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ASSESSMENT OF THE COOLING AND ELECTRICAL DEMAND IN COMMERCIAL BUILDINGS IN SELECTED CITIES

On behalf of:
Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

IKI INTERNATIONAL CLIMATE INITIATIVE

Celestial Earth Development Council

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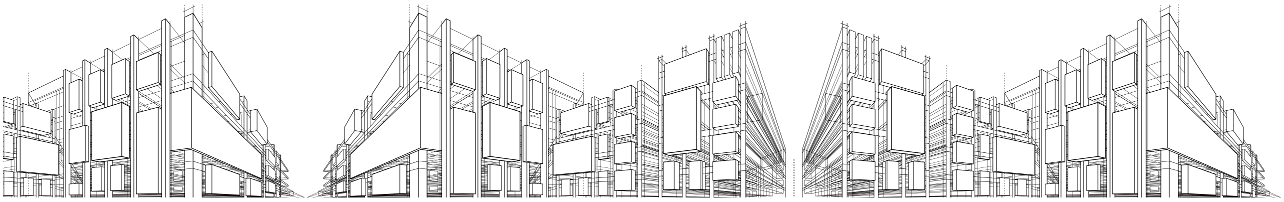

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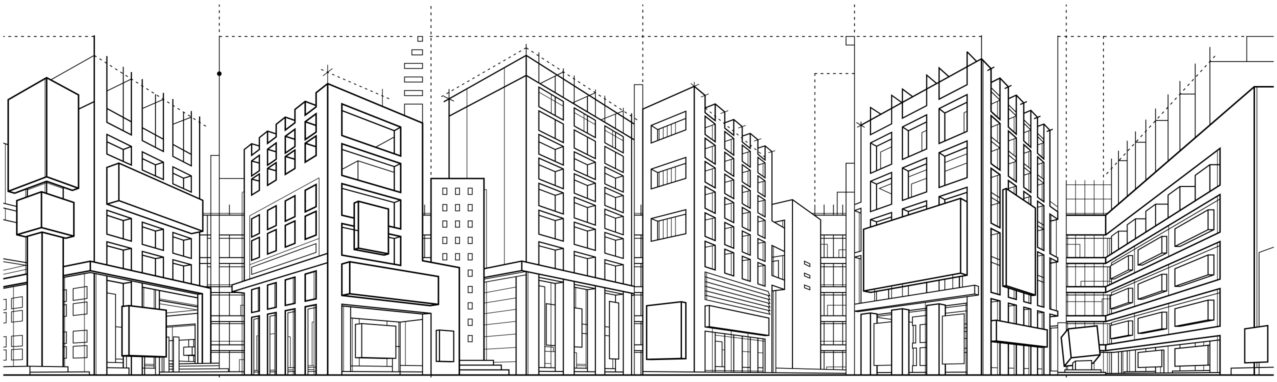

