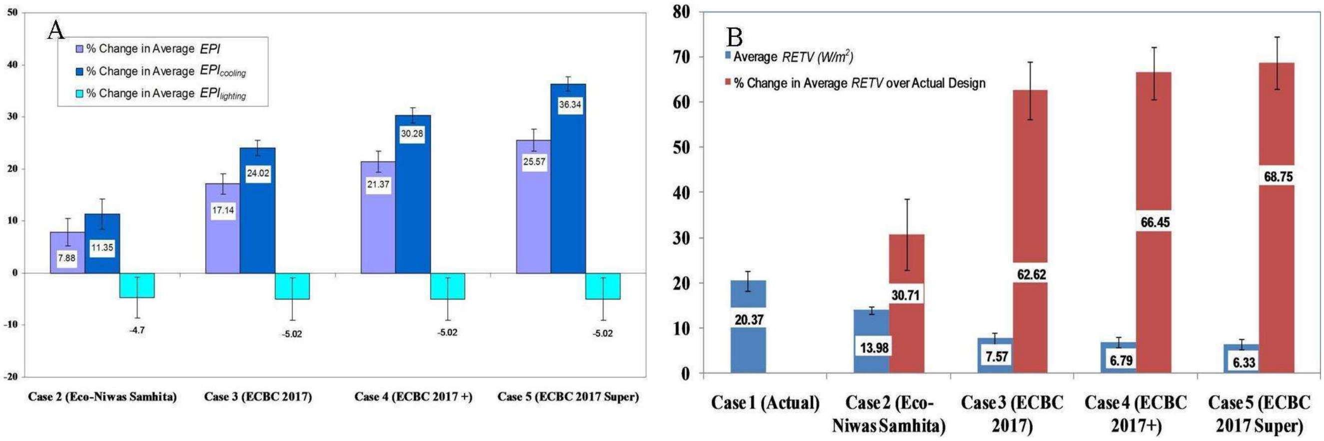


Figure 4.7: Variation of (A) EPI and (B) RETV over Considered Design Cases

The variation in internal annual lighting energy consumption performance expressed in terms of change in $EPI_{lighting}$, represents the day-lighting performance of the considered design cases. For the actual design (Case-1), the *VLT* of the common clear float glass is maximum (87.87%) and the corresponding day-lighting performance and $EPI_{lighting}$ is best compared to the code-specified minimum values at which the VLT for the remaining considered desig cases are set (28% for Case-2 and 27% for Case-3, Case-4, and Case-5). As expected, the $EPI_{lighting}$ of the code-compliant design cases increased slightly from the actual design and the percentage enhancement over the same became negative (-4.70% for Case-2 and -5.02% for Case-3, Case-4, and Case-5). However, this margial increment in $EPI_{lighting}$ failed to influence the improvement in overall *EPI* as it is overwhelmed by the much-improved performance in $EPI_{cooling}$.

The average RETV (averaged for the ten buildings under study) varies over the suggested design cases is given in Figure 4.7 (B), and the percentage improvement in the same illustrates the impact of changing the envelope parameters. The Case-2 design exhibits a 30.71% improvement over the Case-1 design, while the Case-3, Case-4, and Case-5 designs show improvements of 62.62%, 66.45%, and 68.75%, respectively.

4.4.2 Impact of Implementing Individual Compliance Parameters of Eco-Niwas Samhita, 2018 on $EPI_{cooling}$ and $EPI_{lighting}$

In the previous section, the overall impact of Eco-Niwas Samhita, 2018 code compliance on the operational energy performance of the considered buildings is reported by comparing the performances of the Case-1 and Case-2 models. To investigate the isolated impact of each of the compliance envelope parameters specified in the code viz. Openable Window to Floor Area Ratio (WFR_{op}), Visible Light Transmittance (*VLT*), Residential Envelope Transmittance Value (*RETV*) and Roof Thermal Transmittance (U_{roof}), and four additional subvariations in the Case-2 models (denoted as Case-2A, Case-2B, Case-2C and Case-2D) were considered. The subvariation Case-2A models all parameters were kept the same as the Case-2 compliant models, except WFR_{op} values which were kept unchanged from actual Case-1 models. The remaining three subvariations were built following the same method with remaining compliance parameters viz. U_{roof}, *RETV,* and *VLT* taking each one at a time. The results highlights the isolated impact of these individual parameters on building cooling and lighting energy performance.

Table 4.6 and 4.7 report the consequential impacts on $EPI_{cooling}$ and $EPI_{lighting}$ respectively. The increase in window area does not have significant impact on the $EPI_{cooling}$. It has caused a little more heat gain through the larger window area resulting in only a marginal 0.532% average increment in $EPI_{cooling}$. Reduction in roof thermal trasmittance value helped in reducing the building heat gain through the roof. The net average cooling energy savings in terms of improvement (reduction) in $EPI_{cooling}$ is 1.200% (0.879 kWh/m^2). All the buildings considered in the this study are high-rise apartment buildings (10-24 storeyed) and therefore, the envelope area is relatively higher compared to the roof area (12.60 times higher on average). As a result, restricting the RETV value alone has significantly improved (lowered) $EPI_{cooling}$ by 13.719% (10.361 kWh/m^2 on average).

Table 4.6: Isolated Impact of Changed WFR_{op}, $U_{roof,}$ and *RETV* on $EPI_{cooling}$

Building		**Design Cases**						
		Eco-Niwas Samhita	**Effect of WFR_{op}**		**Effect of U_{roof}**		**Effect of *RETV***	
		Case 2	**Case 2A**		**Case 2B**		**Case 2C**	
Parameters		**Energy Performance Index**	**Energy Performance Index**	**Percent Improvement over Case 2**	**Energy Performance Index**	**Percent Improvement over Case 2**	**Energy Performance Index**	**Percent Improvement over Case 2**
Symbol		$EPI_{cooling}$	$EPI_{cooling}$	$I_{EPI cooling}$	$EPI_{cooling}$	$I_{EPI cooling}$	$EPI_{cooling}$	$I_{EPI cooling}$
Unit		kWh/m^2	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Cooling ($EPI_{cooling}$)	Building 1	70.322	70.322	0.000	70.98	0.777	84.16	16.336
	Building 2	51.487	51.487	0.000	52.176	1.244	55.104	6.526
	Building 3	68.044	67.319	-0.952	69.157	1.461	83.156	19.85
	Building 4	73.523	73.52	-0.003	75.017	1.748	84.27	12.566
	Building 5	68.122	68.128	0.009	69.072	1.274	73.784	7.589
	Building 6	68.891	68.891	0.000	70.063	1.464	78.788	12.371
	Building 7	63.336	62.133	-1.723	63.428	0.132	77.299	19.983
	Building 8	69.922	69.922	0.000	70.742	1.05	77.293	9.441
	Building 9	45.457	45.457	0.000	46.35	1.733	50.735	10.242
	Building 10	72.747	70.593	-2.649	73.653	1.113	90.873	22.289
	Average	**65.185±9.35**	**64.777±9.18**	**-0.532±0.95**	**66.064±9.47**	**1.200±0.48**	**75.546±12.8**	**13.719±5.58**

Table 4.7: Isolated Impact of Changed WFR_{op} and VLT on $EPI_{lighting}$

Building		Design Cases				
		Eco-Niwas Samhita	Effect of WFR_{op}		Effect of VLT	
		Case 2	Case 2A		Case 2D	
Parameters		Energy Performance Index	Energy Performance Index	Percent Improvement over Case 2	Energy Performance Index	Percent Improvement over Case 2
Symbol		$EPI_{lighting}$	$EPI_{lighting}$	$I_{EPI\ lighting}$	$EPI_{lighting}$	$I_{EPI\ lighting}$
Unit		kWh/m^2	kWh/m^2	%	kWh/m^2	%
Lighting ($EPI_{lighting}$)	Building 1	17.256	17.256	0.000	16.577	-4.092
	Building 2	18.690	18.690	0.000	17.921	-4.290
	Building 3	17.140	17.934	4.689	16.576	-3.335
	Building 4	18.277	18.282	0.030	17.043	-7.239
	Building 5	19.390	19.404	0.077	17.946	-8.040
	Building 6	18.248	18.248	0.000	17.248	-5.801
	Building 7	17.334	18.065	4.302	16.730	-3.550
	Building 8	18.771	18.771	0.000	17.364	-8.101
	Building 9	13.807	13.807	0.000	12.586	-9.700
	Building 10	17.310	18.700	7.753	16.860	-2.507
	Average	**17.622±1.55**	**17.916±1.55**	**1.685±2.83**	**16.685±1.52**	**-5.666±2.46**

However, the larger window area is probably going to help with better day lighting, and as predicted, there is an average improvement (reduction) in $EPI_{lighting}$ of 1.685%. Lowering the VLT needed to comply with the code has a negative effect on day-lighting performance, which causing higher $EPI_{lighting}$. On average the value has deteriorated (increased) by 5.666% (0.937 kWh/m^2).

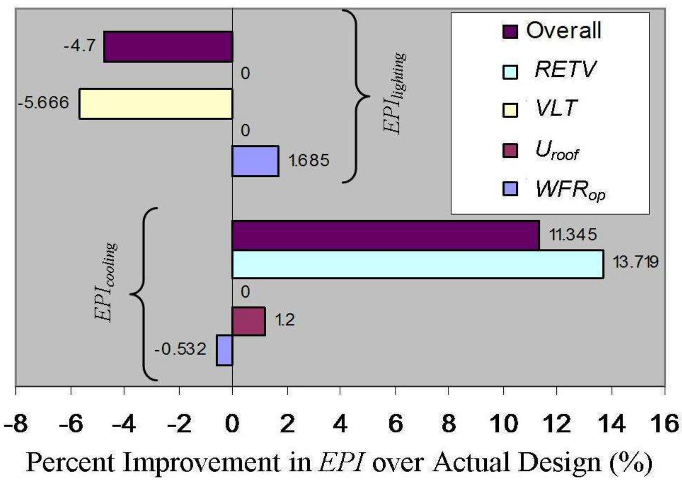


Figure 4.8: Impact of the Compliance Parameters on Percent Improvement in $EPI_{cooling}$ and $EPI_{lighting}$ over Actual Design

The overall impact and the improvement in EPI values for each compliance parameter separately are displayed in Figure 4.8. The code compliance measures as given in Eco-Niwas Samhita, 2018 have clearly resulted in substantial improvement in cooling energy consumption performance in terms of 11.345% (8.535 kWh/m^2) average saving in $EPI_{cooling}$. This is to be expected since the compliant design's heat transmittance and consequent heat gain through vertical facades and roofs were much lower than the actual ones. For lighting performance, the advantage of increased window area in code compliant models is observed to be nullified by the reduction in *VLT*. Overall, there is a minor decline in lighting energy consumption performance, with an increase in $EPI_{lighting}$ of 4.700% (0.767 kWh/m^2).

4.4.3 Correlation Analysis

One common method for determining the statistical relationship between various variables in a multivariate situation is multiple correlation analysis. With "SPSS Statistics" software (version 23), the same is done for both EPI and RETV to determine their relationship with the influencing variables. Both Pearson Correlation Coefficients (r) and Spearman's Rank Correlation Coefficients (r_s) are determined and those having significance at 0.01 level and 0.05 are emphasized and reported. The strong ($\pm 0.5 < r < \pm 1.0$) to moderate ($\pm 0.3 < r < \pm 0.5$) correlations are figure out and discussed.

4.4.3.1 Correlation Analysis for *EPI*

The association of the three energy performance indices viz. *EPI,* $EPI_{cooling,}$ and $EPI_{lighting}$ with the different influencing building design input variables are assessed and reported in Table 4.8. *EPI* is strongly correlated with *EER*, *VLT*, $U_{roof,}$ and *RETV*. A low to moderate negative association is observed with the $A_{envelope}$ and A_{roof}. The same variables are observed to have a similar type of correlation with $EPI_{cooling}$. For $EPI_{lighting}$ a strong positive correlation is observed with WWR_{east} and a moderate negative correlation with WWR_{south}.

Table 4.8: Correlation of Energy Performance Index (EPI) with Different Variables

Variables	*EPI*		$EPI_{cooling}$		$EPI_{lighting}$	
	Correlation Coefficients					
	Pearson Correlation Coefficient (r)	Spearman's Rank Correlation Coefficient (r_s)	Pearson Correlation Coefficient (r)	Spearman's Rank Correlation Coefficient (r_s)	Pearson Correlation Coefficient (r)	Spearman's Rank Correlation Coefficient (r_s)
$H_{building}$	-0.2141	-0.2217	-0.2035	-0.2135	0.0583	0.2142
H_{floor}	-0.0804	-0.0206	-0.0819	0.0049	0.1786	0.029
$A_{built\text{-}up}$	-0.2744	-0.3182*	-0.272	-0.3144*	0.1178	0.1925
A_{carpet}	-0.218	-0.3182*	-0.212	-0.3144*	0.0693	0.1925
$A_{envelope}$	-0.2985*	-0.2709	-0.2978*	-0.2512	0.1338	0.093
A_{roof}	-0.3269*	-0.1822	-0.3430*	-0.1836	0.2539	0.1862
EER	-0.5604**	-0.5939**	-0.5965**	-0.6344**	0.0867	0.1755
WWR	-0.1659	-0.2227	-0.1785	-0.212	0.0747	-0.067
WWR_{north}	-0.1713	-0.2001	-0.1621	-0.1731	-0.1826	-0.2441
WWR_{east}	0.0353	-0.027	-0.012	-0.0541	0.5292**	0.5130**
WWR_{south}	-0.1807	-0.1865	-0.1557	-0.1567	-0.3734**	-0.3700**
WWR_{west}	0.1	0.0579	0.0933	0.0412	0.118	0.2024
WFR_{op}	-0.2237	-0.1564	-0.24	-0.161	0.1291	0.0365
VLT	0.5596**	0.6464**	0.5930**	0.6716**	-0.2137	-0.3191*
U_{roof}	0.6718**	0.6797**	0.7103**	0.7139**	-0.2018	-0.2929*
RETV	0.7045**	0.6237**	0.7434**	0.6641**	-0.19	-0.3571*

** Correlation is significant at 0.01 level * Correlation is significant at 0.05 level

4.4.3.2 Correlation Analysis for *RETV*

Table 4.9 presents the statistical correlation between RETV and the various input variables, as indicated by Equation (4.1). *RETV* is found to be strongly correlated with the thermal transmittance value of the non-opaque windows ($U_{non\text{-}opaque}$ or U_{glass}), opaque wall (U_{opaque} or U_{wall}), and Solar Heat Gain Coefficient of the non-north window glass ($SHGC_{non\text{-}north}$). Moderate correlation is observed for *SHGC* of the north window glass.

Table 4.9: Correlation of Residential Envelope Transmittance Value (*RETV*) with Different Variables

Correlation Coefficients	Variables				
		U_{opaque} or U_{wall}	$U_{non\text{-}opaque}$ or U_{glass}	$SHGC_{north}$	$SHGC_{non\text{-}north}$
Pearson Correlation Coefficient (r)	*RETV*	0.9014**	0.9511**	0.4965**	0.8688**
Spearman's Rank Correlation Coefficient (r_s)	*RETV*	0.8365**	0.8707**	0.2191	0.8707**

** Correlation is significant at 0.01 level * Correlation is significant at 0.05 level

4.4.4 Regression Analysis

Using "SPSS Statistics" software (version 23), multivariate regression analyses are performed in order to create regression equations and establish a mathematical relationship between the three energy performance indices viz. *EPI*, $EPI_{cooling}$, and $EPI_{lighting}$ and the various influencing variables as listed in Table 4.8. For overall *EPI* all the sixteen variables are taken into account. For $EPI_{cooling}$, *VLT* was not considefed from the list as it is not going to influence the cooling energy consumption. For the same reason, *EER*, U_{roof}, and *RETV* are not taken into account while performing regression for $EPI_{lighting}$. Table 4.10 gives the regression outcomes as well as its statistical data.

The multiple R values, which are in the range of 0.9911, 0.9903, and 0.9938, indicate that the resultant regression models are capable of predicting *EPI* values based on input variables with excellent accuracy. Therefore, these regression models are subsequently applied in carrying out the sensitivity analyses as described in the following section.

Table 4.10: Results of the Regression of Energy Performance Index (*EPI*) with Different Variables

Variables	*EPI*	$EPI_{cooling}$	$EPI_{lighting}$
Regression Statistics			
Multiple R	0.9911	0.9903	0.9938
R Square	0.9824	0.9806	0.9876
Adjusted R Square	0.9738	0.972	0.9831
Standard Error	2.3234	2.1779	0.1985
Regression Equation (Intercept and Coefficients)			
Intercept	272.596	85.235	44.495
$H_{building}$	0.66	0.3051	0.011
H_{floor}	-43.7511	4.8374	-6.9662
$A_{built-up}$	0.0026	-0.006	0.0014
A_{carpet}	-0.0036	0.0078	-0.0023
$A_{envelope}$	0.0015	-0.0006	0.0013
A_{roof}	-0.0487	-0.0041	-0.0118
EER	-18.6648	-19.6273	Omitted
WWR	0.0452	-0.9763	0.234
WWR_{north}	5.027	2.5656	0.7477
WWR_{east}	0.1008	0.0295	0.1219
WWR_{south}	-5.5313	-2.9696	-0.7855
WWR_{west}	-0.3013	0.1225	-0.0558
WFR_{op}	1.1224	2.1046	-0.5266
VLT	-0.0913	Omitted	-0.0197
U_{roof}	5.3584	0.2292	Omitted
RETV	0.8137	1.261	Omitted

4.4.5 Sensitivity Analysis

4.4.5.1 Sensitivity Analysis for *EPI*

To estimate the uncertainty of different input parameters and their influence on the three energy performance indices viz. EPI, $EPI_{cooling,}$ and $EPI_{lighting}$, three sensitivity analyses or 'What-If' analyses were run and the results are reported in Fig. 4.9.

Both the tornado diagrams and spider diagrams represent the sensitivity of the energy performance indices to all the input variables as considered in the regression models described in the previous section. However, to draw significant conclusions only those variables having statistically significant moderate to strong correlation with the *EPI* (as reported in Table 4.8) are focussed. Amongst such input parameters, the percent change in overall *EPI* is found to be most sensitive to A_{roof} followed by $A_{envelope}$, *RETV*, U_{roof}, *EER* and *VLT*. For $EPI_{cooling}$ the order of the influencing input parameters however changed to *RETV* being the most influencing one followed by $A_{envelope}$, A_{roof}, *EER,* and U_{roof}. WWR_{south} is found to be having a greater influence on $EPI_{lighting}$ than WWR_{east} among the correlated variables.

4.4.5.2 Sensitivity Analysis for *RETV*

For *RETV*, variables in Eqn. (4.1) are varied across the considered design cases for each of the considered buildings in an iterative way. The result of the analysis is reported in Fig. 4.10 in the form of a tornado diagram (A) and a spider diagram (B).

The percent change in *RETV* is observed to be most sensitive to *SHGC* of the non-north window glass ($SHGC_{non\text{-}north}$) followed by the thermal transmittance of the opaque wall (U_{opaque} or U_{wall}). Amongst other variables, the non-opaque window area of the eastern façade ($A_{non\text{-}opaque\ east}$) and opaque wall area of the western façade (($A_{opaque\ west}$) influence the change in *RETV* most. Therefore, while deciding on the *RETV*, these are the variables to be looked into with the most importance.

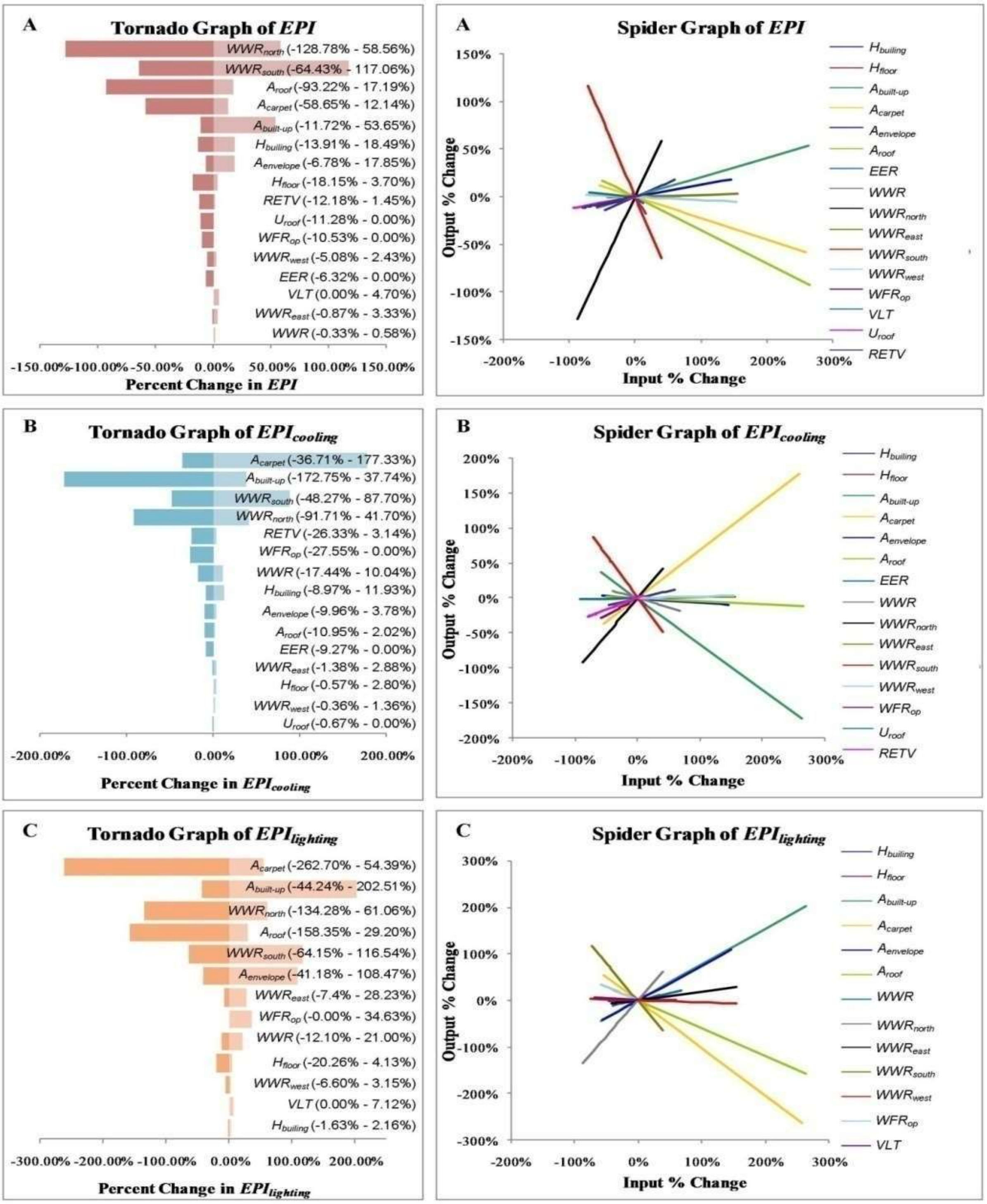


Figure 4.9: Sensitivity of Energy Performance Index (*EPI*) on Different Variables (A) Overall *EPI* (B) $EPI_{cooling}$ (C) $EPI_{lighting}$

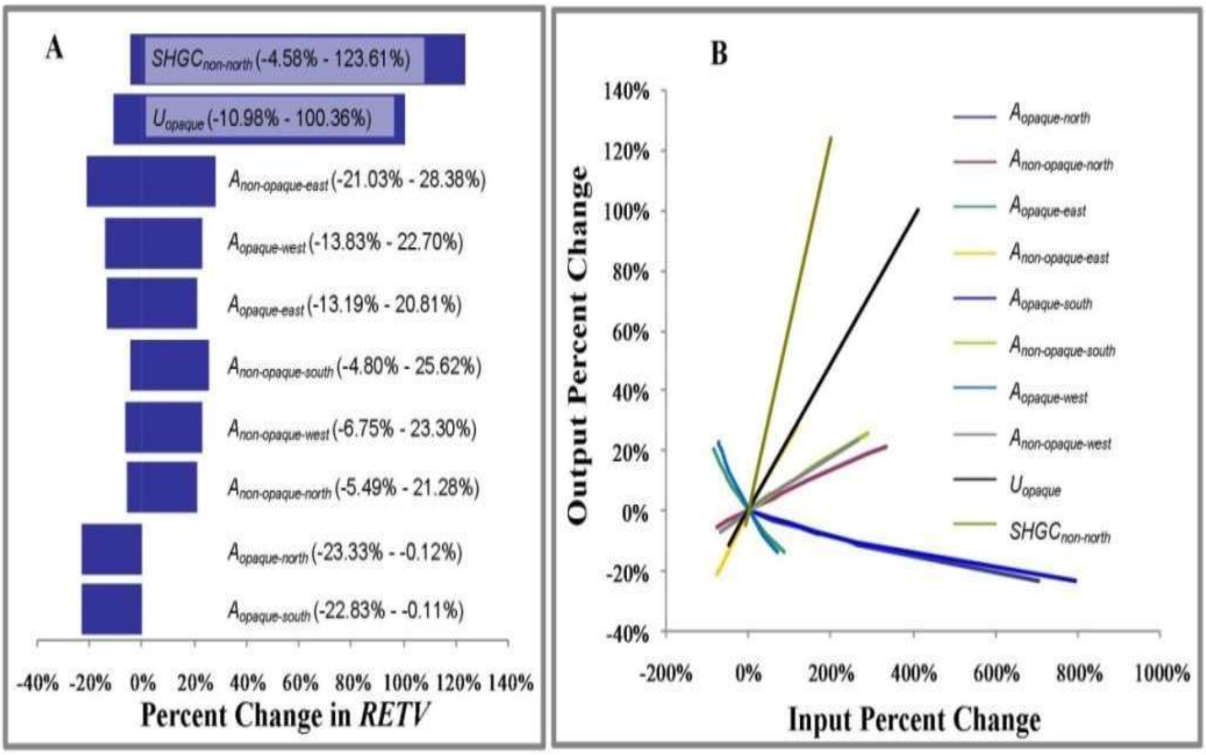


Figure 4.10: Sensitivity of RETV on Different Variables (A) Tornado Diagram (B) Spider Diagram

4.5 Summary and Outcome

The study in the present chapter has been carried out for high-rise residential apartment buildings in the warm-humid climate of Kolkata city. It has assessed the energy performance improvement of the buildings by complying with building envelope requirements in Eco-Niwas Samhita, 2018 (Part-1) and ECBC, 2017. The study results show, that compliance with the envelope standards of the codes has huge potential for overall and cooling energy savings (7.88-25.57% and 11.35-36.34% respectively) for residential apartments of Kolkata. Both overall *EPI* and $EPI_{cooling}$ are found to be strongly correlated with *RETV* (r = 0.7045, 0.7434), U_{roof} (r = 0.6718, 0.7103), *EER* (r = 0.5604, 0.5965) and *VLT* (r = 0.5596, 0.5930). In the warm-humid climate of Kolkata, cooling energy accounts for the major part of building operational energy. The study, through sensitivity analysis of the influencing parameters, identifies that the thermal transmittance of the building envelope in terms of *RETV* is going to play a key role in influencing cooling energy efficiency. The efficiency of the HVAC system in terms of *EER* also impacts the cooling energy efficiency significantly. Therefore, various envelope options and HVAC systems are explored in more detail in the subsequent chapters.