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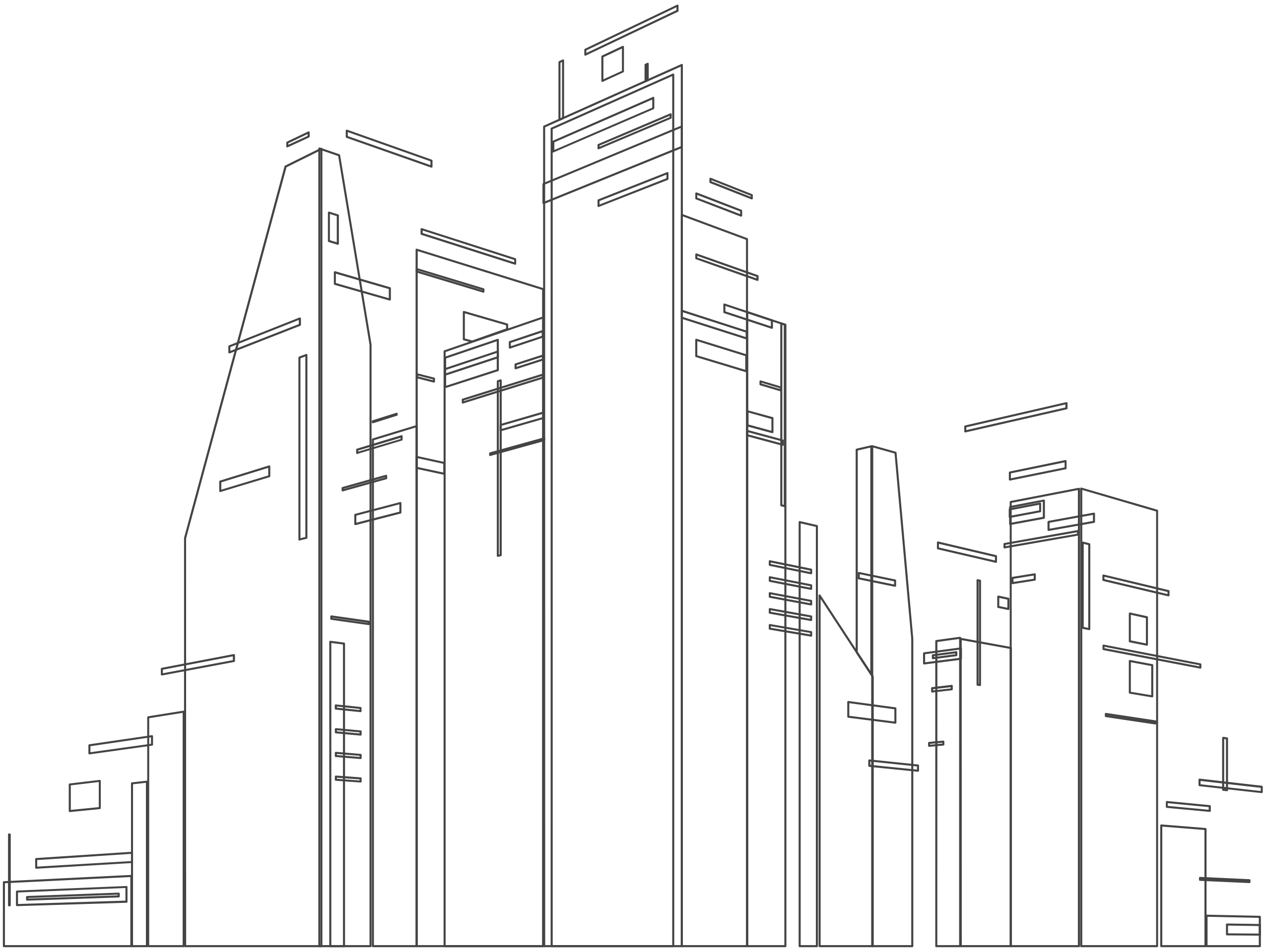

Abbreviations

AAhEPI	Average Annual hourly Energy Performance Index
AC	Air conditioning
BAU	Business-as-usual
BEE	Bureau of Energy Efficiency
BPO	Business process outsourcing
CEA	City Energy Analyst
CEEW	Council on Energy, Environment and Water
CO2	Carbon dioxide
CSV	Comma-Separated Values
DCS	District cooling system
ECBC	Energy Conservation Building Code
EPI	Energy Performance Index
EPW	EnergyPlus Weather
FAR	Floor Area Ratio
GFA	Gross floor area
GHG	Greenhouse gas
GJ/sqm	Gigajoule per Square Meter
HadCM3	Hadley Centre Coupled Model, version 3
HVAC	Heating, ventilation and air conditioning
ICAP	India Cooling Action Plan
IPCC DDC	Intergovernmental Panel on Climate Change Data Distribution Centre
ISHRAE	Indian Society of Heating, Refrigerating, and Air Conditioning Engineers
IT	Information Technology
kWh/sqm	Kilowatt-hour per square metre
kWh/yr	Kilowatt-hours per year
LEED	Leadership in Energy and Environmental Design
ML	Machine Learning
Mwhyr	Megawatt-hour per year
NASA	National Aeronautics and Space Administration
OSM	Open Street Map
PG	Paying Guest
QGIS	Quantum Geographic Information System
RCP	Representative Concentration Pathways
RH	Relative humidity
SPIBEAT	Spatially Integrated Building Energy Assessment Tool
SRES	Special Report on Emissions Scenarios
TAR	Third Assessment Report
TERI	The Energy and Resources Institute
VRF	Variable refrigerant flow

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महानिदेशक

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(विद्युत मंत्रालय, भारत सरकार)

BUREAU OF ENERGY EFFICIENCY
(Ministry of Power, Government of India)

Message

The growing impacts of climate change, along with rapid urbanization, are significantly increasing cooling demand in commercial buildings across Indian cities. This trend is emerging as a major driver of electricity consumption, with important implications for peak load management and greenhouse gas emissions.

The report, "Assessment of Cooling and Electrical Demand for Commercial Buildings in Four Cities," presents an analysis of current and projected cooling demand across Delhi, Mumbai, Bengaluru, and Hyderabad, representing diverse climatic zones. It provides insights into how local climate conditions influence cooling requirements and energy use patterns in commercial buildings.

The findings highlight the strong interlinkage between cooling demand and electricity consumption, emphasizing the need for integrated strategies that combine passive design measures, energy-efficient cooling technologies, and climate-responsive planning. The report also underlines the importance of strengthening building energy codes, promoting BEE-rated systems, and integrating renewable energy solutions.

This report aims to support policymakers, urban planners, and industry stakeholders in advancing energy-efficient and climate-resilient commercial building development in India.

K.C. Panigrahy

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Foreword

India's rapid urbanization, economic growth, and rising temperatures have significantly increased the demand for cooling in the built environment. Cooling today is no longer a matter of comfort alone it is central to ensuring public health, productivity, and climate resilience. At the same time, the growing cooling demand poses critical challenges in terms of energy consumption, peak electricity load, and greenhouse gas emissions.

In this context, the present study, "Assessment of the Cooling and Electrical Demand in Commercial Buildings in Selected Cities," provides timely and valuable insights into the evolving dynamics of cooling demand across major Indian cities. Covering diverse climatic zones Delhi, Mumbai, Bangalore, and Hyderabad the study highlights how regional variations, building typologies, and urban growth patterns influence energy consumption and cooling requirements.

This report, developed under GIZ's Energy Efficient Cooling Programme in partnership with the Bureau of Energy Efficiency (BEE), demonstrates the importance of adopting a data-driven and forward-looking approach to sustainable cooling. By leveraging innovative tools such as geospatial analysis and building energy modelling, the study presents a comprehensive assessment of current trends as well as future scenarios up to 2050. The findings clearly underline that without targeted interventions, cooling demand is expected to rise significantly, placing additional pressure on India's energy systems and climate commitments.

Encouragingly, the analysis also showcases the transformative potential of energy-efficient technologies, improved building design, and policy interventions. Strategies such as passive cooling, high-efficiency HVAC systems, and adherence to frameworks like the India Cooling Action Plan can substantially reduce energy demand, emissions, and costs, while enhancing thermal comfort and urban resilience.

At GIZ, we are committed to supporting India's transition towards sustainable and climate-resilient development pathways. Through collaborative initiatives with national and state partners, we aim to strengthen policy frameworks, build technical capacity, and promote the adoption of innovative energy efficiency solutions across sectors.

We hope that this report will serve as a valuable resource for policymakers, urban planners, industry stakeholders, and practitioners in advancing the agenda of sustainable cooling in India. The insights presented herein can inform evidence-based decision-making and contribute to achieving national and global climate goals.