Chapter 5

Impact of Variation in Exterior Wall Assemblies on Energy and Environmental Performance of the Buildings

5.0 Introduction

The envelope of a building separates the habitable space from the outer environment, protects the building occupants from the adversities of the outer environment, and provides a chance to make the living space comfortable for the building occupants as per their needs. The indoor environment and the energy required to maintain it depend largely on the nature of the façade of a building. Facades serve as the envelope's vertical parts comprising opaque (walls) and transparent (glazed openings) elements, which essentially impart a character to the building. Since the indoor thermal and visual environment depends largely on the nature of the façade of a building, the energy required to maintain the occupant's comfort (space cooling, space heating, and space lighting components of the building's operational energy) is directly related to the same. The materials used in and the construction method of a building façade also determine the embodied energy of the same. These energy components and associated greenhouse gas (GHG) emissions over a building's life cycle contribute to the environmental impact of the building.

The study in Chapter 4, has identified that the thermal transmittance of the building facade is going to play a key role in influencing building cooling energy efficiency. In the present chapter, the energy and environmental performance of typically practiced façade options and their sustainable alternatives are dealt with in detail. Operational and embodied energy performance and associated GHG emissions of nine exterior wall assemblies are also compared for the same ten typical high-rise residential apartment buildings in Kolkata, India. The overall energy performance and GHG emission for the studied buildings are assessed by combining their embodied energy component with operational energy component considering a building lifespan of fifty years.

5.1 Different Alternatives for Exterior Wall Assemblies and their Thermal Properties and Environmental Impacts

Masonry is the simplest, and most widely used technique used to build opaque envelopes since the beginning of human civilization, where small pieces of masonry units like stone, bricks, etc. are stacked upon one another in numerous patterns to reach the desired shape and design (Allen and Iano, 2019). These masonry units are bound together using binder mortars placed between two adjacent units. Once the masonry walls are built, they are covered both inside and outside with plasters and finished by applying paints. The combination acts as the skin to the masonry to protect the same against natural adversities like water moisture, wind, other atmospheric elements, etc. to prevent weathering decay. Both these skins and additional insulating materials further prevent unwanted transport of heat across the opaque envelope to maintain a comfortable indoor thermal environment.

Figure 5.1: Masonry Unit Alternatives

Rising concern about climate change and the role of building construction in it has resulted in widespread research regarding the energy and environmental performance of wall construction materials along with others. The possibility of reduction in energy consumption and operational and embodied GHG emission reduction by enhancing the envelope design is evident from the results of such studies. In the present study, six types of masonry units presently popular in the construction of residential apartment buildings in India as shown in Fig. 5.1 are studied in terms of their energy and environmental performance. The physical, thermal, and environmental properties of different variations of these masonry units are summarized in Table 5.1. Energy Conservation Building Codes (BEE, 2017; BEE, 2018] by the Bureau of Energy Efficiency (BEE), the Government of India has also identified these units as potential candidates for masonry units. The composition of material constituents and the production process of the same are discussed briefly in the subsequent sections.

Table 5.1: Physical, Thermal Properties, and Environmental Impacts of Different Masonry Units

Serial No.	Masonry Units		Physical and Thermal Properties			Environmental Impact	
	Name	Description	Density	Thermal Conductivity	Specific Heat Capacity	Embodied Energy Coefficient	Global Warming Potential
Symbol			ρ	λ	c	EE_{coef}	GWP
Unit			kg/m^3	W/m.K	kJ/kg.K	MJ/kg	kg CO_2 eq/kg
1	M1_SBCB	Solid Burnt Clay Brick	1600	0.740	0.80	4.40	0.390
2	M2_REHB	Resource Efficient Hollow Brick	1520	0.631	0.65	3.50	0.310
3	M3_FAB	Fly Ash Brick	1650	0.856	0.93	0.83	0.200
4	M4_SCB	Solid Concrete Block 25/50	2427	1.396	0.20	1.30	0.160
5	M5_AACB	Aerated Autoclaved Concrete Block	642	0.184	1.24	3.70	0.500
6	M6_CSEB	Cement Stabilized Soil Block	1700	1.026	1.03	0.11	0.010
7	M7_DCB	Dense Concrete Block	2410	1.740	0.88	1.30	0.160
8	M8_RCC	Reinforced Cement Concrete	2288	1.580	0.88	1.90	0.200

[Source: IFC, 2017; CBERD & MNRE; BEE, 2017; BEE, 2018]

5.1.1 Burnt Clay Bricks

Solid Burnt Clay Bricks (SBCB) of different dimensions and densities are the most popular masonry units for wall construction in India. Most of the low to midrise apartment buildings use SBCB for façade construction. Other available alternative forms of burnt clay bricks are Resource Efficient Hollow Bricks (REHB) and honeycomb bricks are hollow bricks with low water absorptivity, better finish, and improved crushing strength. These bricks use a lesser quantity of materials and provide greater thermal resistance due to insulation provided by the air gaps inside the units. India annually produces about 260 billion bricks and the process of production essentially includes clay extraction and processing, brick forming, drying, and burning the bricks. Bull's Trench Kilns contribute the major share of production (about 70%) followed by Clamp Kilns, High Draught Zigzag Kilns, and Hoffman Kilns. The fuels used at different stages of production are diesel, coal, firewood, and biomass fuels. As much as 24 million metric tons of coal is used annually for brick production in India. As a result, the embodied energy and associated GHG emissions for burnt clay bricks are higher compared to other alternatives (IFC, 2017; CBERD & MNRE).

5.1.2 Fly Ash Bricks or Blocks

The constituents of Fly Ash Bricks or Blocks are fly ash, lime, gypsum, and quarry dust and after mechanical mixing the blocks are cured with water. Since fly ash, the chief constituent is a waste material, embodied energy and associated GHG emissions of the blocks are much lower than the conventional masonry units. They are also cheaper compared to burnt clay bricks and are hugely popular as well (IFC, 2017).

5.1.3 Light, Medium, and Dense Solid Concrete Blocks

Cement, expanded clay, sand, and water are used to prepare hollow or solid lightweight (density around 1100 kg/m^3) and medium-weight (density around 1450 kg/m^3) concrete blocks. Solid and dense concrete blocks (density 1800-2500 kg/m^3) are prepared using OPC, gravel, and sand. Two types of solid concrete blocks (viz. Concrete Block 25/50 and 30/60) also known as concrete masonry units (CMU) are precast with smooth sides and are gaining popularity in the construction industry for making walls. These blocks have higher thermal transmittance than the SBCB but the embodied energy content is comparatively much lower (IFC, 2017; CBERD & MNRE).

5.1.4 Aerated Autoclaved Concrete (AAC) Blocks

Aerated Autoclaved Concrete also known as Aircrete is a porous, lightweight, and resource-efficient precast construction material available as blocks, wall panels, floor and roof panels, and lintels. The main advantages of AAC are many folds including very high thermal resistance, fire, and mould resistance. Compared to other masonry alternatives AAC is much lighter (density around 500-700 kg/m^3) which reduces the material requirement of the RCC frames by reducing the dead load. Aircrete blocks are prepared by steam curing a mix of sand or pulverized fuel ash (PFA), cement, lime, anhydrite (gypsum), and an aeration agent. The easy workability of AAC allows accurate cutting and installation minimizing solid waste generation. India has more than 25 manufacturers of AAC and around 4 million cubic meters of AAC are produced annually. AAC is becoming increasingly popular as a masonry unit alternative and its demand is increasing rapidly (IFC, 2017; CBERD & MNRE).

5.1.5 Cement Stabilized Earthen (Soil) Blocks (CSEB)

Ordinary Portland Cement (OPC), Portland Slag Cement, and Pulverized Fly Ash (PFA) are generally used as stabilizing additives (10%) to extracted, sieved, and processed soil (90%) along with water to produce compressed CSEB. Once compressed, these blocks are cured for 4-5 days in natural air which lowers the embodied energy and associated GHG emission by many folds compared to other alternative masonry units (IFC, 2017; CBERD & MNRE).

5.1.6 Reinforced Cement Concrete (RCC) Walls

Apart from the different masonry units discussed so far, steel-reinforced cement concrete (RCC) walls are also practiced particularly for constructing the exterior walls of high-rise apartment buildings. The ready-mix concrete used in RCC uses either Ordinary Portland Cement (OPC) or Portland Pozzolana Cement (PPC) replacing 30% of OPC. Typical M40 concrete in India has cement (11%), gravel (47%), sand (37%), and water (5.7%) as per IS 10262: 2009 (BIS, 2009). Replacing 30% of cement with pozzolana (fly ash) reduces the embodied energy of the concrete mix as well as the associated GHG emission. To make walls or other structural elements ready-mix concrete is reinforced with steel reinforcement bars or a mesh of steel wires strengthening the structure and holding the concrete in tension (IFC, 2017; CBERD & MNRE).

5.1.7 The Binders: Mortars

Mortars are used to fill the space between masonry units to keep water and wind from penetrating and bind them together into a monolithic structural unit during masonry construction. At the very beginning of masonry constructions, mud, smeared into the joints of the rising wall served as mortars. The knowledge of turning limestone into lime, which developed later, gradually caused the replacement of mud with lime mortar (Allen and Iano, 2019).

Till the early 20th century traditional lime mortars, made from a mix of lime, sand, and water were very popular. It continues to find use principally in the restoration of historic structures. Lime is a non-hydraulic cement, and mortar made with the same cure through a gradual reaction with carbon dioxide in the atmosphere called carbonation. The lime mortar remains partially water-soluble and retains some ability to self-heal in the event of hairline cracking caused by movement within the wall. Lime mortar also allows the masonry to be easily reclaimed and reused at the end of life (Allen and Iano, 2019; IFC, 2017; CBERD & MNRE).

Table 5.2: Physical, Thermal Properties, and Environmental Impacts of Different Mortars

Serial No.	Mortars		Physical and Thermal Properties			Environmental Impact	
	Name	Description	Density	Thermal Conductivity	Specific Heat Capacity	Embodied Energy Coefficient	Global Warming Potential
Symbol			ρ	λ	c	EE_{coef}	GWP
Unit			kg/m^3	W/m.K	kJ/kg.K	MJ/kg	kg CO2
1	MR1_CMR	Cement Mortar	1648	0.719	0.92	1.10	0.140
2	MR2_LMR	Lime Mortar	1646	0.730	0.88	1.60	0.430

[Source: IFC, 2017; CBERD & MNRE; BEE, 2017; BEE, 2018]

Cement mortar, a mixture of cement, sand, and water is the most popular choice of the modern era due to the quick setting and hardening time favorable for rapid construction, owing to the hydraulic property of the cement. As the bond between cement mortar and masonry units is very strong, the resultant masonry cannot be reused at the end of its life. The ratio of cement to sand varies from 1:2-1:6 depending on the necessity and type of construction (Allen and Iano, 2019; IFC, 2017; CBERD & MNRE). Table 5.2 summarizes the mortar properties.

5.1.8 The Skin (Plasters and Claddings)

Plasters and claddings act like skin on the masonry surface to make a smooth finish and to protect it from different weather agents. Cement-based plaster constituted of cement (16%), sand (75%), and water (11%) is the most popular and versatile, weather-resistant material used for the purpose. Gypsum plasters prepared by mixing calcined gypsum with water are generally used as interior coatings for masonry walls and other building interior features. For high-end constructions, exterior walls are often covered with Aluminium composite panels (ACP) or polished stone claddings to give the façade intended luxurious character (IFC, 2017; CBERD & MNRE). The properties are summarized in Table 5.3 as follows.

Table 5.3: Physical, Thermal Properties, and Environmental Impacts of Different Plasters and Claddings

Serial No.	Plasters and Claddings		Physical and Thermal Properties			Environmental Impact	
	Name	Description	Density	Thermal Conductivity	Specific Heat Capacity	Embodied Energy Coefficient	Global Warming Potential
Symbol			ρ	λ	c	EE_{coef}	GWP
Unit			kg/m^3	W/m.K	kJ/kg.K	MJ/kg	kg CO2 eq/kg
1	PL1_CPL	Cement Plaster	1762	0.721	0.84	4.80	0.440
2	PL2_GPL	Gypsum Plaster	1120	0.512	0.96	1.30	0.099
3	CL1_ACP	Aluminum Composite Pannel	1520	0.245	0.84	220.00	18.000
4	CL2_GPL	Polished Stone Cladding				3.70	0.310

[Source: IFC, 2017; CBERD & MNRE; BEE, 2017; BEE, 2018]

5.2 Objectives and Framework of the Study

The study in the present chapter is focused on the following objectives as detailed below. The different stages involved in the study framework are presented in Fig. 5.2.

- To study the impact of façade variations on operational energy performance and associated GHG emissions of the studied buildings
- To study the impact of façade variations on embodied energy performance and associated GHG emissions of the studied buildings

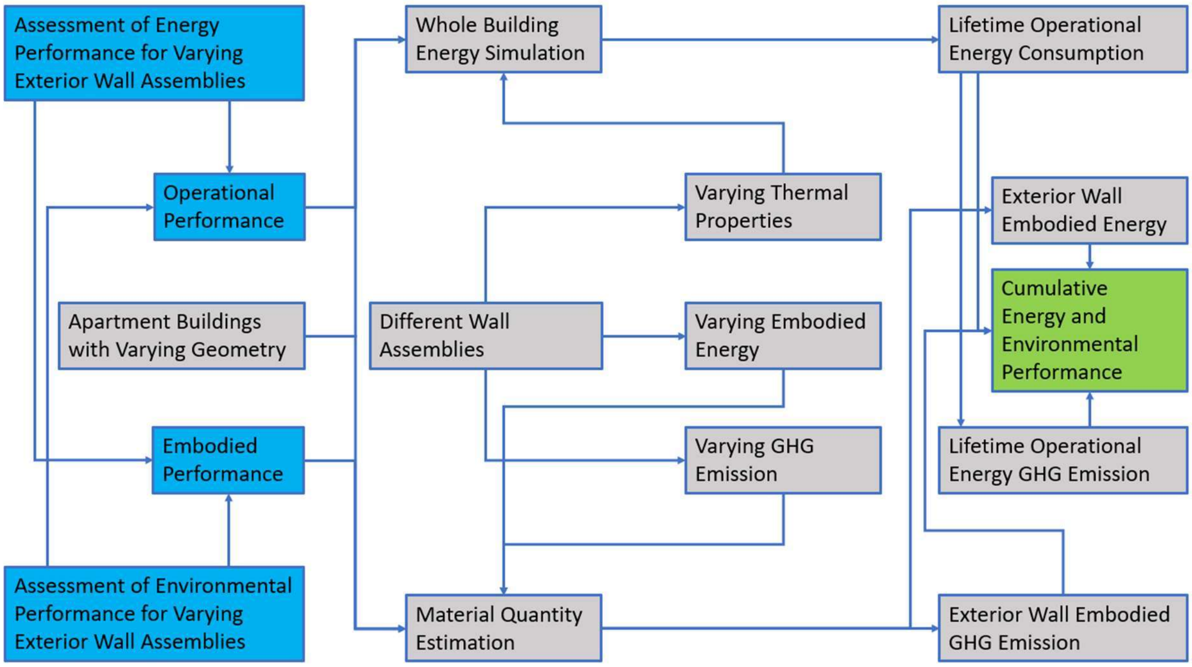


Figure 5.2: Framework of the Study

To assess the overall energy performance and GHG emission for the studied buildings by combining their embodied energy component with operational energy component considering a building lifespan of fifty years for each of the façade options.

5.3 Methodology

5.3.1 Building Operational Energy Performance for Different Exterior Wall Assemblies

Solid Burnt Clay Bricks (SBCB) is a typical choice of masonry units for exterior walls in Kolkata with cement plaster (CPL) applied outside and inside. This along with eight other alternative wall assemblies with different masonry units (as described in Table 5.1) are considered. One SBCB wall assembly, one curtain wall assembly (two layers of SBCB wall with an insulating air gap in between) along with one assembly with Resource Efficient Hollow Bricks (REHB) are chosen for burnt clay bricks. Two variations of concrete blocks (SCB and DCB), one assembly of Cement Stabilized Soil Blocks (CSEB), and one assembly of AAC blocks are also considered. Apart from that two additional wall assemblies with Fly Ash Bricks (FAB) and RCC are also studied. The outside and inside plasters are kept the same for all the cases. No cladding or wall insulation is considered as these are not commonly practiced in apartment buildings.

Table 5.4: Façade Variations Considered in the Simulation Cases

Envelope Parameters	Applicable Simulation Case	Construction Name and Description		Symbol	Unit	Value
Wall Transmittance	Case-1	Wall1_BW	20mm Cement Plaster+203.2mm Solid Burnt Clay Brick+12mm Cement Plaster	U_{wall}	W/m^2°K	2.05
	Case-2	Wall2_CW	20mm Cement Plaster+75mm SBCB+ 50mm air gap+75mm SBCB+12mm Cement Plaster			1.74
	Case-3	Wall3_REHB	20mm Cement Plaster+200mm Resource Efficient Hollow Brick+12mm Cement Plaster			1.88
	Case-4	Wall4_FAB	20mm Cement Plaster+200mm Fly Ash Brick+12mm Cement Plaster			2.23
	Case-5	Wall5_SCB	20mm Cement Plaster+200mm Solid Concrete Block 25/50+12mm Cement Plaster			2.80
	Case-6	Wall6_AACB	20mm Cement Plaster+300mm Autoclaved Aerated Concrete Block+12mm Cement Plaster			0.54
	Case-7	Wall7_CSEB	20mm Cement Plaster+200mm Cement Stabilized Soil Block+12mm Cement Plaster			2.44
	Case-8	Wall8_DCB	20mm Cement Plaster+200mm Dense Concrete Block+12mm Cement Plaster			3.04
	Case-9	Wall9_RCC	20mm Cement Plaster+300mm Reinforced Cement Concrete+12mm Cement Plaster			2.47
Roof Transmittance	Case-1-9	Roof1_RCC	12mm Ceramic Tile+30mm Cement Mortar+152.4mm RCC+12mm Cement Plaster	U_{roof}	W/m^2°K	2.69
Window Glazing Properties	Case-1-9	Window1_SGU 6mm Clear Float Glass	Transmittance	U_{glass}	W/m^2°K	5.69
			Visual Light Transmittance	*VLT*	%	87.87
			Solar Heat Gain Coefficient	*SHGC*		0.81
			Window Shading			Yes

[Source: BEE, 2018; Kumar et al., 2021]

Table 5.4 presents details of the nine wall assemblies with respective thermal transmittance values calculated following the methodology specified in Annexure-5 of Eco-Niwas Samhita, Part-I (2018) (BEE, 2018). Typical RCC roofs as practiced in Kolkata apartments are considered for all the buildings. Kolkata apartments typically use single-glazed units (SGU) with clear float glasses of 6 mm thickness for windows and the same is kept unaltered across all the considered façade variations. Based on the properties of the market available options the values for Transmittance, Visual Light Transmittance, and Solar Heat Gain Coefficient are taken as shown in Table 4.2 of Chapter 4. Therefore, the comparison of energy and environmental performance of the façade assemblies is going to reflect the variation in the masonry units only.

5.3.1.1 Framing Energy Simulation Models

The operational energy of a building is the energy required to run the building during its operational lifetime and consists of energy required for space heating, space cooling, space lighting, running different appliances, etc. (Paul, Thakur, and Chakrabarty, 2011). The annual operational energy requirements for each of the ten studied buildings are assessed through whole building energy simulation using eQUEST 3.65 building energy simulation tool. The energy simulation models of each building are framed for nine different façade variations (as detailed in the previous Section) using the software's 'Design Development Wizard' following drawing and design documents. The building geometry as described in Table 3.2 of Chapter 3 is kept unaltered across all the nine cases for a particular building.

As the main purpose of this study is to see the impact of façade variations on the building energy performance, all other parameters regarding HVAC, lighting, equipment, occupancy, and schedules as described subsequently are kept the same for all the ten buildings across all the considered cases while framing the energy simulation models. Typical split air conditioners with BEE 3 Star efficiency (as recommended baseline by the (BEE, 2021) as generally used for the conditioned spaces of the Kolkata apartments are modelled. The cooling systems are sized by the 'Auto-Size' capability of eQUEST 3.65. For interior lighting power density (LPD) recommendation of ASHRAE (2016) is followed. A daylight control measure was activated during the energy simulation. The receptacle equipment power density (EPD) is kept the same as the software defaults. 5 kW intermittently operating elevators are assigned to the buildings as per the building drawings.