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Foreword

India’s rapid urbanization, rising temperatures, and growing commercial building stock are driving a significant increase in cooling demand. Cooling is now integral to energy security, economic productivity, and climate resilience, making its efficient management a national priority.

The Bureau of Energy Efficiency (BEE), under the Ministry of Power, lead efforts in carrying out the study with support from GIZ for the report “Assessment of the Cooling and Electrical Demand in Commercial Buildings in Selected Cities”. It provides a robust analytical foundation for policy and planning. Covering Delhi, Mumbai, Bangalore, and Hyderabad, it reflects diverse climatic conditions and their implications for cooling demand and electricity consumption.

Using advanced tools such as geospatial analysis, machine learning, and building energy modeling, the study assesses both current trends and future scenarios up to 2050. The findings highlight the scale of the emerging cooling challenge and the associated impact on energy demand and emissions.

The report underscores the need to strengthen Energy Conservation & Sustainable Building Code (ECSBC) implementation, promote high-efficiency cooling technologies, and adopt climate-responsive building design. In line with the India Cooling Action Plan, scaling passive cooling strategies, efficient HVAC systems, and renewable energy integration will be critical. The insights presented will support policymakers and stakeholders in advancing sustainable, low-carbon, and climate-resilient commercial buildings in India.

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Preface

The demand for cooling in India is rising at an unprecedented pace, driven by increasing temperatures, urban expansion, and changing occupancy patterns in buildings. In commercial sectors where cooling is essential for productivity, comfort, and operational continuity this demand translates directly into higher electricity consumption and growing environmental impacts. Understanding and managing this cooling-energy relationship is therefore critical for achieving sustainable urban development.

This report, “Assessment of Cooling and Electrical Demand for Commercial Buildings in Four Cities,” has been developed to provide a detailed, data-driven analysis of cooling demand and associated electricity consumption across Delhi, Mumbai, Bangalore, and Hyderabad. These cities represent distinct climatic zones composite, warm-humid, temperate, and hot-dry allowing for a comparative assessment of how regional conditions shape cooling needs.

A central component of this study is the evaluation of building energy performance using the Energy Performance Index (EPI), expressed in terms of energy consumption per unit area, and its alignment with Bureau of Energy Efficiency (BEE) Star Rating standards. By benchmarking buildings against these nationally recognized indicators, the report provides a robust framework to assess efficiency levels, identify performance gaps, and highlight opportunities for improvement across different building typologies.

The analysis covers a wide range of commercial building categories, including offices, retail spaces, hospitality establishments, educational institutions, and specialized facilities. It examines both baseline conditions and future scenarios, capturing variations in cooling demand, electricity consumption, and energy performance across cities and sectors. The findings reveal significant disparities driven by climatic conditions, building design, operational characteristics, and technology adoption.

Importantly, the report emphasizes the role of integrated cooling strategies combining passive design measures, efficient cooling technologies, and improved building envelopes in reducing energy intensity. It also highlights the importance of adopting higher BEE star-rated systems and strengthening compliance with energy efficiency norms to achieve long-term sustainability outcomes.

Aligned with national frameworks such as the India Cooling Action Plan (ICAP), this report seeks to bridge the gap between technical analysis and policy relevance. It provides actionable insights that can inform urban planning, energy policy, and building design practices, enabling stakeholders to make informed decisions in addressing the growing cooling demand.

Developed through rigorous analysis and a comprehensive methodological approach, this report aspires to serve as a valuable resource for policymakers, practitioners, researchers, and industry stakeholders. It is our hope that the insights presented here will contribute to advancing energy-efficient, low-carbon, and climate-responsive cooling solutions in India’s commercial building sector.

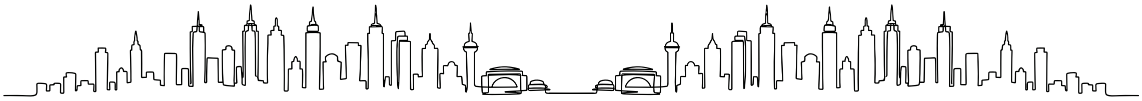


Photo By: Swapnil Potdar @Unsplash

Executive Summary

Cooling is essential for urban resilience, public health, and economic productivity, particularly in the face of climate change and rapid urbanization. This study evaluates the current and future cooling and electricity demand of different categories of commercial buildings in Delhi, Mumbai, Bangalore, and Hyderabad. These four cities represent distinct climatic zones in India. Using SPIBEAT, the analysis estimates energy consumption, cooling demand, and greenhouse gas (GHG) emissions under different climate and policy scenarios for the baseline year (2023) and projections up to 2050. The findings also align with national priorities such as the India Cooling Action Plan (ICAP), which provides a strategic roadmap to sustainable cooling and thermal comfort across sectors.

A. Key Findings

City-Wise Insights

- *Delhi (Composite Climate):* Extreme seasonal variations lead to high cooling and heating energy demand. Without intervention, cooling demand will rise significantly by 2050, necessitating high-efficiency HVAC systems and passive cooling strategies.
- *Mumbai (Warm & Humid Climate):* Year-round cooling is required due to persistent high temperatures and humidity. Reflective roofing, advanced dehumidification, and enhanced insulation can help reduce energy consumption.
- Bangalore (Temperate Climate): A moderate climate results in relatively lower cooling demand, driven primarily by internal heat gains. Natural ventilation and passive cooling can sustain its energy-efficient trajectory.
- Hyderabad (Hot & Dry Climate): High daytime temperatures and low humidity create significant cooling needs. High thermal mass materials, night ventilation, and evaporative cooling can optimize energy use.

Building Category-Wise Findings

The study also evaluates energy performance variations across different commercial building typologies, highlighting key cooling demand trends:

- Office Buildings & Educational Institutions: Mumbai and Hyderabad exhibit higher cooling energy demands due to humidity and extreme heat, respectively, while Bangalore has the lowest due to its mild climate.
- Retail & Hospitality Buildings: Shopping malls and hotels in Mumbai and Hyderabad require the most cooling energy, with significant latent cooling loads from high humidity and high occupant density. Delhi and Bangalore have moderate demand, benefiting from seasonal variations and natural

ventilation.
- Industrial & Special Purpose Buildings: Hyderabad and Mumbai show higher energy use in data centres and industrial facilities due to intensive cooling requirements, while Bangalore remains the most energy-efficient due to lower external cooling loads.

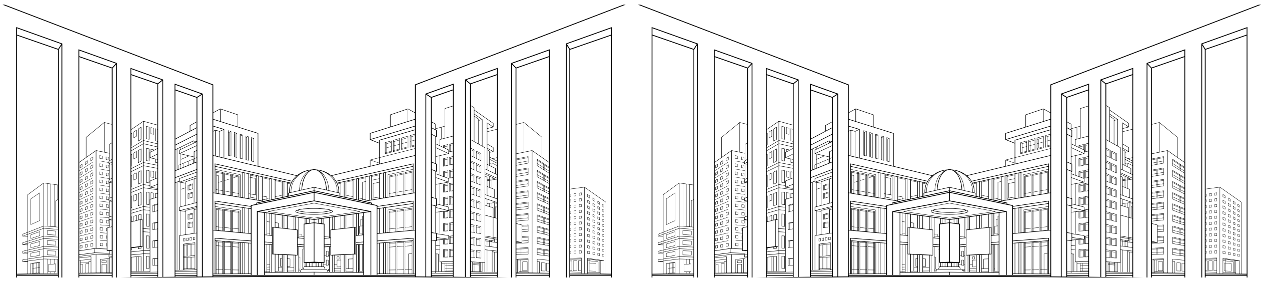
Scenario Analysis

- BAU Scenario: A continuation of current trends, leading to severe warming, increased cooling loads, and high emissions.
- B1 Scenario: A service-based economy shift with moderate climate impacts, resulting in lower energy demand but still requiring further interventions.
- Active & Passive Cooling Scenarios:
    - Passive Cooling: Focuses on building envelope upgrades, improved insulation, and shading devices.
    - Active Cooling: Introduces high-efficiency HVAC systems, demand-controlled ventilation, and optimized cooling technologies.