5.3.1.2 Energy Simulation

Once the energy simulation models were framed the simulations were run to assess the annual operational energy requirement (for 8760 hours) for the studied buildings for all the seventeen façade variations. The energy Plus weather file for Kolkata (IND_Kolkata.428090_ISHRAE.epw) is collected and converted to eQUEST usable format by eQUEST weather processor which is used during the energy simulations. The annual energy consumption (kWh) for each case is normalized as the Operational Energy Performance Index (*EPI_OE* in kWh/m^2/Year) as expressed in Eqn. (5.1). The other simulation input parameters are summarized in Table 5.5.

$$EPI\_OE = \frac{annual\_energy\_consumption}{A_{built-up}}$$ Equation (5.1)

Table 5.5: Different Parameters Considered During Energy Simulation

Simulation Parameters	Symbol	Unit	Values
HVAC System Type	Split System, Single Zone DX		
BEE Star Rating			3 Star
Cooling Energy Efficiency Ratio	*EER*	W/W	3.8
Zone Cooling set point		deg F	78
Zone Heating set point		deg F	68
Occupancy		m^2/Person	12.50 (as per National Building Code, 2016)
Fresh Air Ventilation		CFM/Person	30.00 (Software Default)
Lighting Power Density	*LPD*	W/ ft^2	0.70 (as per ANSI, ASHRAE, IES 90.1- 2016)
Daylight Control	30% light power dimming during daylight hours in the daylit areas		
Equipment Power Density	EPD	W/ ft^2	0.30 (Software Default)
Elevator Power	5 kW/Elevator (number of elevators is as per the actual drawing)		

[Source: ASHRAE, 2016; BIS, 2016]

5.3.2 Building Embodied Energy Performance for Different Exterior Wall Assemblies

In order to find out the embodied energy of the different façade variations considered in the present study, the masonry work quantity for each case is estimated for all ten buildings using the standard centre line method (Chakraborti, 1987). Once the volume of the masonry units, cement mortar, and cement plasters are found out, the mass quantities for each are estimated using the material densities provided in Table 5.1 through Table 5.3. The mass quantities of the masonry items (*M* in kg) are then multiplied by respective embodied energy coefficients (EE_{coef}

in MJ/kg) and are cumulated to find out the embodied energy for the exterior walls of a building per unit built-up area (*EE_Ext_Wall* in kWh/m^2) for a particular façade option using Eqn. (5.2).

$$EE\_Ext\_Wall = 0.2778 \times \left[\frac{\sum M \times EE_{coef}}{A_{built-up}}\right] \quad \text{Equation (5.2)}$$

5.3.3 Combined Energy Performance of the Buildings for Different Exterior Wall Assemblies over Operational Life

The energy simulation estimates a building's annual operational energy requirement. It has to be multiplied by the service life of a building (*SL_Building* in years) to get the total Lifetime Operational Energy Consumption (*OE_Life* in kWh/m^2) of the same during its lifetime as shown in Eqn. (5.3). The reference service life (RSL) is taken as 50 years in this study. *OE_Life* for a building for each of the façade variations is then added with the corresponding *EE_Ext_Wall* to calculate the Cumulative Energy Performance Index (*EPI_Cumulative* in kWh/m^2) as shown in Eqn. (5.4). The process is repeated for all ten buildings and the results are averaged.

$$OE\_Life = EPI\_OE \times SL\_Building \quad \text{Equation (5.3)}$$

$$EPI\_Cumulative = OE\_Life + EE\_Ext\_Wall \quad \text{Equation (5.4)}$$

5.3.4 Environmental Performance of the Considered Variation in Exterior Wall Assemblies

The GHG emission due to operational energy consumed over a building's lifetime (*GHG_OE_Life* in kg CO_2 eq/m^2) is found out by multiplying the Lifetime Operational Energy Consumptions (*OE_Life* in kWh/m^2) with the average GHG emission factor of the Indian electricity grid taken as 0.91 kg CO_2 eq/kWh (Satola et al., 2022) using Eqn. (5.5).

$$GHG\_OE\_Life = 0.91 \times OE\_Life \quad \text{Equation (5.5)}$$

To find out the embodied GHG emission, the following procedure is adopted. The mass quantities of the masonry items (*M* in kg) for a façade alternative are multiplied by respective

Global Warming Potentials (GWP in kg CO_2 eq/kg) using the material data provided in Table 5.1 through Table 5.3. These are cumulated to find out the Exterior Wall Embodied GHG Emission of a building per unit built-up area ($GHG\_Embodied\_Ext\_Wall$ in kg CO_2 eq/m^2) for that particular façade option using Eqn. (5.6). The cumulative GHG emission ($GHG\_Cumulative$ in kg CO_2 eq/m^2) is estimated by adding the operational and embodied components using Eqn. (5.7).

$$GHG\_Embodied\_Ext\_Wall = \left[\frac{\sum M \times GWP}{A_{built-up}}\right] \quad \text{Equation (5.6)}$$

$$GHG\_Cumulative = GHG\_OE\_Life + GHG\_Embodied\_Ext\_Wall \quad \text{Equation (5.7)}$$

5.4 Results and Discussion

5.4.1 Comparison of the Building Operational Energy Performance for different exterior wall assemblies

The energy performance of the façade alternatives as described in Table 5.4 are assessed and compared based on operational and embodied energy. The annual operational energy requirements of the buildings considering the nine alternative exterior wall assemblies are estimated and projected over the operational lifetime of the buildings. The embodied energy is estimated only for the exterior walls with the considered alternatives. Finally, they cumulated and the energy performances are presented per unit area of the considered buildings.

Operational Energy Performance Index (EPI_OE in kWh/m^2/Year) as expressed in Eqn. (5.1) and the result is presented in Table 5.6. Amongst the nine external wall assemblies' variations studied, Wall6_AACB made with AAC blocks as masonry units shows the best performance regarding operational energy consumption (least consumption) for all the buildings while Wall8_DCB uses dense concrete blocks (DCB) is observed to consume the highest operational energy. AAC blocks are composed of fly ash, cement, lime, aluminum powder, and water. and Notable performance of AAC blocks is due to its pore structure that offers thermal insulating properties.

Table 5.6: Operational Energy Requirement of the Studied Buildings for Different Façade Variations

Building	Operational Energy Performance Index								
Symbol	*EPI_OE*								
Unit	kWh/m²/Year								
Construction Name	**Wall1_ BW**	**Wall2_ CW**	**Wall3_ REHB**	**Wall4_ FAB**	**Wall5_ SCB**	**Wall6_ AACB**	**Wall7_C SEB**	**Wall8_ DCB**	**Wall9_ RCC**
Building 1	102.72	101.95	102.32	103.16	104.30	98.64	103.62	104.71	103.68
Building 2	82.26	81.16	81.68	82.90	84.64	76.98	83.58	85.31	83.68
Building 3	95.98	94.72	95.31	96.70	98.70	89.79	97.48	99.48	97.59
Building 4	105.91	104.58	105.21	106.67	108.75	99.33	107.49	109.55	107.60
Building 5	98.98	97.74	98.33	99.69	101.79	92.93	100.48	102.62	100.60
Building 6	99.97	98.83	99.36	100.66	102.68	94.23	101.45	103.46	101.56
Building 7	90.33	89.04	89.65	91.09	93.19	84.24	91.91	94.03	92.02
Building 8	97.35	95.82	96.54	98.23	100.69	90.33	99.19	101.64	99.33
Building 9	75.47	74.50	74.96	76.05	77.72	71.28	76.69	78.39	76.78
Building 10	97.57	96.01	96.74	98.49	101.03	89.90	99.48	102.02	99.63
Mean	**94.65**	**93.43**	**94.01**	**95.36**	**97.35**	**88.76**	**96.14**	**98.12**	**96.25**
S.D.	**9.41**	**9.35**	**9.38**	**9.44**	**9.53**	**8.98**	**9.47**	**9.56**	**9.48**

Table 5.7: Exterior Wall Embodied Energy of the Studied Buildings for Different Façade Variations

Building	Exterior Wall Embodied Energy Consumption								
Symbol	*EE_Ext_Wall*								
Unit	kWh/m²								
Construction Name	**Wall1_ BW**	**Wall2_ CW**	**Wall3_ REHB**	**Wall4_ FAB**	**Wall5_ SCB**	**Wall6_ AACB**	**Wall7_C SEB**	**Wall8_ DCB**	**Wall9_ RCC**
Building 1	381.89	297.81	299.61	122.24	202.41	167.40	69.15	201.42	353.52
Building 2	352.28	274.72	276.38	112.76	186.72	154.43	63.79	185.80	326.11
Building 3	267.49	208.60	209.85	85.62	141.77	117.25	48.44	141.08	247.62
Building 4	414.42	323.19	325.13	132.66	219.66	181.67	75.04	218.58	383.64
Building 5	184.97	144.25	145.12	59.21	98.04	81.08	33.49	97.56	171.23
Building 6	343.44	267.83	269.44	109.93	182.03	150.55	62.19	181.14	317.92
Building 7	268.98	209.76	211.02	86.10	142.56	117.91	48.71	141.87	249.00
Building 8	364.84	284.52	286.23	116.78	193.37	159.93	66.06	192.43	337.74
Building 9	304.18	237.22	238.65	97.37	161.23	133.34	55.08	160.43	281.59
Building 10	318.28	248.20	249.70	101.88	168.69	139.52	57.63	167.87	294.63
Mean	**320.08**	**249.61**	**251.11**	**102.46**	**169.65**	**140.31**	**57.96**	**168.82**	**296.30**
S.D.	**66.83**	**52.12**	**52.43**	**21.39**	**35.42**	**29.30**	**12.10**	**35.25**	**61.87**

5.4.2 Comparison of the Building Embodied Energy Performance for different exterior wall assemblies

The results for all the buildings for all nine façade variations are presented in Table 5.7. Wall7_CSEB made with cement-stabilized soil blocks as masonry units is found to be the most efficient in terms of embodied energy consumption whereas Wall1_BW with conventional solid burnt clay bricks is found to be the least energy efficient. Walls with Fly ash brick (lesser by 212.40%) and AAC blocks (lesser by 128.12%) showed moderate improvement in embodied energy performance compared to brick walls.

5.4.3 Combined Energy Performance of the Buildings for Different Façade Alternatives over Operational Life

The average energy performance of the ten buildings for each of the nine façade variations is presented in Table 5.8. Figure 5.3 shows the percentage change in operational, embodied, and cumulative energy performance of the considered façade variations over solid burnt clay brick wall (Wall1_BW). The AAC Block wall (Wall6_AACB) is found to be the most energy efficient in terms of cumulative energy performance while the reinforced cement concrete wall (Wall9_RCC) is observed to be the least.

5.4.4 Comparison of the Environmental Performance of the considered variations in exterior wall assemblies

The environmental performances of the façade alternatives for each of the ten buildings are estimated in terms of their operational, embodied, and cumulative GHG emission potentials. Each of these three parameters is averaged for the ten buildings and the results are presented in Table 5.8. Figure 5.4 shows the percentage change in operational, embodied, and cumulative GHG emissions of the considered façade variations over solid burnt clay brick wall (Wall1_BW). The operational and cumulative GHG emissions are found to be the least for AAC block walls (Wall6_AACB) and the embodied emission is lowest for walls with cement-stabilized earthen blocks (Wall7_CSEB) showing the same pattern as energy performance. The highest operational and cumulative GHG emissions are observed for dense concrete block walls (Wall8_DCB). For embodied GHG emission, however, reinforced cement concrete wall (Wall9_RCC) is found to be the highest emitter.

Table 5.8: Comparative Energy and Environmental Performance of Different Façade Alternatives

Exterior Wall Construction Name	Energy Performance			Environmental Performance		
	Lifetime Operational Energy Consumption	**Exterior Wall Embodied Energy**	**Cumultaive Energy Performance Index**	**Lifetime Operational Energy GHG Emission**	**Exterior Wall Embodied GHG Emission**	**Cumultaive GHG Emission**
Symbol	*OE_Life*	*EE_Ext_Wall*	*EPI_Cumulative*	*GHG_OE_Life*	*GHG_Embodied_Ext_Wall*	*GHG_Cumulative*
Unit	kWh/m^2	kWh/m^2	kWh/m^2	$kg\ CO_2\ eq/m^2$	$kg\ CO_2\ eq/m^2$	$kg\ CO_2\ eq/m^2$
	Mean ± S.D.	Mean ± S.D.	Mean ± S.D.	Mean ± S.D.	Mean ± S.D.	Mean ± S.D.
Wall1_BW	4732.70 ± 470.33	320.08 ± 66.83	5052.77 ± 489.72	4306.75 ± 428.00	102.69 ± 21.44	4409.44 ± 433.33
Wall2_CW	4671.73 ± 467.48	249.61 ± 52.12	4921.34 ± 482.08	4251.27 ± 425.41	80.20 ± 16.75	4331.48 ± 429.55
Wall3_REHB	4700.47 ± 468.91	251.11 ± 52.43	4951.58 ± 483.51	4277.43 ± 426.71	80.64 ± 16.84	4358.07 ± 430.84
Wall4_FAB	4768.19 ± 471.94	102.46 ± 21.39	4870.65 ± 477.16	4339.06 ± 429.46	61.51 ± 12.84	4400.57 ± 432.50
Wall5_SCB	4867.41 ± 476.39	169.65 ± 35.42	5037.06 ± 485.14	4429.34 ± 433.51	69.41 ± 14.49	4498.75 ± 436.82
Wall6_AACB	4438.23 ± 449.20	140.31 ± 29.30	4578.54 ± 457.21	4038.79 ± 408.77	60.29 ± 12.59	4099.08 ± 412.02
Wall17_CSEB	4806.86 ± 473.69	57.96 ± 12.10	4864.82 ± 476.49	4374.24 ± 431.06	19.11 ± 3.99	4393.35 ± 431.95
Wall8_DCB	4906.03 ± 477.93	168.82 ± 35.25	5074.85 ± 486.46	4464.49 ± 434.92	69.04 ± 14.42	4533.53 ± 438.13
Wall9_RCC	4812.36 ± 473.97	296.30 ± 61.87	5108.66 ± 491.23	4379.25 ± 431.31	109.79 ± 22.92	4489.04 ± 436.90

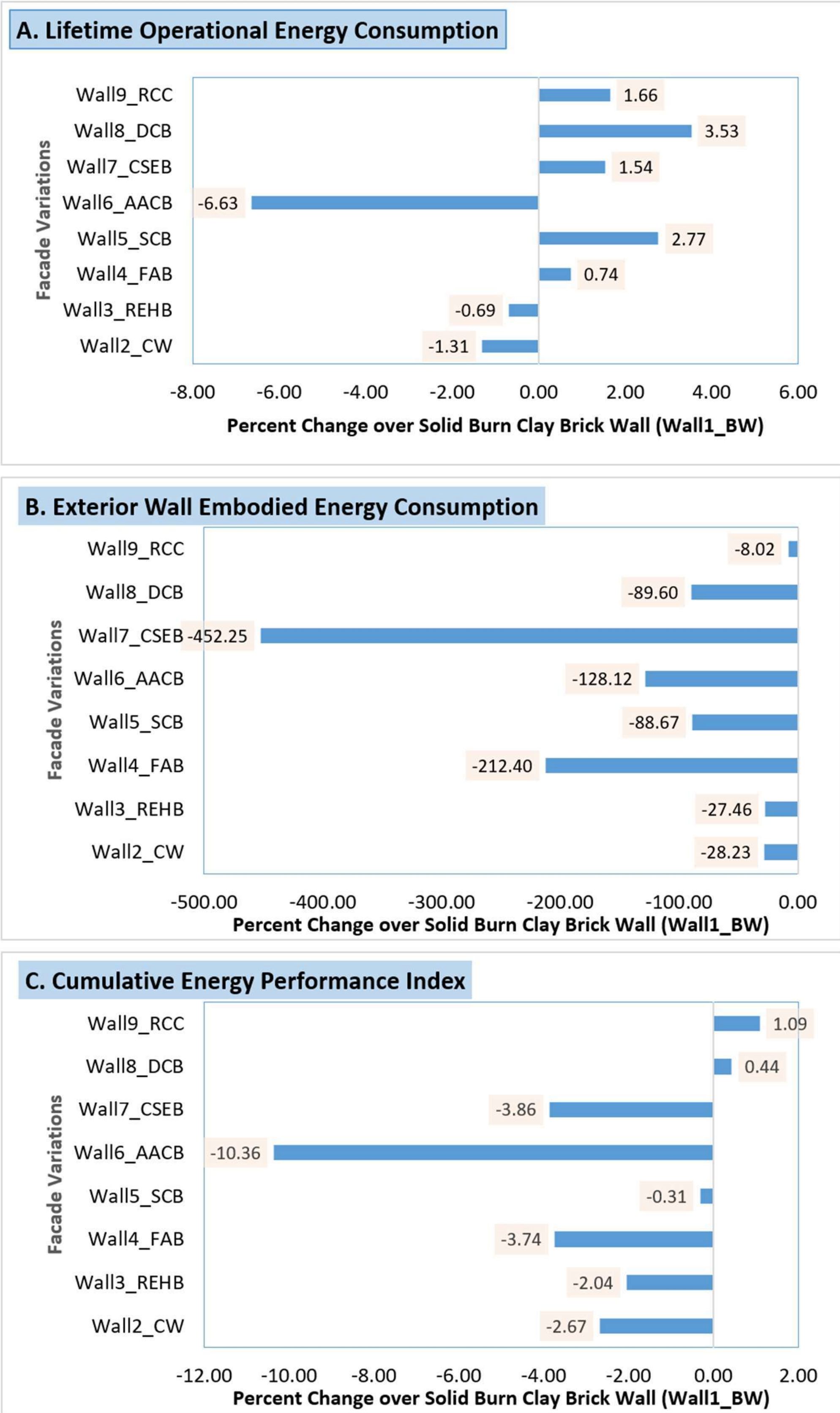


Figure 5.3: Percent Change in the Energy Performance of Façade Alternatives over Solid Burnt Clay Brick Wall

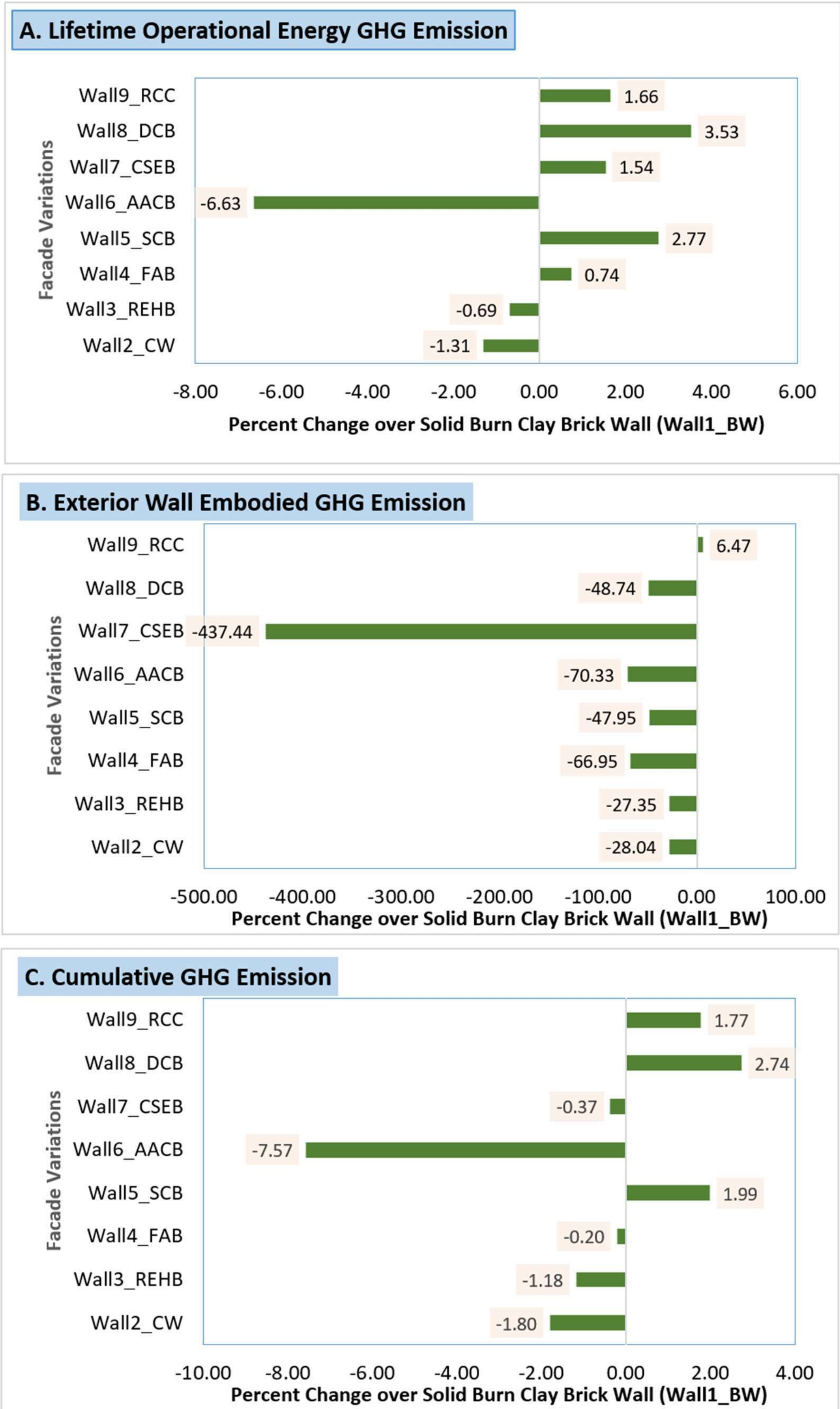


Figure 5.4: Percent Change in the GHG Emission of Façade Alternatives over Solid Burnt Clay Brick Wall

5.5 Summary and Outcomes

The environmental impact of solid burnt clay bricks has always been of great concern because of non-renewable resource consumption, energy consumption, water consumption, GHG emissions, and waste generation. Research is going on to find sustainable alternatives that could reduce the use of virgin clay, recycle different industrial wastes having low embodied energy, and provide improved thermal properties. Besides reviewing the recent research trends in this regard, it also compared the operational and embodied energy performance and associated GHG emissions of eight alternative exterior wall assemblies with the common solid burnt clay brick wall for ten high-rise residential apartment buildings in Kolkata, India. Walls made with AAC blocks showed 6.63% (operational) and 10.36% (overall) improvement in energy performance and 6.63% (operational) and 7.57% (overall) lesser GHG emission compared to brick walls. Walls with cement-stabilized soil blocks showed best embodied energy performance (lesser by 452.25%) and least embodied GHG emission (lesser by 437.44%) than brick walls. Reinforced cement concrete walls and dense concrete block walls are found to be the worst performing in terms of energy and GHG emission amongst the chosen alternatives in this study.

Analysis in the previous chapter (Chapter 4) identified thermal transmittance of the exterior façade and the efficiency of the HVAC systems are the key factors impacting the energy efficiency of high-rise residential buildings in warm-humid climate and need to be explored in detail. The energy performance, combining the embodied and operational energy impacts of different exterior wall options is studied in detail and reported in the present chapter along with associated GHG emissions. In the next chapter (Chapter 6) a detailed integrated methodology to determine the most suitable combination of outside walls with matching RAC out of available options for the best energy efficiency and economy will be presented.

Chapter 6

Impact of Combined Variation in Air Conditioners and Exterior Wall Assemblies on Energy and Economic Performance of the Buildings

6.0 Introduction

India is experiencing enormous urbanization due to rapid economic and population growth. Projections indicate that India's residential built-up area in urban regions will grow over three times over 30 years, from 5.9 billion square meters in 2020 to 22.2 billion square meters by 2050 (Rawal et al., 2020). The expansion of the built-up area increases cooling needs significantly. India's cooling action plan predicts an almost eight-fold increase in overall cooling demand across sectors from 2017–18 to 2037–38. Building space cooling load is projected to grow nearly 11 times during the same period, accounting for 74% of total cooling demand by 2037–38, up from 57% in 2017–18 (MoEF&CC, 2019). Energy-efficient envelope materials combined with efficient AC systems can help manage this increasing cooling energy demand effectively (Stephan and Stephan, 2016).

Energy consumption per unit land area of high-rise buildings is high, specifically for space cooling in warm-humid climates. With the globally increasing high-rise buildings in big cities, the energy efficiency of such buildings is emerging as a critical issue. Properly selected outside walls of buildings combined with the selection of a suitable room air conditioner (RAC) can offer an optimal solution for the best energy efficiency and economy. The energy performance, combining the embodied and operational energy impacts of different exterior wall options is studied in detail as reported in Chapter 5 along with associated GHG emissions. The study in the present chapter reports a detailed integrated methodology to determine the most suitable combination of outside walls with matching RAC out of available options for the best energy efficiency and economy. The study is conducted with the data of the same ten typical high-rise residential apartment buildings in Kolkata, India. The optimum recommended solution is obtained through an iterative process with whole building energy simulation for all possible combinations of wall material, its construction as well as selection of a suitable air conditioner. The methodology is demonstrated with data from Kolkata, India. Though the finally recommended best combination of wall and RAC for this study is based on Indian (specifically, Kolkata) data, the demonstrated methodology is generic and may be used for any other location.

6.1 Objectives and Framework of the Study

The study in the present chapter is focused on the following objectives as detailed below.

- To study the effect of varying combinations of exterior walls and air-conditioners on the operational energy performance of typical high-rise residential apartments in the warm-humid climate of Kolkata.
- To study the cost-effectiveness of the chosen wall-AC combinations
- To find out the optimum wall-AC combination for the possible best energy performance at a minimum cost considering the time value of money.