Policy and Planning Implications

The implementation of the India Cooling Action Plan (ICAP) is critical to achieving sustainable cooling outcomes and building long-term urban heat resilience. ICAP provides a national framework to reduce cooling demand, enhance energy efficiency, and promote the adoption of climate-appropriate technologies. The following city-level strategies should be pursued in alignment with ICAP's goals:

- Strengthening Energy Efficiency Regulations: Enhancing Energy Conservation Building Code (ECBC) compliance to minimize cooling loads.
- Scaling Renewable Energy Integration: Expanding rooftop solar adoption in commercial buildings to offset electricity demand.
- Urban Cooling Strategies: Implementing cool roofs, green infrastructure, and climate-responsive building designs to mitigate urban heat island effects.
- Smart Cooling Technologies: Encouraging advanced HVAC systems, automation, and demand-responsive cooling for optimized energy use.



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1 Introduction

1. Rising Cooling Demand under Climate Change
Increasing heatwaves, urbanization, and rising temperatures are making cooling a necessity rather than a luxury. Demand for cooling is expected to grow significantly, particularly in urban areas, with major implications for energy use, emissions, and public health.

2. Commercial Buildings as a Critical Intervention Area
The building sector, particularly commercial buildings, is a major and growing consumer of cooling energy. Improving energy efficiency and managing cooling demand in this sector is crucial for reducing pressure on energy systems and supporting sustainable urban growth.

3. Evidence for Policy, Planning and Climate Resilience
The study provides evidence-based insights to support policy development, resilient infrastructure planning, and climate-responsive strategies, while aligning cooling practices with national and global sustainability goals.

Cooling is no longer a luxury but a necessity in the face of intensifying climate change and urbanization. It is central to achieving several Sustainable Development Goals (SDGs), including Good Health and Wellbeing (SDG 3), Decent Work and Economic Growth (SDG 8), Sustainable Cities and Communities (SDG 11), and Climate Action (SDG 13). Recognizing this, the India Cooling Action Plan (2019) underscores the critical role of sustainable cooling in ensuring public health, economic growth, and environmental sustainability.

1.1 Significance of Cooling in a Changing Climate

As climate change intensifies, the frequency and severity of heatwaves and global heat stress are increasing. Studies evidence the increase in the frequency of heatwaves in India in the last few decades (Singh et al., 2021). Further, India has currently been witnessing around 1,116 deaths every year due to heatwaves (Bont et al., 2024). Consequently, under such conditions the demand for cooling has risen as cooling is vital for protecting public health, particularly for vulnerable populations such as the urban poor, women, and the elderly. Under such circumstances, air conditioning offers immediate relief but its widespread adoption contributes significantly to greenhouse gas emissions and exacerbates climate change. Although India currently accounts for 5% of the global annual emissions from room ACs, in case business-as-usual conditions continue and cooling demand rise unprecedentedly due to extreme changes in climatic conditions, India is predicted to contribute to 25% of annual global emissions by 2050 due to the unprecedented rise in comfort cooling demand, particularly in the residential sector (World Economic Forum, 2019). Such conditions demand efficient and accessible cooling solutions, especially in urban areas where dense populations and infrastructure amplify the urban heat island effect.

1.2. The Role of the Building Sector

The building sector is one of India's largest energy consumers, playing a central role in economic development. With urbanization accelerating, the demand for cooling in commercial buildings is rising rapidly. This sector's energy consumption for cooling highlights the need for sustainable interventions to balance energy demand, economic growth, and environmental sustainability. Without strategic measures, this rising demand risks overwhelming energy grids, increasing costs, and escalating greenhouse gas emissions.

1.3. Study Scope and Objectives

This report assesses the cooling and electrical demand of commercial buildings in four Indian cities, viz., Delhi, Mumbai, Bangalore and Hyderabad, focusing on:

i. Evaluation of current cooling demands and energy consumption patterns of commercial buildings in the 4 cities.

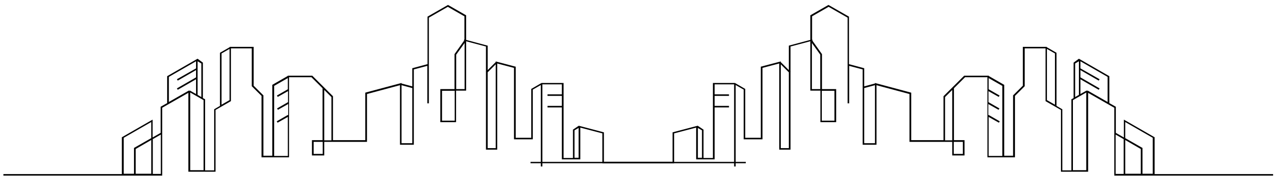
ii. Estimation of building category wise current energy performance index, per square metre of cooling demand and energy consumption of cooling system in the 4 cities.

iii. Scenario-based assessment of cooling demand and energy consumption in the 4 cities.

1.4. Importance of this study

The cooling and electrical demand assessments of the 4 concerned cities are crucial on many grounds. These include:

1. Policy Development: Providing evidence-based insights for policies targeting energy efficiency and emissions reduction.
2. Infrastructure Planning: Guiding the development of resilient energy systems to meet rising cooling demands.
3. Climate Resilience: Reducing heat-related vulnerabilities, especially for marginalized populations.
4. Sustainable Growth: Aligning cooling practices with national and global climate goals, including India's commitment to the Paris Agreement.



2

Background and Study Areas

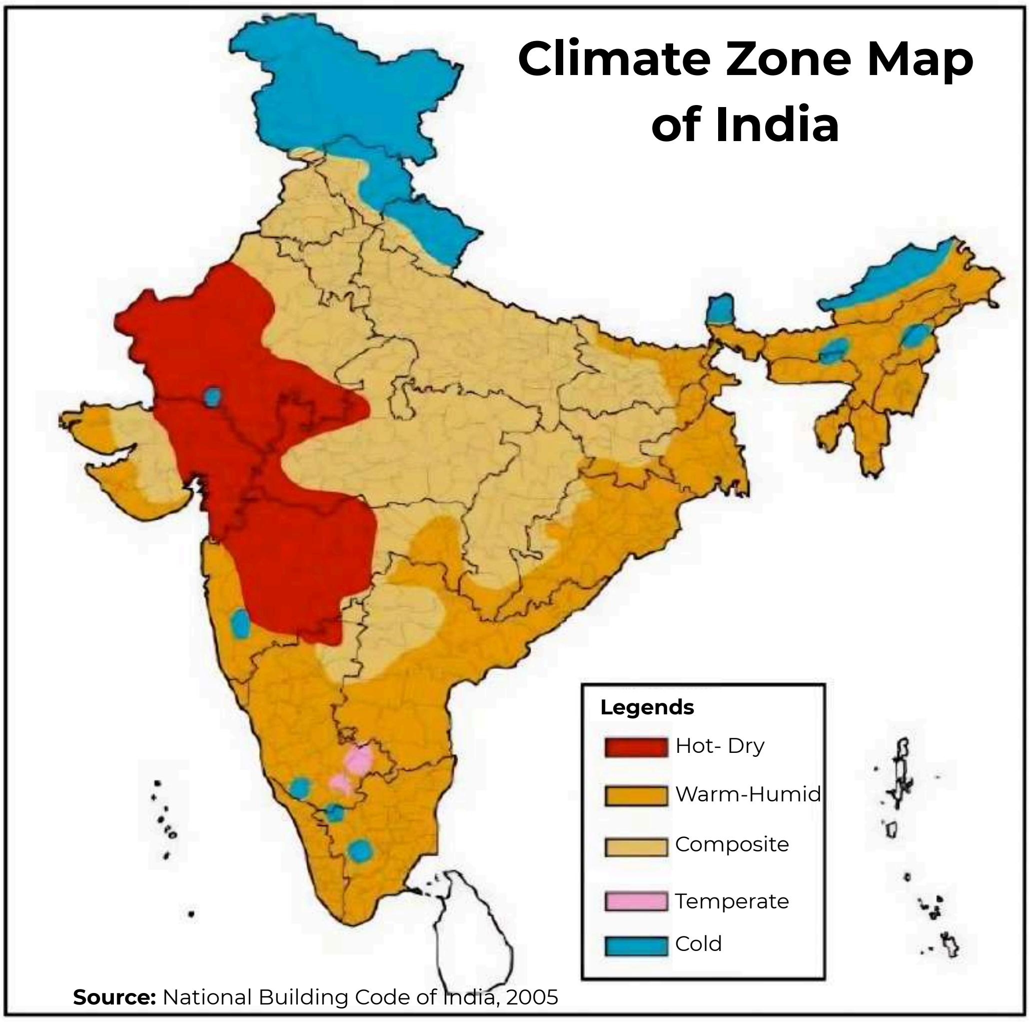
1. Climate-Specific Cooling Needs Across India
India is divided into distinct climatic zones (Hot-Dry, Warm-Humid, Composite, Temperate, Cold), each requiring tailored cooling strategies based on temperature, humidity, and seasonal variations, making a one-size-fits-all approach ineffective.