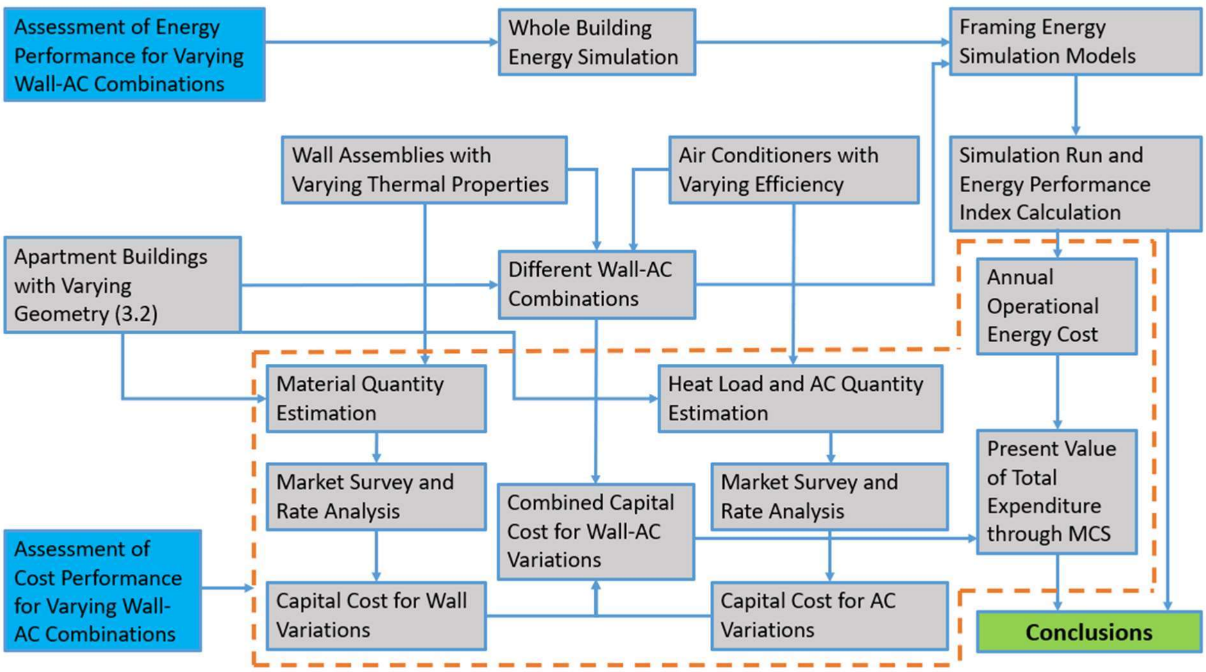


Figure 6.1: Framework of the Study

To fulfill the mentioned objectives, the study in this chapter is carried out on the same ten typical high-rise residential apartment buildings in the warm-humid climate of Kolkata, India. For each building, forty-five wall-AC combinations are modelled and explored considering nine wall configurations and five instances of active cooling measures. A market survey has been conducted for available energy-efficient market products and the corresponding cost-effectiveness is also analyzed. To tackle the uncertainties linked with stochastic input variables, Monte Carlo Simulation (MCS) is used. To find the best technological as well as business solutions for enhancing the operational energy performance of buildings, the cost-effectiveness of the stated combinations is studied considering the cash flow over fifteen years. The different stages involved in the study framework are presented in Fig. 6.1.

6.2 Methodology

6.2.1 Assessment of Energy Performance

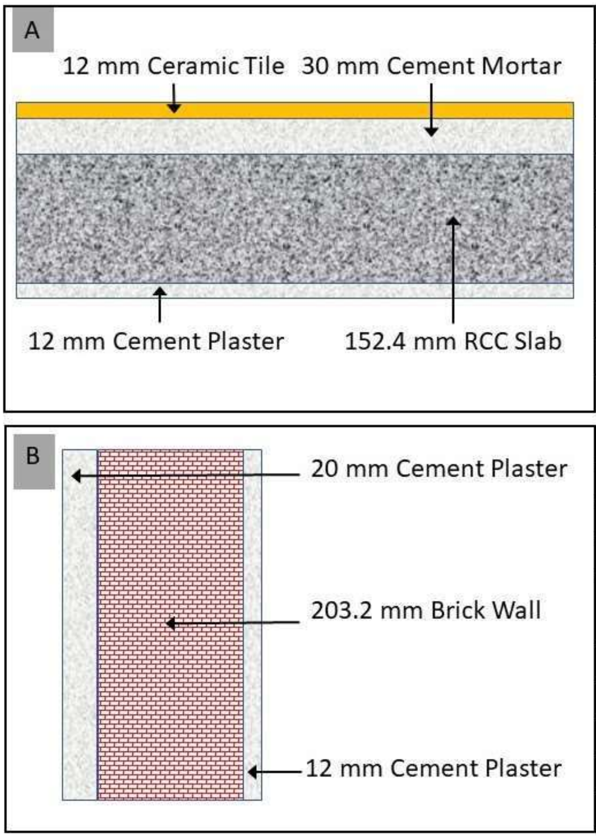
6.2.1.1 Framing Energy Simulation Models

The annual operational energy requirements for each of the ten buildings under this study were assessed through whole building energy simulation using eQUEST 3.65 building energy simulation tool. The energy simulation models of the buildings were framed using the 'Design Development Wizard' of the software following drawing and design documents. The details of the studied buildings are already provided in Chapter 3. Basic building geometry and orientation, as described in Table 3.2, were kept unaltered across all the design cases for a particular building. Typical floor plans and views of the energy simulation models for the studied buildings are shown in Fig. 4.2.

6.2.1.1.1 Baseline Case Envelope Details

In framing the opaque envelope for the baseline design case (Case-1) for the studied buildings, the roof and wall construction typically opted for Kolkata were considered and the material layer combinations with respective thermal properties are shown in Fig. 6.2. In calculating the thermal transmittance of the roof and the wall the calculation methodology as specified in the Annexure-5 of Eco-Niwas Samhita, Part-I (2018) was followed (BEE, 2018).

For window glazing, single-glazed units (SGU) with clear float glasses of 6 mm thickness as typically practiced in Kolkata, were considered. Based on the market available options for such products, the average values are considered for Transmittance (U_{glass} = 5.69 W/m^2°K), Visual Light Transmittance (*VLT* = 87.87%), and Solar Heat Gain Coefficient (*SHGC* = 0.81) (Kumar et al., 2021). The same values were used here across all the design cases.



Material Layer	Thickness	Conductivity	Resistance
Symbol	t_i	k_i	R_i
Unit	mm	W/m°K	m²°K/W
Ceramic Tile	12.0	1.5996	0.0075
Cement Mortar	30.0	0.7190	0.0417
RCC Slab	152.4	1.5800	0.0965
Cement Plaster	12.0	0.7210	0.0166
Interior Surface Film Thermal Resistance (R_{si})			0.1700
Exterior Surface Film Thermal Resistance (R_{se})			0.0400
Total Thermal Resistance (R_T)			0.3723
Roof Thermal Transmittance (U_{roof}) = 2.6860 W/m²°K			

Material Layer	Thickness	Conductivity	Resistance
Symbol	t_i	k_i	R_i
Unit	mm	W/m°K	m²°K/W
Cement Plaster	20.0	0.7210	0.0277
Solid Burnt Clay Brick	203.2	0.7400	0.2746
Cement Plaster	12.0	0.7210	0.0166
Interior Surface Film Thermal Resistance (R_{si})			0.1300
Exterior Surface Film Thermal Resistance (R_{se})			0.0400
Total Thermal Resistance (R_T)			0.4889
Wall Thermal Transmittance (U_{wall}) = 2.0454 W/m²°K			

Figure 6. 2: Typical Construction of the Opaque Envelope (A) Roof (B) Exterior Wall for the Baseline Case (Case-1).

Table 6.1: Envelope Parameters Considered in the Simulation Cases

Envelope Parameters	Applicable Simulation Case	Construction Name and Description		Symbol	Unit	Value
Wall Transmittance	Case-1	Wall1_BW	20mm Cement Plaster+203.2mm Solid Burnt Clay Brick+12mm Cement Plaster	U_{wall}	W/m²°K	2.05
	Case-2	Wall2_CW	20mm Cement Plaster+75mm SBCB+ 50mm air gap+75mm SBCB+12mm Cement Plaster			1.74
	Case-3	Wall3_REHB	20mm Cement Plaster+200mm Resource Efficient Hollow Brick+12mm Cement Plaster			1.88
	Case-4	Wall4_FAB	20mm Cement Plaster+200mm Fly Ash Brick+12mm Cement Plaster			2.23
	Case-5	Wall5_SCB	20mm Cement Plaster+200mm Solid Concrete Block 25/50+12mm Cement Plaster			2.80
	Case-6	Wall6_AACB	20mm Cement Plaster+300mm Autoclaved Aerated Concrete Block+12mm Cement Plaster			0.54
	Case-7	Wall7_CSEB	20mm Cement Plaster+200mm Cement Stabilized Soil Block+12mm Cement Plaster			2.44
	Case-8	Wall8_DCB	20mm Cement Plaster+200mm Dense Concrete Block+12mm Cement Plaster			3.04
	Case-9	Wall9_RCC	20mm Cement Plaster+300mm Reinforced Cement Concrete+12mm Cement Plaster			2.47
Roof Transmittance	Case-1-9	Roof1_RCC	12mm Ceramic Tile+30mm Cement Mortar+152.4mm RCC+12mm Cement Plaster	U_{roof}	W/m²°K	2.69
Window Glazing Properties	Case-1-9	Window1_SGU 6mm Clear Float Glass	Transmittance	U_{glass}	W/m²°K	5.69
			Visual Light Transmittance	*VLT*	%	87.87
			Solar Heat Gain Coefficient	*SHGC*		0.81
			Window Shading			Yes

[Source: BEE, 2018; Kumar et al., 2021]

6.2.1.1.2 Wall Construction Options

Apart from the typical brick wall as modelled in the baseline design case (Case-1), eight additional wall variations (Case-2 through Case-9) as detailed in Table 6.1, were modelled for each building. These wall materials were chosen from Annexure-5 of Eco-Niwas Samhita, Part-I, 2018 namely solid burnt clay brick (SBCB), Resource-efficient hollow brick (REHB), fly ash brick (FAB), solid concrete block (SCB), autoclaved aerated concrete block (AACB), cement stabilized soil block (CSEB), dense concrete block (DCB), and reinforced cement concrete (RCC) (BEE, 2018). The thermal transmittance of these wall materials was calculated as before. Other properties for roof and window glazing were retained unaltered from Case-1 to Case-9.

6.2.1.1.3 Heating, Ventilation, and Air Conditioning (HVAC) Options

Split air conditioners are typically used in high-rise residential buildings of Kolkata and were also modelled here with five efficiency variations (Case-A through Case-E). For the baseline design case (Case-A), 1 star-rated AC as per the preceding BEE Star Rating applicable from 1st January 2018 to 31st December 2020 was considered (BEE, 2021a). BEE specified HVAC system efficiencies (3-star, 4-star, and 5-star rated AC as per prevailing BEE Star Rating applicable from 1st January 2021 to 31st December 2023) were followed in Case-B, Case-C, and Case-D models (BEE, 2021 a, b). For the Case-E model, 5-star rated AC as per the next proposed BEE star rating was considered. For all the simulation runs, the cooling systems were sized by the 'Auto-Size' capability of eQUEST 3.65. Different HVAC-related parameters used in framing the energy simulation models are summarized in Table 6.2.

6.2.1.1.4 Lighting and Other Loads

For all the design cases American Society of Heating, Refrigerating and Air-Conditioning Engineers recommended values were considered for the interior lighting power density (*LPD*) [40]. As the main purpose of the study is to explore the impact of wall and HVAC variation on building energy consumption, exterior lighting was not considered during energy simulation. However, the impact of day-lighting was considered by activating the daylight control feature of the software during energy simulation. Being residential apartments, the operational schedules for the studied buildings were typically considered as daytime unoccupied (on weekdays) residential ones, and the schedule for occupancy, internal lighting, and equipment was chosen accordingly. The relevant information is summarized in Table 6.3.

Table 6.2: Heating, Ventilation, and Air Conditioning (HVAC) Parameters Considered for the Different Design Cases

HVAC Parameters	Symbol	Unit	Design Cases				
			BEE (Old)	BEE (Prevailing)			BEE (Proposed)
			Case-A	Case-B	Case-C	Case-D	Case-E
HVAC System Type			Split System, Single Zone DX				
BEE Star Rating			1 Star	3 Star	4 Star	5 Star	5 Star
Cooling Energy Efficiency Ratio	*EER*	W/W	3.1	3.8	4.4	5.0	5.5
Zone Cooling set point		deg F	78	78	78	78	78
Zone Heating set point		deg F	68	68	68	68	68
Occupancy		m^2/Person	12.50 (as per National Building Code, 2016)				
Fresh Air Ventilation		CFM/Person	30.00 (Software Default)				

Table 6.3: Lighting and other Load Details

Simulation Parameters	Symbol	Unit	Values
Lighting Power Density	*LPD*	W/ ft^2	0.70 (as per ANSI, ASHRAE, IES 90.1- 2016)
Daylight Control			30% light power dimming during daylight hours in the daylit areas
Equipment Power Density	EPD	W/ ft^2	0.30 (Software Default)

6.2.1.1.5 Annual Operational Energy Requirements

Energy simulations for a total of forty-five design cases with nine wall variations (Case-1 to Case-9) and five AC variations (Case-A to Case-E) were carried out for each of the ten studied buildings. Operational energy requirements for each of these cases were determined through energy simulation following the 'Whole Building Performance Method' as described in ECBC, 2017 (BEE, 2017). The simulation tool used was eQUEST 3.65, a front-end to the DOE-2.2 engine. The Energy Plus weather file for Kolkata (IND_Kolkata.428090_ISHRAE.epw) was used in the simulations, which was converted to eQUEST usable format by the eQUEST weather processor. The latest urban commercial tariff rate from Calcutta Electric Supply Corporation, the electricity provider in Kolkata city, was used as the electricity tariff in the energy simulations (CESC, 2022). The simulations were run to assess the annual operational energy requirement (for 8760 hours) under different heads. The annual operational energy consumption (*OE_Annual* in kWh/Year) for each simulation case was normalized as the operational energy performance index (*EPI_OE* in kWh/m^2/Year) as expressed in Eqn. (6.1) while reporting.

$$EPI\_OE = \frac{OE\_Annual}{A_{built-up}}$$ Equation (6.1)

6.2.2 Financial Impact of Wall and AC Variations

6.2.2.1 Wall Cost Estimation

The quantities of required materials for the nine alternative wall assemblies considered in the study were estimated for all ten buildings using the standard centre-line method (Chakraborti, 1987). Once the quantities of materials (in m^3 for masonry and m^2 for cement plaster and cavity) were found, the corresponding mass quantities (in kg) for each were estimated using the material densities provided in Table 6.4.

Table 6.4: Density and Cost Rates of Wall Construction Materials

Wall Materials	Density	Cost Rates	
		Material Cost Rates	Construction Cost Rates
Symbol	ρ	C_{Wall_Mat}	C_{Wall_Con}
Unit	kg/m^3	INR/m^3 *INR/m^2	INR/m^3 *INR/m^2
Solid Burnt Clay Brick	1600	5500	9400
Resource Efficient Hollow Brick	1520	11430	15300
Fly Ash Brick	1650	4450	10400
Solid Concrete Block	2427	9800	14400
Aerated Autoclaved Concrete Block	642	3510	8100
Cement Stabilized Soil Block	1700	8310	12200
Dense Concrete Block	2410	13350	19000
Reinforced Cement Concrete	2288	12670	16640
20 mm Cement Plaster*	1762	142	584
12 mm Cement Plaster*	1762	85	527
Cavity in Wall2_CW*			194

[Source: BEE, 2017; BEE, 2018; CPWD, 2021; Market Survey by Authors]

A market survey was conducted to get the present market rates of different masonry items considered in the nine alternative wall assemblies studied presently. The average material cost rates ($C_{Wall\text{-}Mat}$ in INR/m^3 for masonry and INR/m^2 for cement plaster) were calculated based on the survey data obtained from multiple vendors. Construction cost rates ($C_{Wall\text{-}Con}$ in INR/m^3 for masonry and in INR/m^2 for cement plaster and cavity) for each were calculated based on these material cost rates following the ‘analysis of rates’ as specified by the Central Public Works Department (CPWD, 2021). The cost rates are provided in Table 6.4.

The quantities of the masonry items were then multiplied by respective construction cost rates and were cumulated to estimate the wall construction costs for each of the buildings for all nine wall assembly alternatives using Eqn. (6.2). The resulting cost is presented as the wall capital cost (CC_Wall in INR/m^2) per unit built-up area of the building for a particular façade option.

$$CC\_Wall = \left[\frac{\sum Q \times C_{Wall\_Con}}{A_{built-up}}\right] \qquad \text{Equation (6.2)}$$

6.2.2.2 HVAC Cost Estimation

The present study explored split air conditioners with five efficiency variations for all the studied buildings. A step-by-step methodology elaborated subsequently was followed to assess the cost impact of choosing more efficient air conditioners (Case-B, Case-C, Case-D, and Case-E) compared to the baseline case (Case-A). The process involved in estimating the associated cost is to find out how many split air conditioners of what capacity would be required to cater to the cooling load of the conditioned spaces of a building. The cost of the air conditioners with different efficiency ratings was then estimated through a market survey.

6.2.2.2.1 Cooling Load Estimation

In the first step, the cooling load of each of the conditioned spaces (bedrooms and living rooms) of an apartment on the typical floor of a building was determined. Cooling load is the rate at which heat must be extracted from a space to maintain a desired room condition. Heat gain occurs through the building envelope whenever the exterior temperature exceeds the interior temperature. The rate is affected primarily due to the properties of the covering materials (glazing, roof, side walls, doors, window frames, and end walls). The other sources of heat gain are from the lighting, equipment, occupancy, infiltration, and ventilation air.

The cooling load of the conditioned spaces (bedrooms and living rooms) of an apartment was estimated following the guidelines of the ISHRAEE HVAC Handbook, 2007, and ASHRAE Handbook - Fundamentals, 2017 (ISHRAE, 2007; ASHRAE, 2017). A summary of the design parameters considered during cooling load estimation for air conditioner sizing is shown in Table 6.5. A typical industry-practiced heat load calculation spreadsheet format utilizing the total equivalent temperature differential (TETD) method was used to perform the required calculation in a structured manner considering the following steps.

In the first step, the solar heat gain through glazing (SHG_{glass}) was calculated considering the radiation heat entering through all the window glazing facing North, East, West, and South as well as the skylight glasses. As 6 mm clear float glasses were considered in the study, 'Ordinary Glass' at 22°N latitude at 3 PM in the month of June was considered for fixing the solar heat gain factor (*SHGF*). Appropriate shading correction factor (*SCF*) was considered for ordinary single pane glass with light color inside Venetian blind.

Secondly, the solar heat gain through the opaque envelope (SHG_{opaque}) consisting of the exterior walls and the exposed roof was calculated. The complex dynamic nature of heat transmission through exterior walls and roofs was handled with the equivalent temperature difference (ETD) concept. Generally, in the northern hemisphere, the south side wall would have the highest load around noon and therefore, contribute the maximum load around 3-4 PM. The envelope construction with solid burnt clay brick wall (Wall1_BW) and RCC roof (Roof1_RCC) as considered for the baseline design case (Case-1) was considered for transmission coefficients (*U*) calculation. Corrected equivalent temperature difference (*EqTD*) was calculated, accounting for outside and inside design temperatures and applicable correction factors for all orientations by referring to the ISHRAE design handbook.

The third part of the cooling load estimation included heat load calculation due to transmission on account of the temperature difference between the external temperature and the inside temperature. This part included all glass areas added together with partition walls, ceilings, floors, and the sensible heat component of infiltration air load. This calculation was based on accounting transmission coefficient for glass and partitions (*U*), area of glass (*A*), and temperature difference (ΔT) between the surroundings and the conditioned space.

In the next step, different internal loads due to space occupants, light, and equipment were assessed. The human body generates heat and releases it into surrounding space. The amount of heat generated depends upon the activity level of the person. Human beings contribute sensible as well as latent heat (Q_{sensible} and Q_{latent}). The occupancy, internal lighting, and equipment load were considered as per Table 6.5.

Table 6.5: Summary of the Design Parameters for Estimation of Cooling Load for Air Conditioner Capacity

Parameters	Symbol	Unit	Values	Guidelines Followed
Outside Design Condition				
Dry Bulb Temperature	DBT_O	°C	37.8	At 0.4% occurrence value as per ISHRAE HVAC Handbook, 2007
Wet Bulb Temperature	WBT_O	°C	28.3	
Inside Design Condition				
Dry Bulb Temperature	DBT_i	°C	24.0±1.0	Aas per the recommendations of BEE
Wet Bulb Temperature	WBT_i	°C	17	
Relative Humidity	RH	%	50.0±5.0	
Envelope				
Exterior Wall Construction	Wall1_BW		20mm Cement Plaster+203.2mm Solid Burnt Clay Brick+12mm Cement Plaster	
Wall Transmittance	U_{wall_ext}	W/m^2°K	2.05	
Interior Wall Construction	Wall_I_BW		9mm Cement Plaster+101.6mm Solid Burnt Clay Brick+9mm Cement Plaster	
Wall Transmittance	U_{wall_int}	W/m^2°K	2.37	
Roof Construction	Roof1_RCC		12mm Ceramic Tile+30mm Cement Mortar+152.4mm RCC+12mm Cement Plaster	
Roof Transmittance	U_{roof}	W/m^2°K	2.69	
Window Glazing	Window1_SGU		6mm Clear Float Glass (Ordinary Glass)	
Glass Transmittance	U_{glass}	W/m^2°K	5.69	
Solar Head Gain Factor	$SHGF$	W/m^2	North	North-East, East, South-East, South, South-West, West, North West
			78.75	44.10, 44.10, 44.10, 44.10, 207.90, 450.45, 384.30
Shading Correction Factor	SCF		0.56	As per ISHRAE HVAC Handbook, 2007
Occupancy, Fresh Air Ventilation, Lighting, Equipment, and other Internal Heat Gains				
Occupancy		m^2/Person	12.5	As per National Building Code, 2016
Fresh Air Ventilation		CMH/Person	9.0	Ventilation Air as per ASHRAE 62.1-2010, 2010, Higher of the Two Values
		ACH	1.0	
Lighting Power Density	LPD	W/ ft^2	0.7	As per ANSI, ASHRAE, IES 90.1- 2016
Daylight Control			30% light power dimming during daylight hours in the daylit areas	
Equipment Power Density	EPD	W/ ft^2	0.3	Software Default

Table 6.6: Cooling Load Requirement and Number of Air Conditioners Provided for the Typical Floors of the Studied Buildings

Building	Number of Typical Floors	Number of Apartments	Conditioned Area	Cooling Load Requirment to be Met	Cooling Capacity Provided	No. of Air Conditioners Provided to Meet the Requirement					
						1.0 TR		1.5 TR		2.0 TR	
Symbol	N_{TF}	$N_{apartments\_TF}$	$A_{conditioned\_TF}$	CL_{req_TF}	CL_{prv_TF}	N_{AC_TF}	N_{AC_B}	N_{AC_TF}	N_{AC_B}	N_{AC_TF}	N_{AC_B}
Unit			m^2	TR	TR						
Building 1	16	6	465.90	31.96	38.00	19	304	6	96	5	80
Building 2	21	8	747.21	48.58	54.00	26	546	8	168	8	168
Building 3	14	8	571.82	38.52	44.00	28	392	0	0	8	112
Building 4	9	4	385.55	25.80	30.00	16	144	4	36	4	36
Building 5	19	8	641.46	42.24	48.00	26	494	4	76	8	152
Building 6	16	8	418.44	30.83	39.50	26	416	5	80	3	48
Building 7	24	12	1112.53	67.76	79.00	28	672	2	48	24	576
Building 8	19	6	507.03	33.34	39.00	18	342	6	114	6	114
Building 9	18	6	484.78	32.50	38.00	20	360	4	72	6	108
Building 10	24	2	554.53	28.16	32.00	2	48	4	96	12	288

Finally, the effective room total heat (*ERTH*) and grand total cooling loads (GTCL) were estimated. The *ERTH* refers to the combined impact of room sensible heat load, room latent heat load, and supply air losses. It takes into consideration factors such as infiltration, ventilation rates, and air changes per hour. The *GTCL* includes room loads, supply air losses, return air losses, and outdoor air loads. The effective room load, which accounts for the sensible and latent heat load components of supply air losses, determines the amount of air that needs to be cooled and dehumidified by the cooling coil.

6.2.2.2.2 Air Conditioner Requirement Estimation

Once the cooling loads for all the conditioned spaces of an apartment were found, the total number of split air conditioners (of 1.0 TR, 1.5 TR, and 2.0 TR capacity as per the requirement of the space) required to cater to that estimated cooling load was calculated. The same process was repeated for all the buildings on a typical floor of the concerned building and the number of split air conditioners was added up.

Once the total number of split air conditioners, required for a typical floor of the concerned building (N_{AC_TF}) was calculated, multiplying the same with the number of typical floors (N_{TF}) resulted in the total number of split air conditioners required for that building (N_{AC_B}). The same process was repeated for all the ten buildings under study using Eqn. (6.3), and Table 6.6 summarizes the results.

$$N_{AC\_B} = N_{AC\_TF} \times N_{TF} \qquad \text{Equation (6.3)}$$

6.2.2.2.3 HVAC Cost Estimation for Different Cases

The costs of the air conditioners with different efficiency ratings were then estimated through a market survey. The unit price of split air conditioners (with different capacities and efficiency ratings as considered in the present study) from all leading manufacturers were collected and the average market price (C_{AC}) for each kind was calculated as presented in Table 6.7.

The building HVAC cost for a particular case was obtained by multiplying the average market price (C_{AC}) of a particular kind of split air conditioner by the total number of the same required for that building (N_{AC_B}) and cumulating the results for 1.0TR, 1.5TR, and

2.0TR machines. The resulting cost is presented in terms of HVAC capital cost (*CC_AC* in INR/m^2) per unit built-up area of the building as expressed by Eqn. (6.4).

$$CC\_AC = \frac{\sum C_{AC} \times N_{AC\_B}}{A_{built-up}} \qquad \text{Equation (6.4)}$$

Table 6.7: Average Market Price of the Considered Split Air Conditioners

Split Air Conditioner	Cooling Energy Efficiency Ratio	Average Market Price					
Symbol	*EER*			C_{AC}			
Unit	W/W			INR			
		1.0 TR		1.5 TR		2.0 TR	
Case-A	3.1	32213.00	± 762.17	36695.00	± 2165.74	48337.50	± 1796.32
Case-B	3.8	32744.25	± 1498.07	38857.50	± 1438.92	48470.00	± 3124.03
Case-C	4.4	36677.25	± 2088.09	44742.25	± 2630.25	55990.00	± 1414.21
Case-D	5.0	42093.00	± 4307.52	48659.67	± 7633.70	59990.00	± 7000.00
Case-E	5.5	48701.50	± 6663.07	49479.67	± 2154.46	65492.77	± 3300.64

6.2.3 Cost Impact Assessment over Time

In order to assess the combined cost impact of wall and HVAC variations a step-by-step approach was followed. The wall capital cost (*CC_Wall*) and HVAC capital cost (*CC_AC*) for different wall assemblies (Case-1 to Case-9) and AC options (Case_A to Case_E) were found and averaged for all the buildings. These averaged capital costs were added to estimate the average initial capital investments required for different wall-AC combinations considered in the study and presented in terms of combined capital cost (*CC_Comb* in INR/m^2) for a particular case (Case-1A to Case-9E) as shown in Eqn. (6.5).

$$CC\_Comb = CC\_Wall + CC\_AC \qquad \text{Equation (6.5)}$$

The latest urban commercial tariff rate from Calcutta Electric Supply Corporation (CESE, 2022), the electricity provider in Kolkata City, was used to prepare the electricity tariff used in the energy simulations. For each simulation case, the annual cost for operational energy consumption (*C_OE_Annual*) was extracted from the simulation reports and presented in terms of annual operational energy costs (*C_OE* in INR/m^2/Year) as expressed by Eqn. (6.6) while reporting. The results were averaged for all the buildings for a particular case (case-1A to case-9E).

$$C\_OE = \frac{C\_OE\_Annual}{A_{built-u}} \qquad \text{Equation (6.6)}$$

The cost impact of the considered variations was estimated over the average life span of split air conditioners (L) which was considered to be fifteen years. The future annual expenditures for paying electricity bills were calculated considering the annual inflation rate (r) of electricity. The corresponding future cash flow for each case was converted to its present value by applying the appropriate discount factor (i). The present value of the cash flow was added to the combined capital cost for the corresponding case to estimate the present value of the total expenditure ($C\_TotalPV$ in INR/m^2) for a particular case (Case-1A to Case-9E) as shown in Eqn. (6.7). Results for all the cases were compared to the baseline case i.e. Case-1A.

$$C\_Total\_PV = CC\_Comb + \sum_{t=1}^{L} \frac{C\_OE(1+r)^t}{(1+i)^t} \qquad \text{Equation (6.7)}$$

6.2.3.1 Handling the Stochastic Inputs

All the input variables used in Eqn. (6.7) are stochastic in nature and the Monte Carlo Simulation (MCS) was used to determine the risk. The probability distributions of the input variables were fed to the MCS model of '@Risk' software (version 5.5) of Palisade Decision Tools Suite (2009) and the simulations were run for 10000 iterations. The resulting present value of the total expenditure (*C_Total_PV* in INR/m^2) for each case was noted as probability distribution in term of its mean (μ) and standard deviation (σ).

For each of the forty-five simulation cases the combined capital costs (*CC_Comb* in INR/m^2) and annual operational energy costs (*C_OE* in INR/m^2/Year) were averaged for all the ten studied buildings and were fed into the MCS model as normal distributions with mean (μ) and standard deviation (σ). For discount factor (i), the social time preference rate (STPR) was used. Murty et al. (2018, 2020) estimated the STPR as 8% for projects with gestation period of less than 30 years for India. For climate change mitigation projects, the study suggested a STPR of 6% because of its longer run. In the present study a triangular distribution for the discount rate was used in MCS with an average value of 7% (High: 8%, Low: 6%). The annual percentage increase in electricity cost for India was recorded for the period of 2009-2010 to 2019-2020 (CERC, 2021). The average rate of annual inflation in electricity cost (r) over the period was estimated to be 5.75 ± 4.98% and used in the MCS model as normal distribution.

6.3 Results and Discussion

6.3.1 Operational Energy Consumption for Wall and AC Variations

A total of forty-five simulations (Case-1A to Case-9E) were run with different combinations of walls and split air conditioners for each of the studied buildings and the operational energy consumption (*OE_Annual* in kWh) under different heads for each simulation case. Figure 6.3 shows typical simulation outputs for building-1 for three different combinations viz. baseline Case-1A (Wall1_BW and AC_A), least energy consuming Case-6E (Wall6_AACB and AC_E), and most energy consuming Case-8A (Wall8_DCB and AC_A). Similar trends are also observed for all the buildings.

The results for all the simulation cases are converted to operational energy performance index (*EPI_OE* in kWh/m^2/Year). For each of the Wall-AC combinations the performance is averaged for all the studied buildings and the result is presented in Table 6.8 and Fig. 6.4.

Thermal transmittance of the exterior wall assemblies plays a significant role in determining cooling load and associated energy consumption. Lower thermal transmittance allows less heat from outside to penetrate to the interior spaces and keeps the space cool reducing the energy required to maintain the desired thermal comfort (modelled as cooling set-points). On the other hand, higher HVAC efficiency requires lesser energy to produce same cooling output. The results obtained clearly corroborates the same. For Case-6E, the lowest thermal transmittance (U_{wall} = 0.54 W/m^{2o}K) of AACB block wall and highest cooling efficiency (*EER* = 5.5 W/W) of 5-star AC results in 37.53% improvement (reduction) in energy consumption over baseline. Case-8A with highest thermal transmittance (U_{wall} = 3.04 W/m^{2o}K) of DCB wall and lowest cooling efficiency (*EER* = 3.1 W/W) of 1-star AC results in 3.87% more energy consumption over baseline.

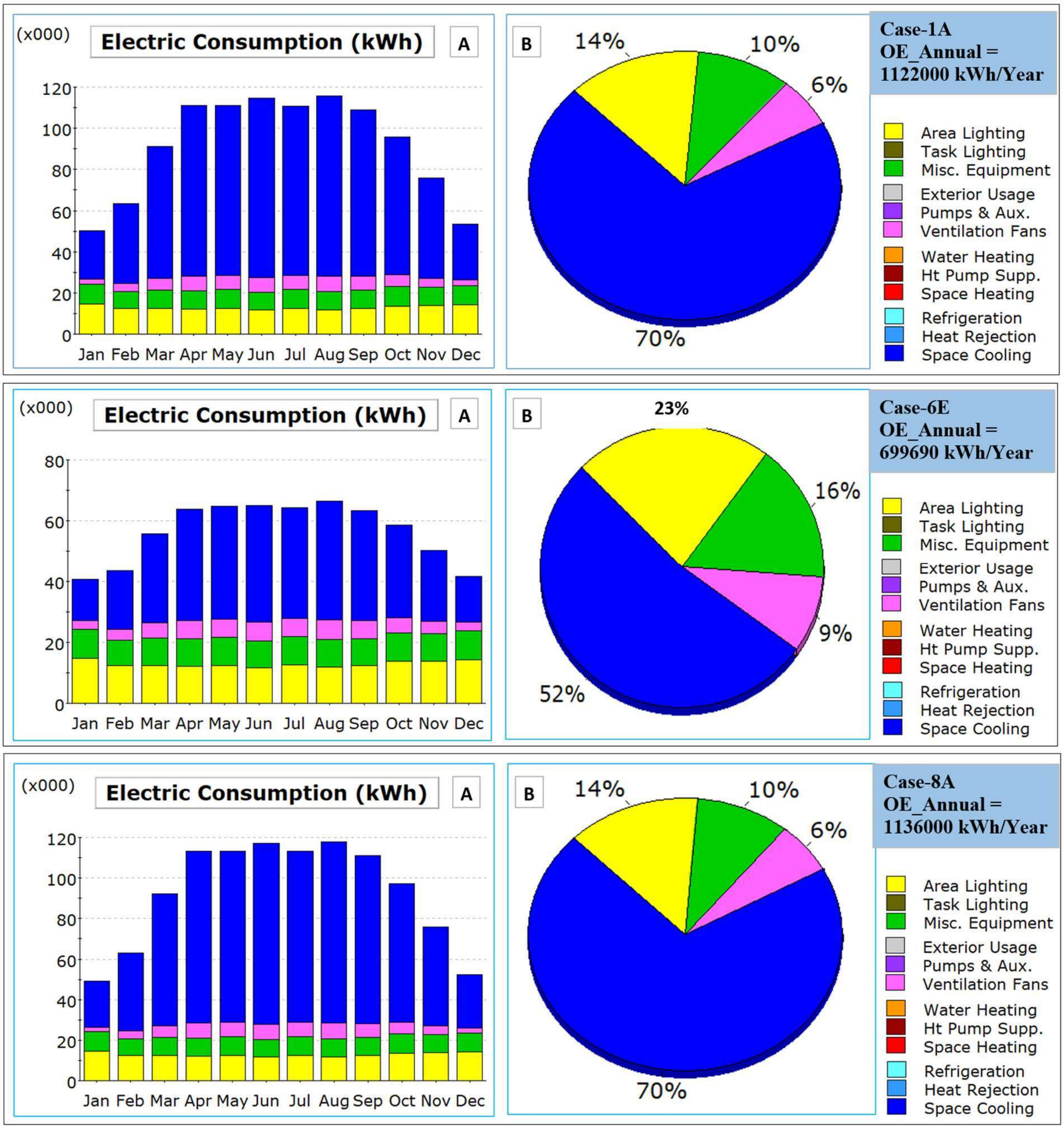


Figure 6. 3: Annual Operational Energy Consumption for Building-1 for Baseline (Case-1A), Least Energy Consuming (Case-6E), and Most Energy Consuming (Case-8A) Cases: (A) Monthly Consumption Trends (B) Percentage Break-Up under Different Heads

Table 6.8: Average Operational Energy Performance Index of the Studied Buildings for Different Wall Variations (Case-1 to Case-9) and AC Variations (Case-A to Case-E)

Parameter		**Operational Energy Performance Index**														
Symbol		*EPI_OE*														
Unit		kWh/m^2/Year														
Simulation Case		**Case-A**			**Case-B**			**Case-C**			**Case-D**			**Case-E**		
	AC Name	**AC_A**			**AC_B**			**AC_C**			**AC_D**			**AC_E**		
	Wall Name	Mean		S.D.	Mean		S.D.	Mean		S.D.	Mean		S.D.	Mean		S.D.
Case-1	**Wall1_BW**	110.00	±	11.41	94.65	±	9.41	85.37	±	8.20	78.32	±	7.29	73.62	±	6.69
Case-2	**Wall2_CW**	108.50	±	11.33	93.43	±	9.35	84.32	±	8.16	77.40	±	7.25	72.78	±	6.65
Case-3	**Wall3_REHB**	109.21	±	11.37	94.01	±	9.38	84.82	±	8.18	77.83	±	7.27	73.17	±	6.67
Case-4	**Wall4_FAB**	110.88	±	11.44	95.36	±	9.44	85.99	±	8.23	78.86	±	7.31	74.10	±	6.71
Case-5	**Wall5_SCB**	113.31	±	11.56	97.35	±	9.53	87.70	±	8.30	80.36	±	7.38	75.46	±	6.76
Case-6	**Wall6_AACB**	101.16	±	10.72	87.48	±	8.86	79.20	±	7.74	72.91	±	6.89	**68.72**	**±**	**6.33**
Case-7	**Wall7_CSEB**	111.83	±	11.49	96.14	±	9.47	86.65	±	8.26	79.44	±	7.34	74.64	±	6.73
Case-8	**Wall8_DCB**	**114.26**	**±**	**11.60**	98.12	±	9.56	88.37	±	8.33	80.95	±	7.40	76.01	±	6.78
Case-9	**Wall9_RCC**	111.96	±	11.50	96.25	±	9.48	86.75	±	8.26	79.52	±	7.34	74.71	±	6.73

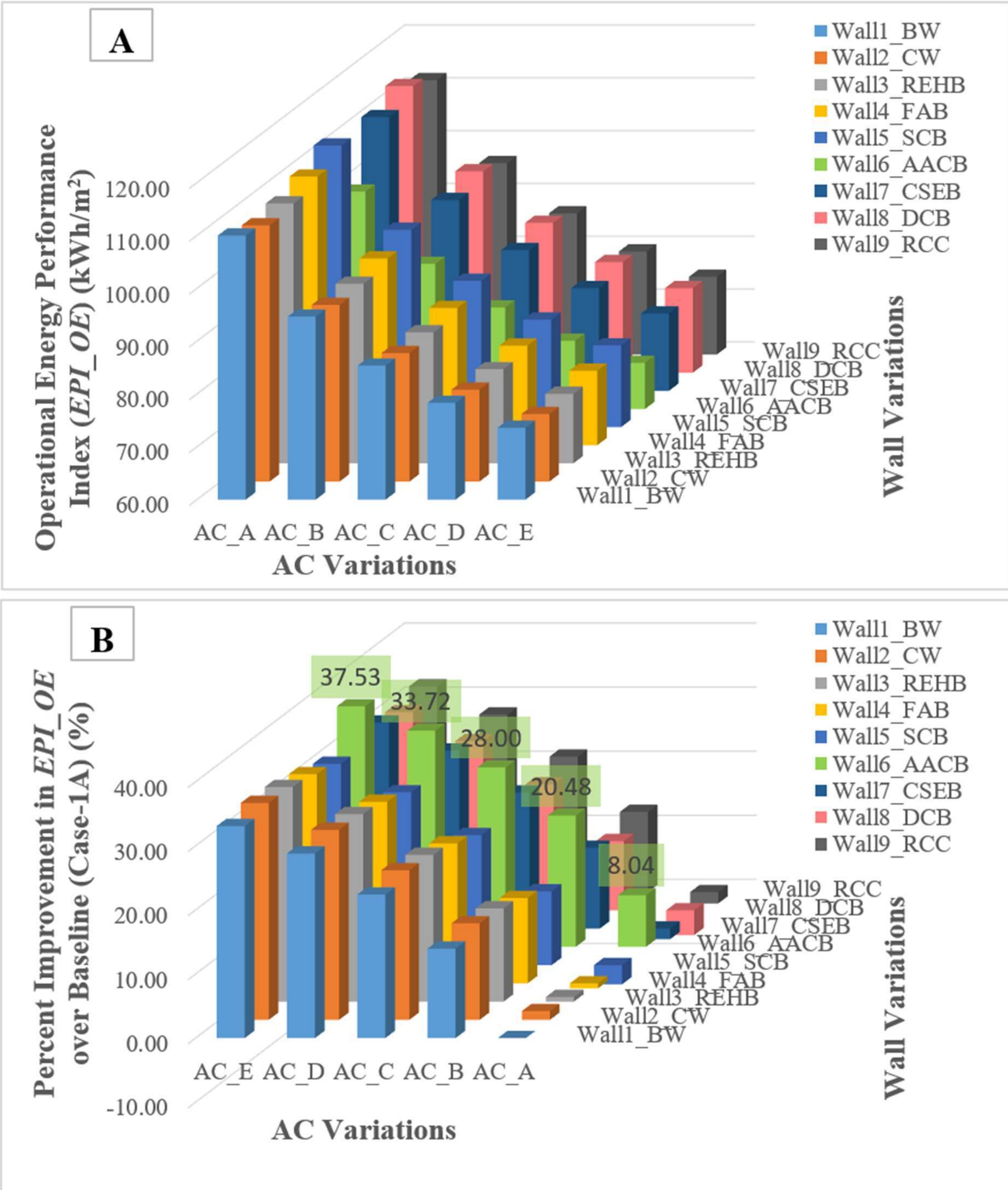


Figure 6.4: Impact of Wall and AC Variations on Operational Energy Consumption of the Studied Buildings (A) Variation in *EPI_OE* (B) Percent Change in *EPI_OE* over the Baseline (Case-1A)

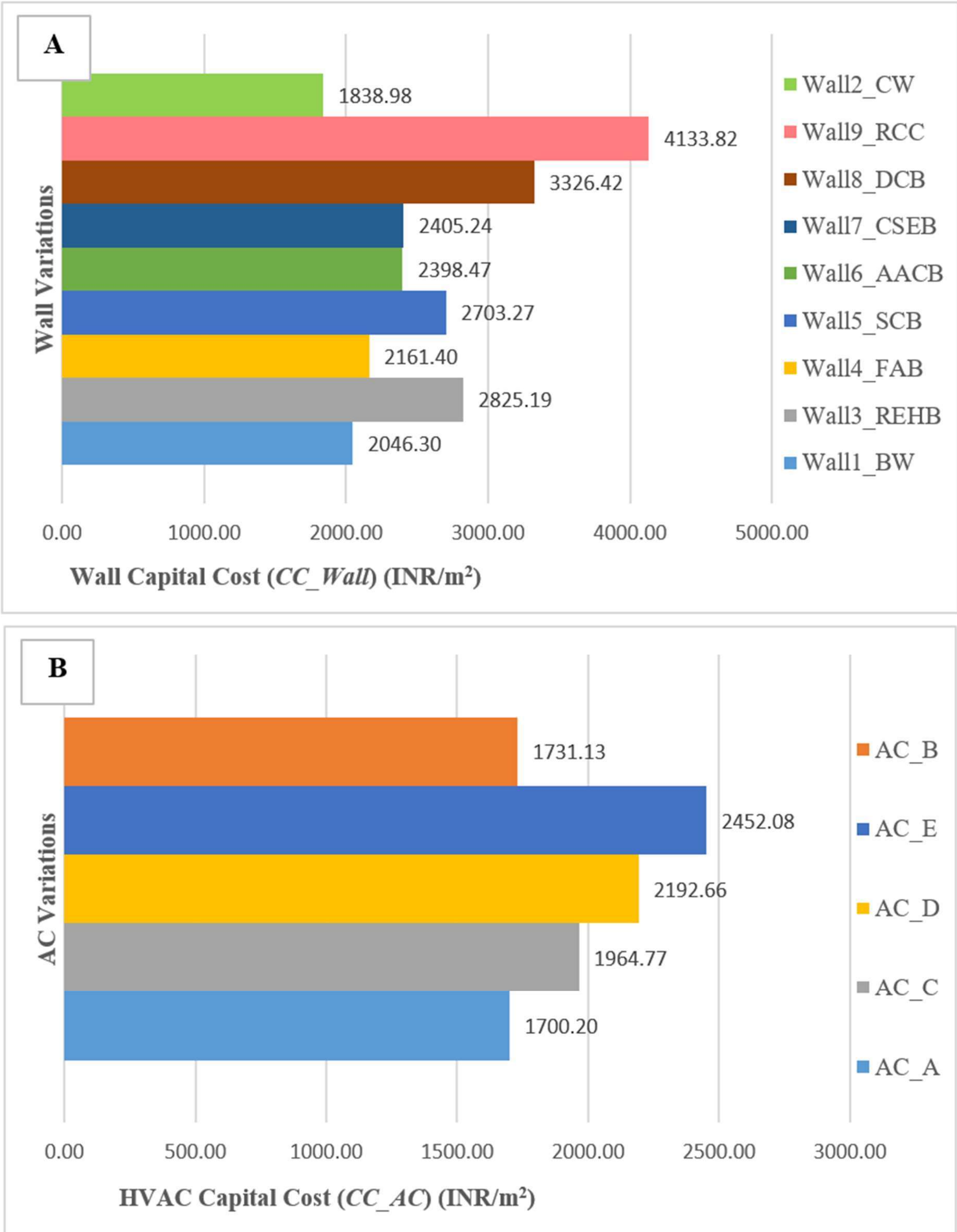


Figure 6.5: Variation in Average Capital Costs for (A) Different Wall Variations (Case-1 to Case-9) and (B) Different AC Variations (Case-A to Case-E)

6.3.2 Financial Impact of Wall and AC Variations

6.3.2.1 Impact on the Capital Cost

Capital costs of wall variations (*CC_Wall*) and AC variations (*CC_AC*) were determined for all the buildings. The average values are compared in Fig. 6.5. Reinforced cement concrete wall (Wall9_RCC) is the costliest (*CC_Wall* = 4133.82 ± 863.11 INR/m^2) which is 102.01% greater than that (*CC_Wall* = 2046.30 ± 427.25 INR/m^2) of the baseline burnt-clay brick wall (Wall1_BW). The higher cost of steel reinforcements, cement, and skilled labour is the reason. The curtain walls with burnt clay bricks (Wall2_CW) is the cheapest (*CC_Wall* = 1838.98 ± 383.96 INR/m^2) and 10.13% lower than the baseline. For the most energy efficient wall option (Wall6_AACB), the capital cost (*CC_Wall* = 2398.47 ± 500.78 INR/m^2) is however found to be 14.68% higher than the baseline. Regarding HVAC variations, average cost of providing buildings with higher efficiency air-conditioners are also higher and most efficient Case_E, i.e., 5-star split air conditioners are found to be the highest (*CC_AC* = 2452.08 ± 481.85 INR/m^2).

The combined capital costs for providing the buildings with different Wall-AC combinations (Case-1A – Case-9E) were estimated for all the buildings. The average values are presented in Table 6.9 and Fig. 6.6. Case-2A with the combination of curtain wall (Wall2_CW) and one star (old rating) split air conditioners (AC_A) shows the lowest combined capital cost (*CC_Comb* = 3539.18 ± 514.10 INR/m^2) which is 5.86% lower compared to the baseline Case-1A. Case-9E with RCC wall (Wall9_RCC) and new efficient five star split air conditioner (AC_E) is the costliest option (*CC_Comb* = 6585.89 ± 1018.49 INR/m^2) being 43.11% costlier than the baseline Case-1A. For most energy efficient combination (Case-6E) the required capital investment (*CC_Comb* = 4850.54 ± 719.64 INR/m^2) is expectedly higher by 29.47% higher than the baseline.

Table 6.9: Average Combined Capital Costs for Different Wall Variations (Case-1 to Case-9) and AC Variations (Case-A to Case-E) for the Studied Buildings

Parameter		**Combined Capital Cost**														
Symbol		*CC_Comb*														
Unit		INR/m^2														
Simulation Case		**Case-A**			**Case-B**			**Case-C**			**Case-D**			**Case-E**		
	AC Name	**AC_A**			**AC_B**			**AC_C**			**AC_D**			**AC_E**		
	Wall Name	Mean		S.D.	Mean		S.D.	Mean		S.D.	Mean		S.D.	Mean		S.D.
Case-1	**Wall1_BW**	3746.50	±	549.15	3777.44	±	557.74	4011.07	±	582.40	4238.96	±	623.39	4498.38	±	666.72
Case-2	**Wall2_CW**	**3539.18**	**±**	**514.10**	3570.12	±	522.84	3803.75	±	548.76	4031.64	±	591.71	4291.06	±	637.48
Case-3	**Wall3_REHB**	4525.39	±	689.24	4556.33	±	697.32	4789.96	±	718.07	5017.85	±	752.82	5277.27	±	788.21
Case-4	**Wall4_FAB**	3861.59	±	569.10	3892.53	±	577.61	4126.16	±	601.60	4354.05	±	641.56	4613.47	±	683.60
Case-5	**Wall5_SCB**	4403.47	±	666.63	4434.40	±	674.79	4668.04	±	696.07	4895.93	±	731.68	5155.35	±	768.19
Case-6	**Wall6_AACB**	4098.66	±	611.11	4129.60	±	619.46	4363.23	±	642.19	4591.12	±	680.14	4850.54	±	719.64
Case-7	**Wall7_CSEB**	4105.44	±	612.32	4136.37	±	620.67	4370.00	±	643.37	4597.90	±	681.27	4857.32	±	720.70
Case-8	**Wall8_DCB**	5026.62	±	784.00	5057.56	±	791.80	5291.19	±	810.64	5519.08	±	842.21	5778.50	±	873.49
Case-9	**Wall9_RCC**	5834.01	±	941.07	5864.95	±	948.50	6098.58	±	964.96	6326.47	±	992.51	**6585.89**	**±**	**1018.49**

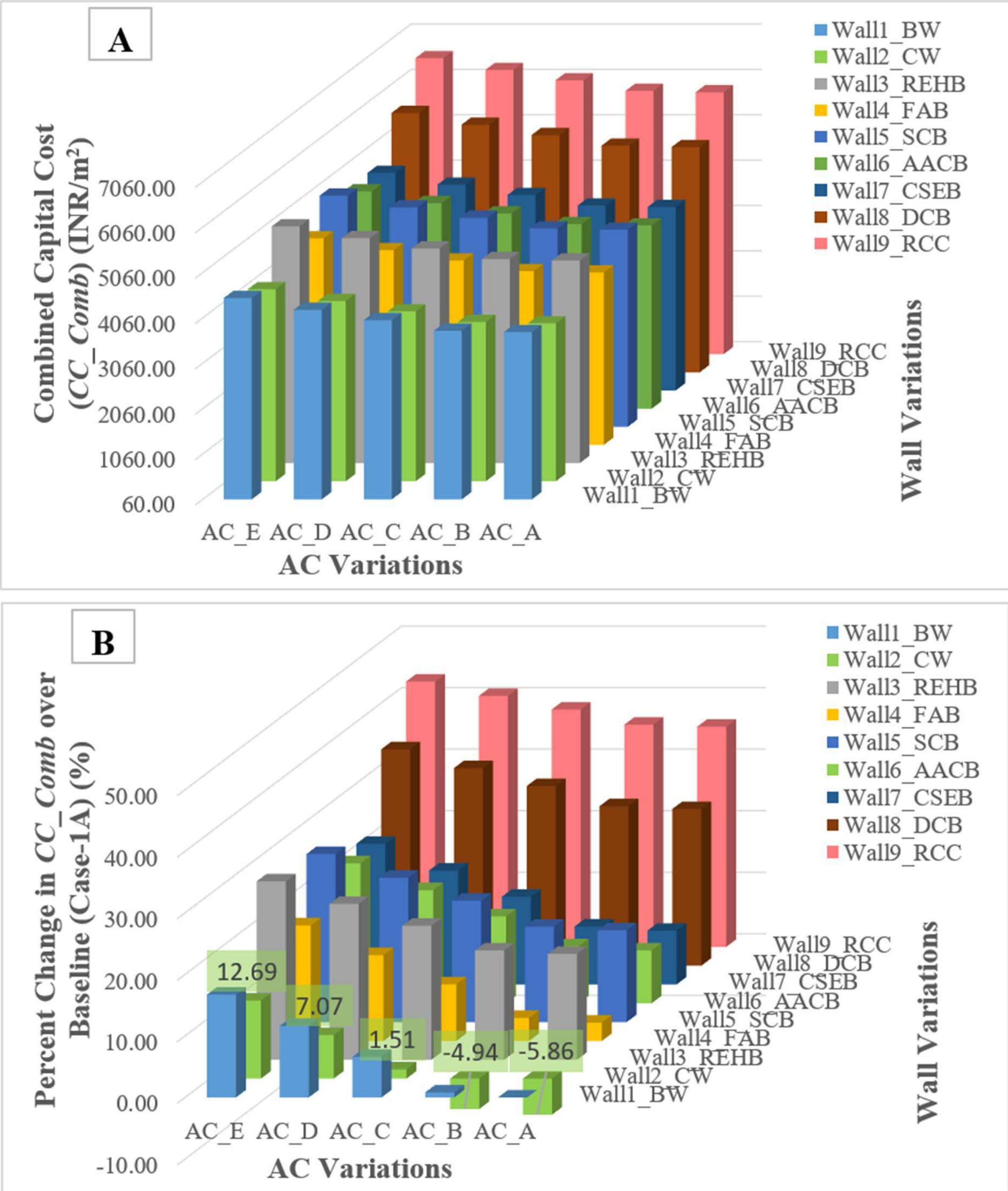


Figure 6.6: Variation in Combined Capital Costs of Installing Different Combinations of Wall and AC (Case-1A to Case-9E) for the Studied Buildings (A) Variation in *CC_Comb* (B) Percent Change in *CC_Comb* over the Baseline (Case-1A)

Table 6.10: Average Annual Operational Cost of the Studied Buildings for Different Wall Variations (Case-1 to Case-9) and AC Variations (Case-A to Case-E)

Parameter		**Annual Operational Energy Cost**														
Symbol		*C_OE*														
Unit		INR/m^2/Year														
Simulation Case		**Case-A**			**Case-B**			**Case-C**			**Case-D**			**Case-E**		
	AC Name	**AC_A**			**AC_B**			**AC_C**			**AC_D**			**AC_E**		
	Wall Name	Mean		S.D.	Mean		S.D.	Mean		S.D.	Mean		S.D.	Mean		S.D.
Case-1	**Wall1_BW**	1018.53	±	104.85	876.22	±	86.43	790.19	±	75.34	724.79	±	66.95	681.21	±	61.38
Case-2	**Wall2_CW**	1004.57	±	104.19	864.86	±	85.92	780.41	±	74.91	716.21	±	66.58	673.43	±	61.05
Case-3	**Wall3_REHB**	1011.15	±	104.51	870.22	±	86.17	785.02	±	75.12	720.25	±	66.76	677.10	±	61.22
Case-4	**Wall4_FAB**	1026.65	±	105.20	882.83	±	86.72	795.89	±	75.58	729.79	±	67.15	685.76	±	61.56
Case-5	**Wall5_SCB**	1049.34	±	106.21	901.33	±	87.53	811.85	±	76.27	743.83	±	67.74	698.51	±	62.08
Case-6	**Wall6_AACB**	936.31	±	98.59	809.51	±	81.43	732.86	±	71.10	674.59	±	63.28	**635.76**	**±**	**58.10**
Case-7	**Wall7_CSEB**	1035.50	±	105.61	890.04	±	87.04	802.10	±	75.85	735.25	±	67.38	690.72	±	61.75
Case-8	**Wall8_DCB**	**1058.18**	**±**	**106.56**	908.54	±	87.81	818.08	±	76.51	749.31	±	67.95	703.49	±	62.27
Case-9	**Wall9_RCC**	1036.76	±	105.67	891.06	±	87.09	802.99	±	75.89	736.03	±	67.42	691.42	±	61.80

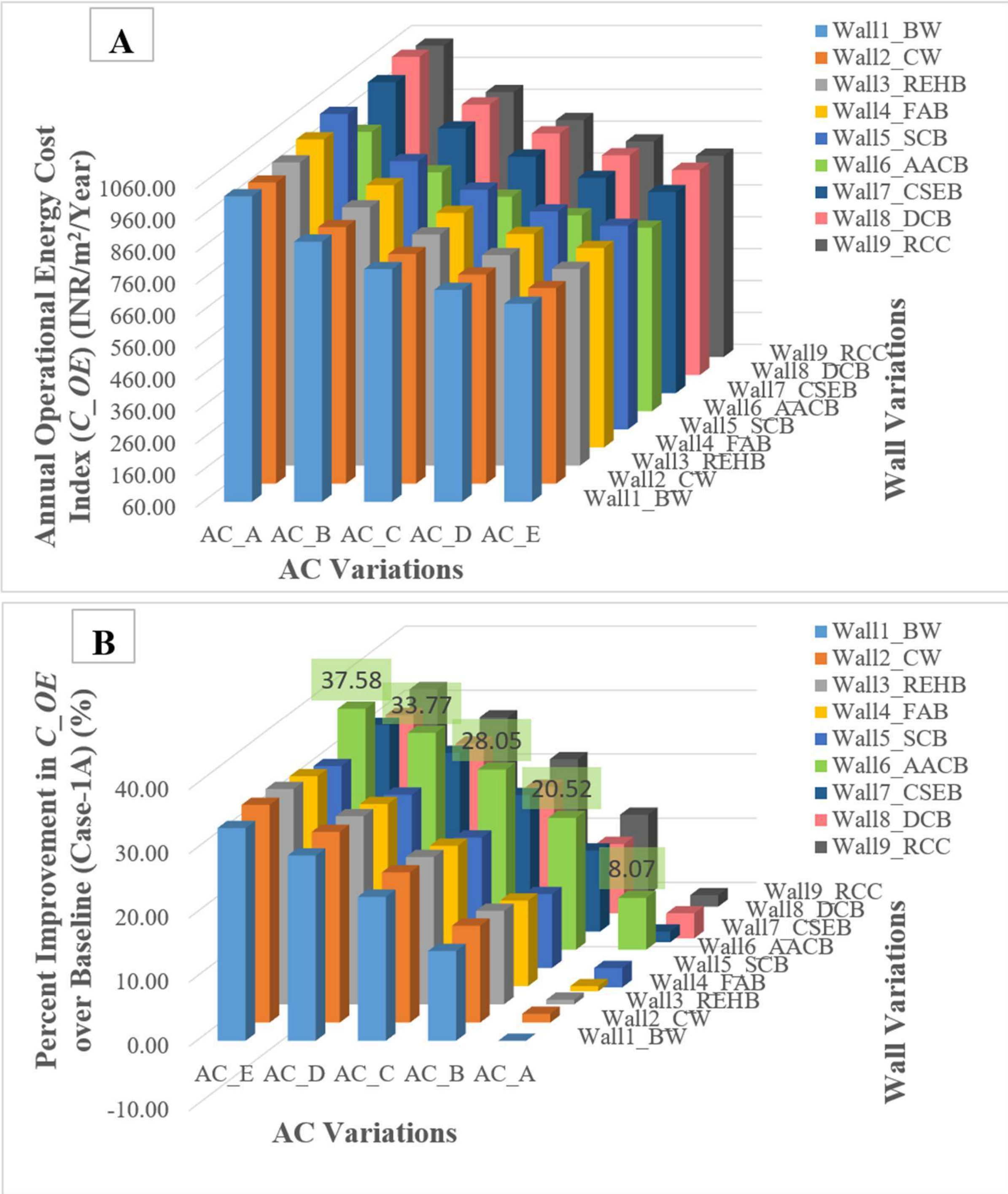


Figure 6.7: Impact of Wall and AC Variations on Annual Operational Energy Cost of the Studied Buildings (A) Variation in *C_OE* (B) Percent Change in *C_OE* over the Baseline (Case-1A)

6.3.2.2 Impact on the Annual Operational Energy Costs

The annual operational energy costs (*C_OE*) for the different wall-AC combinations were estimated through whole building energy simulations using the latest CESC tariff and averaged for all the buildings. The results are presented in Table 6.10 and Fig. 6.7. Case-6E (Wall6_AACB and AC_E) with lowest *EPI_OE* shows the lowest value for annual operational energy cost (*C_OE* = 635.76 ± 58.10 INR/m^2/Year) as well which is 37.58% lower than the baseline case-1A. Case-8A (Wall8_DCB and AC_A) is found to be the costliest (*C_OE* = 1058.18 ± 106.56 INR/m^2/Year), 3.89% greater than baseline Case-1A.

6.3.2.3 Cost Impact over a Time Span

The cost impacts of the considered variations of wall-AC combinations are finally estimated over a future span of fifteen years which is the average life span of split air conditioners. The present value of the entire cash flow is estimated for all the cases considering appropriate values of the annual inflation rate (r) for electricity in India and discount factor (i) in terms of STPR. The risks of the input variables are dealt with through MCS and the present values of the total expenditure (*C_Total_PV*) for each of the cases are calculated. The resulting distributions of three combinations viz. baseline Case-1A (Wall1_BW and AC_A with *C_Total_PV* = 18836.87±6151.87 INR/m^2), least expensive Case-6E (Wall6_AACB and AC_E with *C_Total_PV* = 14265.00±3867.60 INR/m^2), and most expensive Case-9A (Wall9_RCC and AC_A with *C_Total_PV* = 21203.08±6332.41 INR/m^2) are presented in Fig. 6.8.

Results for all the cases are summarized in Table 6.11 and Fig. 6.9. Case-9A is proved to be the most expensive with a 12.56% greater expenditure compared to the baseline Case-1A. The much higher capital cost of the RCC wall (102.01% higher than baseline brick wall) could not justify it as a sustainable choice as in terms of energy efficiency.

It may be noted that 29.47% higher capital investment of Case-6E over baseline gets well compensated by the 37.58% lower annual expenditure for operational energy making the combination not only most energy-efficient but most cost-effective as well for a longer operational lifetime of the building when future cash-flow is considered.

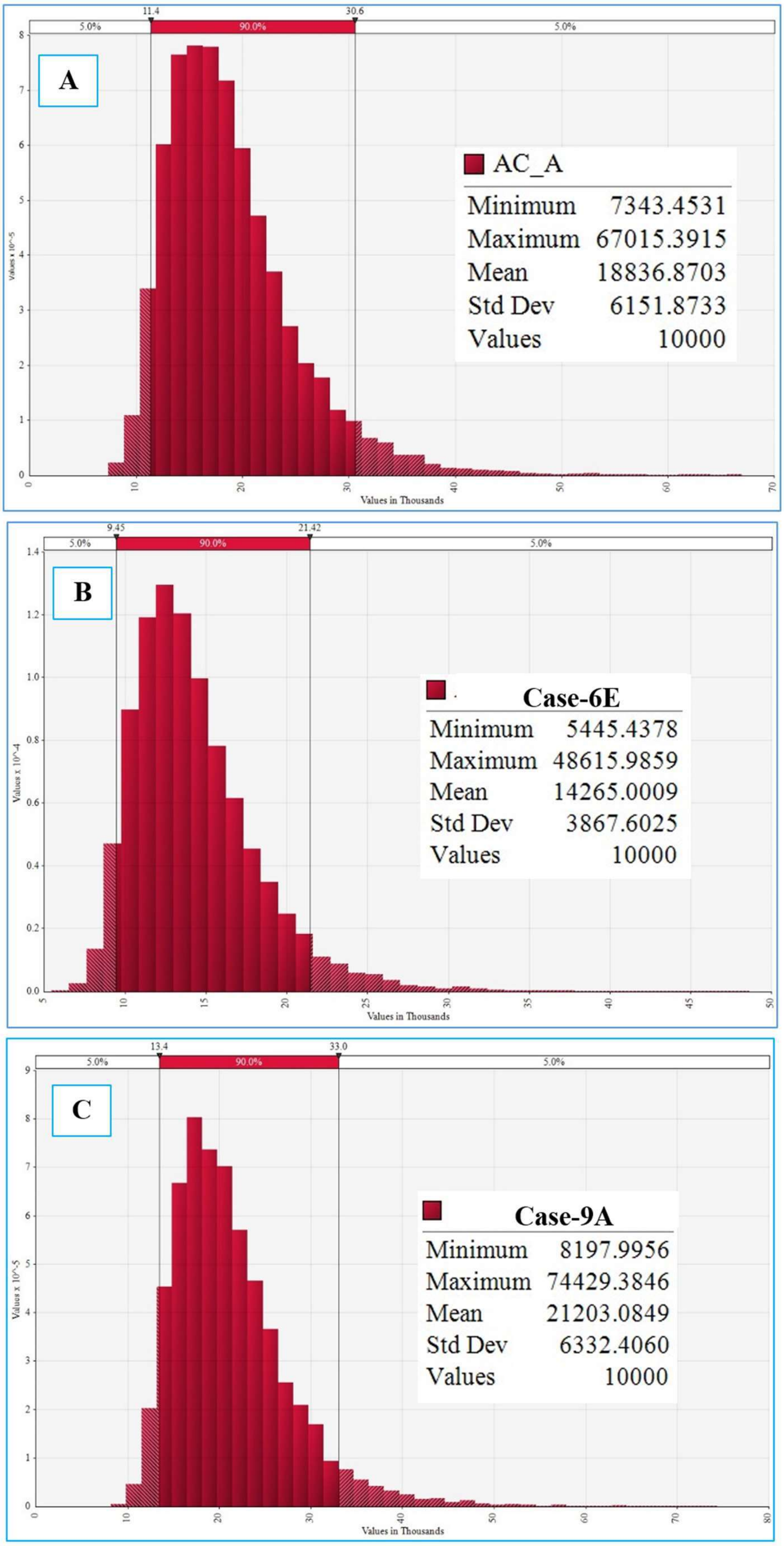


Figure 6.8: Results of MCS Estimating Present Value of total Expenditure for (A) Baseline (Case-1A) (B) Least Expensive (Case-6E) (C) Most Expensive (Case-9A)

Table 6.11: Present Value of Total Expenditure for Different Wall-AC Combinations Estimated through MCS (Case-1A to Case-9E)

Parameter		**Present Value of Total Expenditure**									
Symbol		*C_Total_PV*									
Unit		INR/m^2									
Simulation Case		**Case-A**		**Case-B**		**Case-C**		**Case-D**		**Case-E**	
	AC Name	**AC_A**		**AC_B**		**AC_C**		**AC_D**		**AC_E**	
	Wall Name	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Case-1	**Wall1_BW**	18836.87 ±	6151.87	16752.24 ±	5276.72	15717.31 ±	4776.76	14989.42 ±	4435.69	14597.59 ±	4151.00
Case-2	**Wall2_CW**	18425.10 ±	6071.54	16389.00 ±	5234.13	15363.78 ±	4714.28	14646.53 ±	4361.00	14274.48 ±	4110.32
Case-3	**Wall3_REHB**	19520.45 ±	6198.40	17451.61 ±	5289.64	16421.37 ±	4759.32	15688.08 ±	4372.68	15313.61 ±	4156.16
Case-4	**Wall4_FAB**	19079.33 ±	6263.94	16977.22 ±	5364.05	15921.16 ±	4842.89	15167.73 ±	4413.76	14777.08 ±	4166.25
Case-5	**Wall5_SCB**	19956.54 ±	6385.35	17789.17 ±	5459.34	16691.06 ±	4889.66	15925.49 ±	4525.36	15500.64 ±	4233.65
Case-6	**Wall6_AACB**	17971.05 ±	597.76	16118.36 ±	4885.34	15230.15 ±	4492.90	14585.30 ±	4098.85	**14265.00 ±**	**3867.60**
Case-7	**Wall7_CSEB**	19457.42 ±	6339.76	17331.08 ±	5412.33	16267.10 ±	4913.38	15492.14 ±	4472.15	15089.45 ±	4180.63
Case-8	**Wall8_DCB**	20712.44 ±	6460.33	18535.77 ±	5545.46	17422.02 ±	5007.37	16624.17 ±	4567.13	16206.01 ±	4304.92
Case-9	**Wall9_RCC**	**21203.08 ±**	**6332.41**	19064.39 ±	5408.51	17997.40 ±	4935.56	17232.13 ±	4513.63	16831.56 ±	4254.35

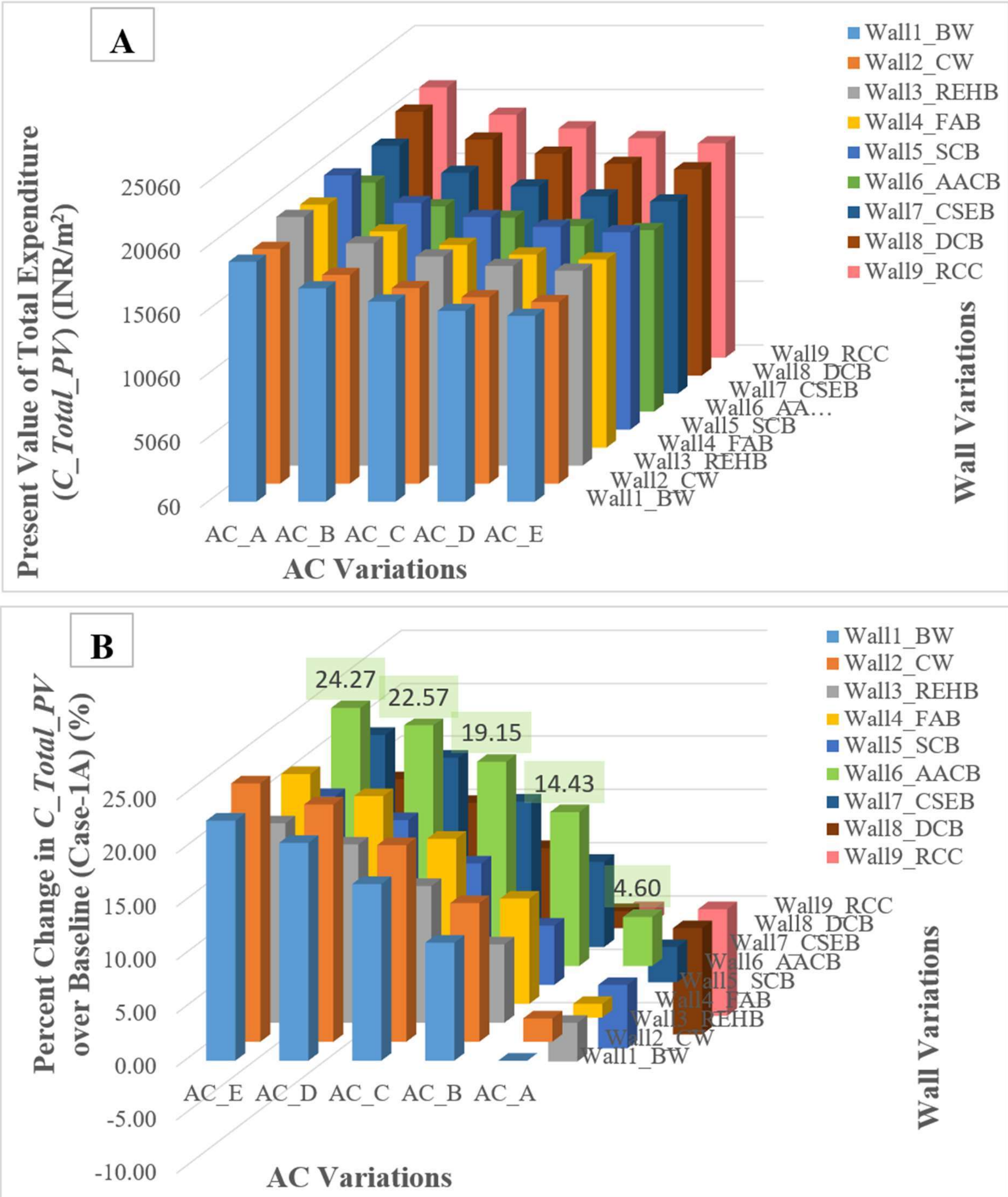


Figure 6. 9: Impact of Wall and AC Variations on Present Value of Total Expenditure over a Period of Fifteen Years (A) Variation in *C_Total_PV* (B) Percent Change in *C_Total_PV* over the Baseline (Case-1A)

6.4 Summary and Outcome

The study in the present chapter demonstrates a detailed methodology for selecting the optimum combination of walls and air conditioners for the possible best economic and energy efficiency performance of high-rise buildings in a typical warm-humid climate. The study is conducted with data from the same ten typical high-rise residential apartment buildings in Kolkata, India. The optimum recommended solution is obtained through an iterative process with whole building energy simulation for all possible combinations of wall material, its construction as well as selection of a suitable air conditioner.

Results show that in terms of operational energy performance combination of AACB block walls and 5 Star AC is proved to be the best and the combination of dense concrete block walls and 1 Star AC shows the highest energy consumption. In terms of combined capital costs, the combination of curtain wall and 1 star AC is found to be the cheapest and the combination of RCC wall and new efficient 5 Star AC is the costliest option. To combine the energy and cost performance of the wall-AC variations the respective annual costs for paying electricity bills (*C_OE*) over a fifteen-year time-period is cumulated with the respective capital costs for construction and installation. The future cash flow is converted to present value by applying the appropriate discount rate (i) and inflation rate (r). The resulting present value for total expenditure (*C_Total_PV*) for each wall-AC combination is chosen as the comparison metric. Because of its much-improved energy performance, the combination of AAC block wall and 5 Star split air conditioner proved to be the most energy-efficient and least expensive option showing a 37.53% lesser energy consumption and 24.27% reduction in total expenditure over the future fifteen years as compared to typically practiced baseline.

Though the methodology is demonstrated using typical building data of Kolkata, the same methodology may be used for other climatic conditions also investigating site-specific wall material options and HVAC systems available there. Hence the obtained optimum solution is specific for Kolkata, India, but the demonstrated methodology is generic for other climatic conditions.

Chapter 7

Conclusions and Future Scope of Work

7.0 Conclusions

The study explores pressing issues of building energy performance associated with escalating urban population density, particularly in expanding cities of developing nations. High-rise buildings forced to be accepted as vertical solutions with horizontal spatial constraints, emerge as focal points for energy optimization and environmental stewardship due to higher use of material resources per unit land area. The culmination of this thesis emphasizes the pivotal role of early design stage sustainable practices in high-rise residential building energy efficiency, particularly in warm-humid climates such as Kolkata. Through an in-depth analysis of energy performance, environmental impact, and economic considerations, several key conclusions emerge, each contributing significantly to the discourse on sustainable urban development, specifically for highly populated cities. This research details the pathway for applying energy efficiency to residential high-rise buildings, which can be demonstrated through careful integration of envelope materials, spatial design features as prescribed in the code, and efficient cooling system choice in the early design stage.

Suitable policy in terms of code and standards at national and sub-national levels is a key driver for any design stage adoption for energy efficiency. The Eco-Niwas Samhita (ECBC for residential buildings) code recommendation for building envelope design and its efficacy in terms of operational energy performance required investigation for more adoption and building science development, given the known fact that the code was recently developed. Embodied energy associated with any energy efficiency measures is a missing link in all policy frameworks and early design decisions due to a lack of data and low research priority. The residential segment is more cost-sensitive, and the success of any design solution highly depends on cost-effectiveness and the demonstration of values to all stakeholders. In this thesis, the influence of envelope parameters, statistical association of energy performance with different design variables as specified in code, sensitivity analysis for critical influencing factors for building operational energy, and cooling demand are explored. Further analysis of the overall energy performance, which combines the operational and embodied energy impacts of various exterior wall options and the corresponding greenhouse gas emissions, is considered as one of the most important features of this study. Finally, a techno-economic analysis is performed for the integrated wall-AC combination while taking the time value of money into account to achieve the best energy performance. The specific findings addressing the research questions framed in Section 2.9 (Chapter 2: Literature Review) are summarized subsequently.

The first research question (RQ1) was framed to assess the extent of enhancement in the energy efficiency of typical high-rise residential apartment buildings in the warm-humid climate of Kolkata as a result of implementing the updated energy conservation building codes in India and to identify the pivotal factors influencing the improvement. The first major finding in this regard pertains to the efficacy of enhancing building envelope standards, as delineated in Eco-Niwas Samhita, 2018, and ECBC, 2017. This study showcases the substantial savings achievable in overall operational energy consumption (7.88-25.57%) and even more in cooling energy consumption (11.35-36.34%), for high-rise residential buildings by adhering to these standards. Both overall and cooling energy performance indices (EPI and $EPI_{cooling}$) are found to be strongly correlated with thermal transmittance of building envelope components and energy efficiency of air conditioning systems. The sensitivity analysis also revealed the critical dependence of the buildings' operational energy performance on the said parameters.

The second research question (RQ2) investigated the influence of different exterior wall assembly materials on the embodied and operational energy performance and environmental sustainability of high-rise residential structures. To address the same, further investigation into sustainable alternatives to conventional building materials by accounting for embodied energy alongside the operational energy, exemplified by autoclaved aerated concrete blocks (AACB) and cement stabilized soil blocks (CSEB), elucidates a pathway towards greener construction practices. Walls with fly ash brick and AACB showed moderate improvement in embodied energy performance compared to brick walls. The superior energy performance of AACB and the relatively reduced environmental footprint in terms of GHG emissions of these alternatives underscore the importance of embracing eco-friendly materials in modern construction paradigms. The results not only highlight the potential for environmental conservation but also underline the economic benefits associated with reduced energy consumption.

The third and final research question (RQ3) explored the effect of variations in wall material compositions and air conditioning system specifications on the overall energy usage and cost-effectiveness of high-rise residential buildings. Addressing the same, the work is carried out further to demonstrate a detailed methodology for selecting optimal wall-air conditioner combinations. The process not only improves energy efficiency but also aligns with cost-effectiveness, thereby demonstrating a holistic approach towards sustainable building operations. Furthermore, the study emphasizes the critical role of space cooling in high-rise buildings, especially in warm-humid climates. With cooling energy constituting a significant portion of overall energy consumption, strategic interventions in material selection and HVAC system design are imperative. The findings underscore the potential for substantial economic savings and environmental benefits through the adoption of energy-efficient technologies and practices. One of the noteworthy outcomes is the identification of the AACB wall and 5-Star split air conditioner combination as the most energy-efficient and cost-effective option showing a 37.53% lesser energy consumption and 24.27% reduction in total expenditure over the future fifteen years as compared to typically practiced baseline. This exemplifies the synergy between sustainable building materials and advanced HVAC systems in achieving optimal energy performance. Conversely, traditional approaches using dense concrete block walls and lower-rated air conditioners exhibit higher energy consumption and overall expenditure, highlighting the necessity for paradigm shifts in building design and operation.

Importantly, while the energy-efficient design approach is demonstrated using typical data of Kolkata, representing warm and humid climates, the methodologies and insights presented are transferrable to diverse climatic contexts. The generic nature of the approach ensures its applicability in addressing sustainability challenges in high-rise buildings across various regions, thereby fostering a global discourse on environmentally conscious urban development.

In conclusion, the thesis underscores the intricate interplay between energy efficiency, environmental sustainability, and economic viability in high-rise building design. The new contribution of this work is the demonstration of a method through a newly adopted code to design low-energy, low-carbon, cost-effective, and optimal high-rise buildings. By advocating for enhanced building standards, embracing sustainable materials, and optimizing HVAC systems, it advocates for a future where urban growth aligns harmoniously with ecological stewardship. This comprehensive approach not only helps prospective residents but also creates the foundation for future generations of urban high-rise infrastructure designers and developers to work with resilience and sustainability.

7.1 Future Scope of Work

As the present thesis concludes, it represents not only the completion of research work but also the start of a journey towards making bigger and more meaningful contributions to sustainable building design. This section discusses the future possibilities for research and residential building science development, focusing on improving energy efficiency, and the overall environmental impact of buildings.

- **Expansion to Diverse Climate Zones:** The present study is limited to a warm and humid climate zone with a generic methodology. By tailoring the same methodology to other climate conditions and integrating ENS code compliance, a more precise estimation of energy performance can be achieved. This extension will also necessitate an investigation of critical design variables that significantly influence energy performance across different climates.
- **Enhanced Sustainability and Carbon Neutrality:** To advance towards enhanced sustainability and achieve carbon neutrality goals, the inclusion of a broader spectrum of building materials and services is imperative. Future research could explore optimizing operational and embodied energy during the design stage for all building materials. Additionally, conducting GHG emission benchmarking will facilitate the development of a more robust sustainable design approach.
- **Exploration of Alternative Cooling Options in High-Rise Developments:** Leveraging the advantage of height and premium construction in high-rise developments, there is an opportunity to explore alternative cooling options. Integrating natural ventilation or Variable Refrigerant Flow (VRF) systems, alongside experimenting with various façade materials, can significantly contribute to achieving optimal energy with reduced cooling demands.
- **Exploration of the Variation in Energy Consumption of Different Blocks of the Same High-Rise Building through Cost-effective and Optimized Instrumentation:** Future research should explore the use of cost-effective and optimized instrumentation methods for accurately measuring the likely variations in energy consumption and efficiency across different blocks within the same high-rise buildings. This would help to address different issues regarding the variation in energy consumption patterns within the same building and find the optimum efficiency measures complementing the design optimization strategies explored in this study.

These avenues for future research not only expand the scope of the current work but also pave the way for more sustainable and energy-efficient practices in the realm of building and operation.

References

Abden, M. J., Tao, Z., Alim, M. A., Pan, Z., George, L., & Wuhrer, R. (2022). Combined use of phase change material and thermal insulation to improve energy efficiency of residential buildings. *Journal of Energy Storage, 56*, 105880.

Abhyankar, N., Shah, N., Park, W. Y., & Phadke, A. A. (2017). Accelerating energy efficiency improvements in room air conditioners in India: Potential, costs-benefits, and policies.

Agarwal, R., Garg, M., Tejaswini, D., Garg, V., Srivastava, P., Mathur, J., & Gupta, R. (2023). A review of residential energy feedback studies. *Energy and Buildings*, 113071.

Ahmad, T., Chen, H., Guo, Y., & Wang, J. (2018). A comprehensive overview on the data driven and large scale based approaches for forecasting of building energy demand: A review. *Energy and Buildings, 165*, 301-320.

Ahmadi, P. S., Khoshgard, A., & Ashtiani, H. A. D. (2024). The impacts of residential buildings' energy compliance standards on Iran's GHG emissions toward achieving the Paris Agreement. *Journal of Engineering Research*.

Ajam, L., Ouezdou, M. B., Felfoul, H. S., & El Mensi, R. (2009). Characterization of the Tunisian phosphogypsum and its valorization in clay bricks. *Construction and building materials, 23*(10), 3240-3247.

Ali, W., Sajid, M. B., Alquaity, A. B., Abbas, S., Iftikhar, M. A., Sajid, J., & Abbas, A. (2022). Energy conservation and climate change mitigation potential of improving efficiency of room air conditioners in Pakistan. *Energy Reports, 8*, 6101-6109.

Allard, I., Nair, G., & Olofsson, T. (2021). Energy performance criteria for residential buildings: A comparison of Finnish, Norwegian, Swedish, and Russian building codes. *Energy and Buildings, 250*, 111276.

Allen, E., & Iano, J. (2019). *Fundamentals of building construction: materials and methods*: John Wiley & Sons.

American Society of Heating, R. a. A.-C. E. A. (2016). ANSI/ASHRAE/IES Standard 90.1-2016: Energy Standard for Buildings Except Low-Rise Residential Buildings. In.

Andrade, Á., Restrepo, Á., & Tibaquirá, J. E. (2021). EER or Fcsp: A performance analysis of fixed and variable air conditioning at different cooling thermal conditions. *Energy Reports, 7*, 537-545.

Ashuri, B., & Durmus-Pedini, A. (2010). An overview of the benefits and risk factors of going green in existing buildings. *International Journal of Facility Management, 1*(1).

Attia, S., Lacombe, T., Rakotondramiarana, H. T., Garde, F., & Roshan, G. (2019). Analysis tool for bioclimatic design strategies in hot humid climates. *Sustainable Cities and Society, 45*, 8-24.

Authority, C. E. (2022). All India Electricity Statistics. CEA, Government of India. Retrieved from https://cea.nic.in/wp-content/uploads/general/2022/GR_2022_FINAL.pdf

Authority., C. E. (2017). Growth of electricity sector in India from 1947-2017. CEA, Government of India. . Retrieved from http://www.cea.nic.in/reports/others/planning/pdm/growth_2017.pdf.

Aydin, E., & Brounen, D. (2019). The impact of policy on residential energy consumption. *Energy, 169*, 115-129.

Azar, E., & Al Ansari, H. (2017). Framework to investigate energy conservation motivation and actions of building occupants: The case of a green campus in Abu Dhabi, UAE. *Applied energy, 190*, 563-573.

Bano, F., & Sehgal, V. (2018). Evaluation of energy-efficient design strategies: Comparison of the thermal performance of energy-efficient office buildings in composite climate, India. *Solar Energy, 176*, 506-519.

Bansal, D., Minocha, V. K., & Kaur, A. (2020). Componentwise-embodied energy analysis of affordable houses in India. *Asian Journal of Civil Engineering, 21*(1), 137-145.

Bansal, D., Minocha, V. K., & Kaur, A. (2021). Embodied energy, CO2e, and construction cost of indian housing: model of low-rise versus high-rise development. *Journal of Architectural engineering, 27*(3), 04021017.

Bansal, N. K., & Minke, G. (1988). Climatic zones and rural housing in India. Part 1 of the Indo-German project on passive space conditioning.

Barkokebas, R. D., Chen, Y., Yu, H., & Al-Hussein, M. (2019). Achieving housing energy-efficiency requirements: Methodologies and impacts on housing construction cost and energy performance. *Journal of Building Engineering, 26*, 100874.

BEE. (2017). Energy Conservation Building Code. Retrieved from https://beeindia.gov.in/sites/default/files/BEE_ECBC%202017.pdf

BEE. (2018). Eco-Niwas Samhita (Energy Conservation Building Code for Residential Buildings) Part I: Building Envelope. Retrieved from https://www.beeindia.gov.in/sites/default/files/ECBC_BOOK_Web.pdf

BEE. (2021). Eco-Niwas Samhita (Code Compliance and Part II – Electro-Mechanical and Renewable Energy Systems). Retrieved from https://www.keralaenergy.gov.in/files/pdf2022/ENS_2021_1.pdf

BEE. (2021(a)). Label Schedule for Room Air Conditioners. Bureau of Energy Efficiency, Government of India. . Retrieved from https://beeindia.gov.in/sites/default/files/IAC_Notification.pdf

BEE. (2021(b)). Eco-Niwas Samhita (Energy Conservation Building Code for Residential Buildings) Part II: Electro-Mechanical and Renewable Energy Systems.

Belkhouane, H., Hensen, J., & Attia, S. (2017). *Thermal comforts models for net zero energy buildings in hot climates.* Paper presented at the 2nd International Conference on Energy and Indoor Environment for Hot Climates-ASHRAE, HotClimates 2017.

Berardi, U. (2017). A cross-country comparison of the building energy consumptions and their trends. *Resources, Conservation and Recycling, 123*, 230-241.

Bhanware, P. K., Jaboyedoff, P., Maithel, S., Lall, A., Chetia, S., Kapoor, V. P., . . . Nisar, A. (2019). Development of RETV (Residential Envelope Transmittance Value) Formula for Cooling Dominated Climates of India for the Eco-Niwas Samhita 2018. *Indo-Swiss Building Energy Efficiency Project (BEEP): New Delhi, India*, 3976-3983.

Bhatnagar, M., Mathur, J., & Garg, V. (2019a). *Climate zone classification of India using new base temperature.* Paper presented at the Building Simulation 2019.

Bhatnagar, M., Mathur, J., & Garg, V. (2019b). Development of reference building models for India. *Journal of Building Engineering, 21*, 267-277.

Biswas, S., Chowdhury, D., Roy, A., Yohanis, Y., & Neogi, S. (2013). Thermal performance of a multistoried residential apartment in winter season at Kolkata. *Int J Emerg Technol Adv Eng, 3*, 321-328.

Bruegge, C., Deryugina, T., & Myers, E. (2019). The distributional effects of building energy codes. *Journal of the Association of Environmental and Resource Economists, 6*(S1), S95-S127.

Calero, M., Alameda-Hernandez, E., Fernández-Serrano, M., Ronda, A., & Martín-Lara, M. Á. (2018). Energy consumption reduction proposals for thermal systems in residential buildings. *Energy and Buildings, 175*, 121-130.

CBERD & MNRE, U.-I. J. C. f. B. E. R. a. D. C. a. M. o. N. a. R. E. M. (2017). Thermo-Physical-Optical Property Database of Construction Material

Retrieved from https://carbse.org/reportsarticles/thermo-physical-optical-property-database-of-construction-materials/

Cell, O. (2019). India cooling action plan. *New Delhi: Ministry of Environment, Forest and Climate Change, Government of India. http://www. ozonecell. com/viewsection. jsp*.

Chakrabarti, S. (2022). Simulating the "city of joy": state choreography and the re-appropriation of public spaces in Kolkata. *Urban Geography, 43*(6), 886-894.

Chakraborti, M. (1987). *Estimating, Costing and Specification In Civil Engineering*: The anthor.

Chandel, S. S., Sharma, A., & Marwaha, B. M. (2016). Review of energy efficiency initiatives and regulations for residential buildings in India. *Renewable and sustainable energy reviews, 54*, 1443-1458.

Che, W. W., Tso, C. Y., Sun, L., Ip, D. Y., Lee, H., Chao, C. Y., & Lau, A. K. (2019). Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system. *Energy and Buildings, 201*, 202-215.

Chedwal, R., Mathur, J., Agarwal, G. D., & Dhaka, S. (2015). Energy saving potential through Energy Conservation Building Code and advance energy efficiency measures in hotel buildings of Jaipur City, India. *Energy and Buildings, 92*, 282-295.

Chel, A., & Kaushik, G. (2018). Renewable energy technologies for sustainable development of energy efficient building. *Alexandria engineering journal, 57*(2), 655-669.

Chen, L., Liu, S., Cai, W., Chen, R., Zhang, J., & Yu, Y. (2024). Carbon inequality in residential buildings: Evidence from 321 Chinese cities. *Environmental Impact Assessment Review, 105*, 107402.

Chen, X., Yang, H., & Wang, Y. (2017). Parametric study of passive design strategies for high-rise residential buildings in hot and humid climates: miscellaneous impact factors. *Renewable and sustainable energy reviews, 69*, 442-460.

Cherian, P., Palaniappan, S., Menon, D., & Anumolu, M. P. (2020). Comparative study of embodied energy of affordable houses made using GFRG and conventional building technologies in India. *Energy and Buildings, 223*, 110138.

Chiang, K.-Y., Chou, P.-H., Hua, C.-R., Chien, K.-L., & Cheeseman, C. (2009). Lightweight bricks manufactured from water treatment sludge and rice husks. *Journal of hazardous materials, 171*(1-3), 76-82.

Chiang, K., Chou, P., Chien, K., Chen, J., & Wu, C. (2009). Novel lightweight building bricks manufactured from water treatment plant sludge and agricultural waste. *J Residuals Sci Technol, 6*, 185-191.

Chihab, Y., Bouferra, R., Garoum, M., Essaleh, M., & Laaroussi, N. (2022). Thermal inertia and energy efficiency enhancements of hollow clay bricks integrated with phase change materials. *Journal of Building Engineering, 53*, 104569.

Chihab, Y., Garoum, M., & Laaroussi, N. (2022). Dynamic thermal performance of multilayer hollow clay walls filled with insulation materials: Toward energy saving in hot climates. *Energy and Built Environment*.

Corporation, C. E. S. (2022). Calcutta Electric Supply Corporation Retrieved from 15 May

Corporation, C. E. S. (July 2018). Tariff and Associated Terms and Conditions. Retrieved from https://www.cesc.co.in/wp-content/uploads/tariff/TARIFF%20AND%20ASSOCIATED%20CONDITIONS.pdf.

Corporation, I. F. (2017). India construction materials database of embodied energy and global Potential: METHODOLOGY REPORT. Retrieved from https://edgebuildings.com/wp-content/uploads/2022/04/IFC-India-Construction-Materials-Database-Methodology-Report.pdf

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment, 43*(4), 661-673.

De Boeck, L., Verbeke, S., Audenaert, A., & De Mesmaeker, L. (2015). Improving the energy performance of residential buildings: A literature review. *Renewable and sustainable energy reviews, 52*, 960-975.

Demir, I. (2008). Effect of organic residues addition on the technological properties of clay bricks. *Waste management, 28*(3), 622-627.

Department, C. P. W. (2021). Delhi Schedule of Rates. Volume-I. Central Public Works Department. Government of India. Retrieved from https://www.daojharkhandgroup.in/wp-content/uploads/2021/09/DSR-2021.pdf.

Dhaka, S., Mathur, J., & Garg, V. (2012). Combined effect of energy efficiency measures and thermal adaptation on air conditioned building in warm climatic conditions of India. *Energy and Buildings, 55*, 351-360.

Dissanayake, D., Jayasinghe, C., & Jayasinghe, M. (2017). A comparative embodied energy analysis of a house with recycled expanded polystyrene (EPS) based foam concrete wall panels. *Energy and Buildings, 135*, 85-94.

Dixit, M. K. (2017). Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. *Renewable and sustainable energy reviews, 79*, 390-413.

Do, S. L., Shin, M., Baltazar, J.-C., & Kim, J. (2017). Energy benefits from semi-transparent BIPV window and daylight-dimming systems for IECC code-compliance residential buildings in hot and humid climates. *Solar Energy, 155*, 291-303.

Doraj, P., Aluclu, I., & Hossein Eskandani, O. (2021). The impact of architectural structures from past to present on developing tourism (example of the city of paris). *International Journal of Scientific and Technological Research (JSTR), 7*(9), 8-19.

Dutta, A., & Neogi, S. (2013). *Energy savings in building through the implementation of ECBC and LEED guideline: case study.* Paper presented at the Proceeding: conference WEEC.

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., & Castellazzi, L. (2020). Review of 50 years of EU energy efficiency policies for buildings. *Energy and Buildings, 225*, 110322.

Efficiency, B. o. E. (2021). Label Schedule for Room Air Conditioners. Retrieved from "https://beeindia.gov.in/sites/default/files/IAC_Notification.pdf

El-Mahllawy, M. S. (2008). Characteristics of acid resisting bricks made from quarry residues and waste steel slag. *Construction and building materials, 22*(8), 1887-1896.

Enker, R. A., & Morrison, G. M. (2017). Analysis of the transition effects of building codes and regulations on the emergence of a low carbon residential building sector. *Energy and Buildings, 156*, 40-50.

Evans, M., Roshchanka, V., & Graham, P. (2017). An international survey of building energy codes and their implementation. *Journal of Cleaner Production, 158*, 382-389.

Evans, M., Yu, S., Staniszewski, A., Jin, L., & Denysenko, A. (2018). The international implications of national and local coordination on building energy codes: Case studies in six cities. *Journal of Cleaner Production, 191*, 127-134.

Fan, H., MacGill, I., & Sproul, A. B. (2015). Statistical analysis of driving factors of residential energy demand in the greater Sydney region, Australia. *Energy and Buildings, 105*, 9-25.

Fayaz, R., & Kari, B. M. (2009). Comparison of energy conservation building codes of Iran, Turkey, Germany, China, ISO 9164 and EN 832. *Applied energy, 86*(10), 1949-1955.

Feng, X., Yan, D., Wang, C., & Sun, H. (2016). A preliminary research on the derivation of typical occupant behavior based on large-scale questionnaire surveys. *Energy and Buildings, 117*, 332-340.

Franco, S., Mandla, V. R., & Rao, K. R. M. (2017). Urbanization, energy consumption and emissions in the Indian context A review. *Renewable and sustainable energy reviews, 71*, 898-907.

Fumo, N. (2014). A review on the basics of building energy estimation. *Renewable and sustainable energy reviews, 31*, 53-60.

Gagnon, R., Gosselin, L., & Decker, S. (2018). Sensitivity analysis of energy performance and thermal comfort throughout building design process. *Energy and Buildings, 164*, 278-294.

Gao, K., Fong, K., Lee, C., Lau, K. K.-L., & Ng, E. (2024). Balancing thermal comfort and energy efficiency in high-rise public housing in Hong Kong: Insights and recommendations. *Journal of Cleaner Production, 437*, 140741.

Garg, N., Kumar, A., Pipralia, S., & Garg, P. (2019). Initiatives to achieve energy efficiency for residential buildings in India: A review. *Indoor and Built Environment, 28*(6), 731-743.

GBPN. (2012). Best practice policies for low energy and carbon buildings. A scenario analysis. Research Report. Paris: Center for Climate Change and Sustainable Policy (3CSEP) for the Global Buildings Performance Network

GlobalABC, I. (2020). *GlobalABC Roadmap for Buildings and Construction: Towards a zero-emission, efficient and resilient buildings and construction sector*.

Gokarakonda, S., van Treeck, C., & Rawal, R. (2019). Influence of building design and control parameters on the potential of mixed-mode buildings in India. *Building and Environment, 148*, 157-172.

González-Torres, M., Pérez-Lombard, L., Coronel, J. F., Maestre, I. R., & Yan, D. (2022). A review on buildings energy information: Trends, end-uses, fuels and drivers. *Energy Reports, 8*, 626-637.

Graham, P., & Rawal, R. (2019). Achieving the 2 C goal: The potential of India's building sector. *Building Research & Information, 47*(1), 108-122.

Gui, X.-c., Ma, Y.-t., Chen, S.-q., & Ge, J. (2018). The methodology of standard building selection for residential buildings in hot summer and cold winter zone of China based on architectural typology. *Journal of Building Engineering, 18*, 352-359.

Guo, F., Akenji, L., Schroeder, P., & Bengtsson, M. (2018). Static analysis of technical and economic energy-saving potential in the residential sector of Xiamen city. *Energy, 142*, 373-383.

Gurupatham, S., Jayasinghe, C., & Perera, P. (2021). Ranking of walling materials using eco-efficiency for tropical climatic conditions: A survey-based approach. *Energy and Buildings, 253*, 111503.

Hemsath, T. L., & Bandhosseini, K. A. (2015). Sensitivity analysis evaluating basic building geometry's effect on energy use. *Renewable Energy, 76*, 526-538.

Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N., Ali, S., Tu, Q., . . . Kanaoka, K. (2020). Resource efficiency and climate change. *International Resource Panel (IRP)*.

Himeur, Y., Alsalemi, A., Bensaali, F., Amira, A., Varlamis, I., Bravos, G., . . . Dimitrakopoulos, G. (2022). Techno-economic assessment of building energy efficiency systems using behavioral change: A case study of an edge-based micro-moments solution. *Journal of Cleaner Production, 331*, 129786.

Hong, Y., Deng, W., & Ezeh, C. I. (2019). *Low-rise office retrofit: prerequisite for sustainable and green buildings in Shanghai.* Paper presented at the IOP Conference Series: Earth and Environmental Science.

Hu, M. (2023). A look at residential building stock in the United States-mapping life cycle embodied carbon emissions and other environmental impact. *Sustainable Cities and Society, 89*, 104333.

Hu, S., Yan, D., Guo, S., Cui, Y., & Dong, B. (2017). A survey on energy consumption and energy usage behavior of households and residential building in urban China. *Energy and Buildings, 148*, 366-378.

Huebner, G. M., Hamilton, I., Chalabi, Z., Shipworth, D., & Oreszczyn, T. (2015). Explaining domestic energy consumption–the comparative contribution of building factors, socio-demographics, behaviours and attitudes. *Applied energy, 159*, 589-600.

IEA. (2021a). Energy Efficiency 2021, IEA, Paris Retrieved from https://www.iea.org/reports/energy-efficiency-2021

IEA. (2021b). India Energy Outlook 2021, IEA, Paris https. Retrieved from https://www.iea.org/reports/india-energy-outlook-2021, IEA. (2023). Greenhouse Gas Emissions from Energy Data Explorer, IEA, Paris Retrieved from https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer

IEA, I. (2021). *Greenhouse gas emissions from energy data explorer*.

India, G. (2016(b).). GRIHA Council, Green Rating for Integrated Habitat Assessment. Retrieved from http://www.grihaindia.org/?t=griha_council&#&griha_council

India., G. (2016(a)). Green Rating for Integrated Habitat Assessment. Retrieved from http://www.grihaindia.org/index.php?option=com_content&view=article&id=73&t=Green_Rating_for_I ntegrated_Habitat_Assessment

Islam, R., Nazifa, T. H., Mohammed, S. F., Zishan, M. A., Yusof, Z. M., & Mong, S. G. (2021). Impacts of design deficiencies on maintenance cost of high-rise residential buildings and mitigation measures. *Journal of Building Engineering, 39*, 102215.

Kalhor, K., & Emaminejad, N. (2020). Qualitative and quantitative optimization of thermal insulation materials: Insights from the market and energy codes. *Journal of Building Engineering, 30*, 101275.

Karunathilake, H., Hewage, K., & Sadiq, R. (2018). Opportunities and challenges in energy demand reduction for Canadian residential sector: A review. *Renewable and sustainable energy reviews, 82*, 2005-2016.

Koezjakov, A., Urge-Vorsatz, D., Crijns-Graus, W., & Van den Broek, M. (2018). The relationship between operational energy demand and embodied energy in Dutch residential buildings. *Energy and Buildings, 165*, 233-245.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated.

Krarti, M., & Howarth, N. (2020). Transitioning to high efficiency air conditioning in Saudi Arabia: A benefit cost analysis for residential buildings. *Journal of Building Engineering, 31*, 101457.

Kristensen, M. H., & Petersen, S. (2016). Choosing the appropriate sensitivity analysis method for building energy model-based investigations. *Energy and Buildings, 130*, 166-176.

Kumar, G., Thakur, B., & De, S. (2021). Energy performance of typical large residential apartments in Kolkata: implementing new energy conservation building codes of India. *Clean Technologies and Environmental Policy, 23*, 1251-1271.

Kumari, A., Suman, S., & Garg, T. Substantiating the Scope of Code: Eco-Niwas Samhita. Alliance for a n Energy-Efficient Economy (AEEE); 2021. In.

Kwok, Y. T., Lau, K. K.-L., Lai, A. K. L., Chan, P. W., Lavafpour, Y., Ho, J. C. K., & Ng, E. Y. Y. (2017). A comparative study on the indoor thermal comfort and energy consumption of typical public rental housing types under near-extreme summer conditions in Hong Kong. *Energy Procedia, 122*, 973-978.

Kwok, Y. T., Schoetter, R., & Ng, E. (2022). Towards decarbonisation targets by changing setpoint temperature to avoid building overcooling and implementing district cooling in (sub) tropical high-density cities–A case study of Hong Kong. *Science of the Total Environment, 811*, 152338.

Kwong, Q. J., Adam, N. M., & Sahari, B. (2014). Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: A review. *Energy and Buildings, 68*, 547-557.

Levinson, A. (2016). How much energy do building energy codes save? Evidence from California houses. *American Economic Review, 106*(10), 2867-2894.

Li, C. Z., Zhang, L., Liang, X., Xiao, B., Tam, V. W., Lai, X., & Chen, Z. (2022). Advances in the research of building energy saving. *Energy and Buildings, 254*, 111556.

Li, H., Wang, S., & Cheung, H. (2018). Sensitivity analysis of design parameters and optimal design for zero/low energy buildings in subtropical regions. *Applied energy, 228*, 1280-1291.

Li, X., Zhou, Y., Yu, S., Jia, G., Li, H., & Li, W. (2019). Urban heat island impacts on building energy consumption: A review of approaches and findings. *Energy, 174*, 407-419.

Li, Y., Kubicki, S., Guerriero, A., & Rezgui, Y. (2019). Review of building energy performance certification schemes towards future improvement. *Renewable and sustainable energy reviews, 113*, 109244.

Lima, I., Scalco, V., & Lamberts, R. (2019). Estimating the impact of urban densification on high-rise office building cooling loads in a hot and humid climate. *Energy and Buildings, 182*, 30-44.

Lin, K.-L. (2007). The effect of heating temperature of thin film transistor-liquid crystal display (TFT-LCD) optical waste glass as a partial substitute partial for clay in eco-brick. *Journal of Cleaner Production, 15*(18), 1755-1759.

Lingling, X., Wei, G., Tao, W., & Nanru, Y. (2005). Study on fired bricks with replacing clay by fly ash in high volume ratio. *Construction and building materials, 19*(3), 243-247.

Liu, D., Wang, W., & Liu, J. (2017). Sensitivity analysis of meteorological parameters on building energy consumption. *Energy Procedia, 132*, 634-639.

Lu, M., & Lai, J. H. (2019). Building energy: a review on consumptions, policies, rating schemes and standards. *Energy Procedia, 158*, 3633-3638.

Lynch, G. (1994). Brickwork: History, Technology. *Practice, Donhead, London*.

Maier, D. (2022). Perspective of using green walls to achieve better energy efficiency levels. A bibliometric review of the literature. *Energy and Buildings*, 112070.

Mekhilef, S., Saidur, R., Said, S., Hong, P., & Islam, M. (2014). Techno-economic evaluation of energy efficiency measures in high rise residential buildings in Malaysia. *Clean Technologies and Environmental Policy, 16*, 23-35.

Memon, S. A. (2014). Phase change materials integrated in building walls: A state of the art review. *Renewable and sustainable energy reviews, 31*, 870-906.

Mirrahimi, S., Mohamed, M. F., Haw, L. C., Ibrahim, N. L. N., Yusoff, W. F. M., & Aflaki, A. (2016). The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate. *Renewable and sustainable energy reviews, 53*, 1508-1519.

MoEF&CC. (2019). India Cooling Action Plan. New Delhi. http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf

Monteiro, S., & Vieira, C. (2005). Effect of oily waste addition to clay ceramic. *Ceramics International, 31*(2), 353-358.

Moreira, A. C., Ribau, C. P., & Rodrigues, C. d. S. F. (2022). Green supply chain practices in the plastics industry in Portugal. The moderating effects of traceability, ecocentricity, environmental culture, environmental uncertainty, competitive pressure, and social responsibility. *Cleaner Logistics and Supply Chain, 5*, 100088.

Morrey, H. S., & Ghosh, A. (2024). Energy assessment of gasochromic smart windows for a high-rise apartment block in a temperate climate. *Journal of Building Engineering, 84*, 108625.

Mostafavi, F., Tahsildoost, M., & Zomorodian, Z. (2021). Energy efficiency and carbon emission in high-rise buildings: A review (2005-2020). *Building and Environment, 206*, 108329.

Mujeebu, M. A., & Bano, F. (2022). Energy-saving potential and cost-effectiveness of active energy-efficiency measures for residential building in warm-humid climate. *Energy for Sustainable Development, 67*, 163-176.

Nandgaonkar, S. (2023). Mumbai has 77% tall buildings in India, ranks 17th globally: report. . Retrieved from https://www.hindustantimes.com/cities/mumbai-news/mumbai-dominates-indian-skyline-with-77-share-of-tall-buildings-ranks-17th-worldwide-report-101687979905261.html

Nations, U. (2020). Cities and climate change.

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., & Majid, M. Z. A. (2015). A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). *Renewable and sustainable energy reviews, 43*, 843-862.

Network, G. B. P. (2012). Best practice policies for low energy and carbon buildings. A scenario analysis.

O'Brien, W., Tahmasebi, F., Andersen, R. K., Azar, E., Barthelmes, V., Belafi, Z. D., . . . d'Oca, S. (2020). An international review of occupant-related aspects of building energy codes and standards. *Building and Environment, 179*, 106906.

O'Neill, Z., & Niu, F. (2017). Uncertainty and sensitivity analysis of spatio-temporal occupant behaviors on residential building energy usage utilizing Karhunen-Loève expansion. *Building and Environment, 115*, 157-172.

Pacheco-Torgal, F., & Jalali, S. (2011). Cementitious building materials reinforced with vegetable fibres: A review. *Construction and building materials, 25*(2), 575-581.

Pacheco Torgal, F., Jalali, S., Torgal, F. P., & Jalali, S. (2011a). Binders and concretes. *Eco-efficient construction and building materials*, 75-129.

Pacheco Torgal, F., Jalali, S., Torgal, F. P., & Jalali, S. (2011b). Masonry units. *Eco-efficient construction and building materials*, 131-142.

Pallis, P., Gkonis, N., Varvagiannis, E., Braimakis, K., Karellas, S., Katsaros, M., & Vourliotis, P. (2019). Cost effectiveness assessment and beyond: A study on energy efficiency interventions in Greek residential building stock. *Energy and Buildings, 182*, 1-18.

Pan, Y., Zhu, M., Lv, Y., Yang, Y., Liang, Y., Yin, R., . . . Zeng, F. (2023). Building energy simulation and its application for building performance optimization: A review of methods, tools, and case studies. *Advances in Applied Energy*, 100135.

Papadopoulos, T. C., Spanoudis, G. C., & Georgiou, G. K. (2016). How is RAN related to reading fluency? A comprehensive examination of the prominent theoretical accounts. *Frontiers in psychology, 7*, 213320.

Paul S, T. B., Chakrabarty S. (2011). Operational Energy Consumption and Associated CO2 Emission of an Office Building in Kolkata-A Case Study. *Journal of the IPHE, 3*, 12-19.

Pellegrino, M., Simonetti, M., & Chiesa, G. (2016). Reducing thermal discomfort and energy consumption of Indian residential buildings: Model validation by in-field measurements and simulation of low-cost interventions. *Energy and Buildings, 113*, 145-158.

Pellegrino, M., Thakur, B., Guha, H., & Simonetti, M. (2011). Energy efficient choice of brick façade in Kolkata, India. *Procedia Engineering, 21*, 737-744.

Pinheiro, B., & Holanda, J. (2009). Processing of red ceramics incorporated with encapsulated petroleum waste. *Journal of Materials Processing Technology, 209*(15-16), 5606-5610.

Plan, I. C. A. (2019). Ministry of Environment, Forest & Climate Change, Government of India. Retrieved from http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf

Porras, F., Walter, A., Soriano, G., & Ramirez, A. D. (2023). On the adoption of stricter energy efficiency standards for residential air conditioners: Case study Guayaquil, Ecuador. *Heliyon, 9*(3).

Praseeda, K., Reddy, B. V., & Mani, M. (2016). Embodied and operational energy of urban residential buildings in India. *Energy and Buildings, 110*, 211-219.

Qian, D., Li, Y., Niu, F., & O'Neill, Z. (2019). Nationwide savings analysis of energy conservation measures in buildings. *Energy Conversion and Management, 188*, 1-18.

Randazzo, T., De Cian, E., & Mistry, M. N. (2020). Air conditioning and electricity expenditure: The role of climate in temperate countries. *Economic Modelling, 90*, 273-287.

Rawal, R., Maithel, S., Shukla, Y., Rana, S., Gowri, G., Patel, J., . . . Vardhan, V. (2020). Thermal performance of walling material and wall technology Part-1. In.

Rivalin, L., Stabat, P., Marchio, D., Caciolo, M., & Hopquin, F. (2018). A comparison of methods for uncertainty and sensitivity analysis applied to the energy performance of new commercial buildings. *Energy and Buildings, 166*, 489-504.

Saboya Jr, F., Xavier, G., & Alexandre, J. (2007). The use of the powder marble by-product to enhance the properties of brick ceramic. *Construction and building materials, 21*(10), 1950-1960.

Sadati, S. E., Rahbar, N., & Kargarsharifabad, H. (2023). Energy assessment, economic analysis, and environmental study of an Iranian building: The effect of wall materials and climatic conditions. *Sustainable Energy Technologies and Assessments, 56*, 103093.

Sakah, M., du Can, S. d. l. R., Diawuo, F. A., Sedzro, M. D., & Kuhn, C. (2019). A study of appliance ownership and electricity consumption determinants in urban Ghanaian households. *Sustainable Cities and Society, 44*, 559-581.

Saleki, S., & Bahramani, S. K. (2018). Designing a Low-Carbon Building via LCB Method 3.0, Case Study: An Educational Building in Tehran. *Journal of Construction in Developing Countries, 23*(2), 129-150.

Salvati, A., Roura, H. C., & Cecere, C. (2017). Assessing the urban heat island and its energy impact on residential buildings in Mediterranean climate: Barcelona case study. *Energy and Buildings, 146*, 38-54.

Samara, M., Lafhaj, Z., & Chapiseau, C. (2009). Valorization of stabilized river sediments in fired clay bricks: Factory scale experiment. *Journal of hazardous materials, 163*(2-3), 701-710.

Sanquist, T. F., Orr, H., Shui, B., & Bittner, A. C. (2012). Lifestyle factors in US residential electricity consumption. *Energy Policy, 42*, 354-364.

Satola, D., Houlihan-Wiberg, A., & Gustavsen, A. (2022). Global sensitivity analysis and optimisation of design parameters for low GHG emission lifecycle of multifamily buildings in India. *Energy and Buildings, 277*, 112596.

Saxena, R., Rakshit, D., & Kaushik, S. (2020). Experimental assessment of Phase Change Material (PCM) embedded bricks for passive conditioning in buildings. *Renewable Energy, 149*, 587-599.

Sbci, U. (2009). Buildings and climate change: Summary for decision-makers. *United Nations Environmental Programme, Sustainable Buildings and Climate Initiative, Paris, 1*, 62.

Schwarz, M., Nakhle, C., & Knoeri, C. (2020). Innovative designs of building energy codes for building decarbonization and their implementation challenges. *Journal of Cleaner Production, 248*, 119260.

Shadram, F., Johansson, T. D., Lu, W., Schade, J., & Olofsson, T. (2016). An integrated BIM-based framework for minimizing embodied energy during building design. *Energy and Buildings, 128*, 592-604.

Shah, N., Park, W. Y., & Ding, C. (2021). Trends in best-in-class energy-efficient technologies for room air conditioners. *Energy Reports, 7*, 3162-3170.

Shen, J., Krietemeyer, B., Bartosh, A., Gao, Z., & Zhang, J. (2021). *Green Design Studio: A modular-based approach for high-performance building design.* Paper presented at the Building Simulation.

Shen, P., Braham, W., & Yi, Y. (2019). The feasibility and importance of considering climate change impacts in building retrofit analysis. *Applied energy, 233*, 254-270.

Singh, J., Mantha, S., & Phalle, V. M. (2018). Analysis of technical and economic electricity saving potential in the urban Indian households. *Sustainable Cities and Society, 43*, 432-442.

Singh, M. M., Singaravel, S., Klein, R., & Geyer, P. (2020). Quick energy prediction and comparison of options at the early design stage. *Advanced Engineering Informatics, 46*, 101185.

Singh, R., Lazarus, I. J., & Kishore, V. (2016). Uncertainty and sensitivity analyses of energy and visual performances of office building with external venetian blind shading in hot-dry climate. *Applied energy, 184*, 155-170.

Sinka, M., Bajare, D., Jakovics, A., Ratnieks, J., Gendelis, S., & Tihana, J. (2019). Experimental testing of phase change materials in a warm-summer humid continental climate. *Energy and Buildings, 195*, 205-215.

Standards, B. o. I. (2016a). National building code of India. Retrieved from https://mptownplan.nic.in/act%20&%20Rules/NationalBuilding%20Code%20Part-IV%20(Fire%20Safety).pdf

Standards, B. o. I. (2016b). National Building Code of India (NBC). Vol. 2, Part 8 (Building Services), Section 1 (Lighting and Natural Ventilation). Government of India, BEE. (2017). Energy Conservation Building Code.

. Retrieved from https://beeindia.gov.in/sites/default/files/BEE_ECBC%202017.pdf

Stephan, A., & Stephan, L. (2016). Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Applied energy, 161*, 445-464.

Studio, H. B. (2021). The surge in India's high-rises: A present-day requisite. . Retrieved from https://www.hindustantimes.com/brand-post/the-surge-in-india-s-high-rises-a-present-day-requisite-101632907432707.html

Su, X., Zhang, L., & Liu, Z. (2023). Daylighting and energy performance of the combination of optical fiber based translucent concrete walls and windows. *Journal of Building Engineering, 67*, 105959.

Sun, S., Kensek, K., Noble, D., & Schiler, M. (2016). A method of probabilistic risk assessment for energy performance and cost using building energy simulation. *Energy and Buildings, 110*, 1-12.

Sutcu, M., & Akkurt, S. (2009). The use of recycled paper processing residues in making porous brick with reduced thermal conductivity. *Ceramics International, 35*(7), 2625-2631.

Tian, W. (2013). A review of sensitivity analysis methods in building energy analysis. *Renewable and sustainable energy reviews, 20*, 411-419.

Tian, W., de Wilde, P., Li, Z., Song, J., & Yin, B. (2018). Uncertainty and sensitivity analysis of energy assessment for office buildings based on Dempster-Shafer theory. *Energy Conversion and Management, 174*, 705-718.

Tulsyan, A., Dhaka, S., Mathur, J., & Yadav, J. V. (2013). Potential of energy savings through implementation of Energy Conservation Building Code in Jaipur city, India. *Energy and Buildings, 58*, 123-130.

Udawattha, C., & Halwatura, R. (2017). Life cycle cost of different Walling material used for affordable housing in tropics. *Case studies in construction materials, 7*, 15-29.

Udawattha, C., & Halwatura, R. (2018). Geopolymerized self-compacting mud concrete masonry units. *Case studies in construction materials, 9*, e00177.

UNEP. (2020). Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector. Renewables global status report. .

Ürge-Vorsatz, D., Cabeza, L. F., Serrano, S., Barreneche, C., & Petrichenko, K. (2015). Heating and cooling energy trends and drivers in buildings. *Renewable and sustainable energy reviews, 41*, 85-98.

Varbanov, P. S., Klemeš, J. J., & Wang, X. (2018). Methods optimisation, Process Integration and modelling for energy saving and pollution reduction. In (Vol. 146, pp. 1-3): Elsevier.

Verma, N., & Jakhar, I. (2016). Analysis of energy efficiency in India. *International Journal in Management & Social Science, 4*(4), 142-159.

Vivian, J., Chiodarelli, U., Emmi, G., & Zarrella, A. (2020). A sensitivity analysis on the heating and cooling energy flexibility of residential buildings. *Sustainable Cities and Society, 52*, 101815.

Wang, H., & Zhai, Z. J. (2016). Advances in building simulation and computational techniques: A review between 1987 and 2014. *Energy and Buildings, 128*, 319-335.

Wang, X., Feng, W., Cai, W., Ren, H., Ding, C., & Zhou, N. (2019). Do residential building energy efficiency standards reduce energy consumption in China?–A data-driven method to validate the actual performance of building energy efficiency standards. *Energy Policy, 131*, 82-98.

Xie, Q., Ouyang, H., & Gao, X. (2016). Estimation of electricity demand in the residential buildings of China based on household survey data. *International journal of hydrogen energy, 41*(35), 15879-15886.

Yang, S., Tian, W., Cubi, E., Meng, Q., Liu, Y., & Wei, L. (2016). Comparison of sensitivity analysis methods in building energy assessment. *Procedia Engineering, 146*, 174-181.

Yao, M., & Zhao, B. (2017). Window opening behavior of occupants in residential buildings in Beijing. *Building and Environment, 124*, 441-449.

Yoshino, H., Hong, T., & Nord, N. (2017). IEA EBC annex 53: Total energy use in buildings—Analysis and evaluation methods. *Energy and Buildings, 152*, 124-136.

Yu, S., Tan, Q., Evans, M., Kyle, P., Vu, L., & Patel, P. L. (2017). Improving building energy efficiency in India: State-level analysis of building energy efficiency policies. *Energy Policy, 110*, 331-341.

Zerroug, A., & Dzelzitis, E. (2015). *Analysis of results of energy consumption simulation with eQUEST and energy plus.* Paper presented at the International Conference Civil Engineering.

Zhang, M., Cheng, Z., Li, C., & Deng, N. (2022). Did the energy efficiency upgrades for air conditioners reduce residential electricity consumption? Evidence from China. *Energy and Buildings, 275*, 112471.

Zhang, X., Weerasuriya, A. U., Wang, J., Li, C. Y., Chen, Z., Tse, K. T., & Hang, J. (2022). Cross-ventilation of a generic building with various configurations of external and internal openings. *Building and Environment, 207*, 108447.

Zhao, D., McCoy, A. P., Du, J., Agee, P., & Lu, Y. (2017). Interaction effects of building technology and resident behavior on energy consumption in residential buildings. *Energy and Buildings, 134*, 223-233.

Zou, P. X., Xu, X., Sanjayan, J., & Wang, J. (2018). Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives. *Energy and Buildings*, *178*, 165-181.

G Kumar 23/04/2024
(GUNJAN KUMAR)

S. ... 23/04/24

Professor
Dept. of Mechanical Engineering
Jadavpur University, Kolkata-32

Biswajit Thakur 23/4/24

Dr. Biswajit Thakur
Associate Professor
Civil Engineering Department
Meghnad Saha Institute of Technology

MEGHNAD SAHA INSTITUTE OF TECHNOLOGY