2. Diverse City Selection Reflecting Climatic Variability
The study selects Delhi, Mumbai, Bangalore, and Hyderabad to represent major climatic zones, enabling a comprehensive understanding of how different climates influence cooling demand, energy consumption, and building performance.

3. Need for Climate-Responsive Building Design & Energy Strategies
Each city demonstrates unique challenges, from Delhi's extreme seasonal variation to Mumbai's constant humidity, Bangalore's moderate climate, and Hyderabad's intense heat, highlighting the importance of adaptive building design, efficient HVAC systems, and passive cooling techniques for sustainable urban development.

2.1 Climatic Zones of India

India's diverse climatic conditions necessitate the classification of the country into distinct climatic zones to address the varying cooling needs across regions. These zones include the Hot-Dry, Warm-Humid, Composite, Temperate, and Coldzones, each characterized by unique temperature ranges, humidity levels, and seasonal patterns (India Cooling Action Plan 2019). Consequently, each of these zones have different thermal comfort requirements. For example, the Hot-Dry zone, represented by major parts of States such as Rajasthan, Gujarat, Maharashtra and a few parts of Telangana experiences extremely high temperatures and low humidity, requiring strategies like evaporative cooling and natural ventilation. On the other hand, the Warm-Humid zone, prevalent mainly along the coastal belt and major parts of north-eastern India, demands cooling approaches that focus on dehumidification and cross ventilation. The Composite zone, which mainly includes regions in North India such as Delhi, parts of Uttar Pradesh, Haryana, Madhya Pradesh, Punjab, Chhattisgarh, etc., experiences significant seasonal variation, necessitating a mix of cooling strategies for different times of the year. Only a few States located in the Himalayan foothills, represented by the cold climatic zone, has negligible cooling requirements.



Source: National Building Code of India, 2005

Figure 1: *Climate Zone Map of India*

2.2 Selection of 4 Cities for the Study

Based on the classification of India into distinct climatic zones, the selection of four cities such as Delhi, Mumbai, Bangalore, and Hyderabad provides a comprehensive representation of the diverse climatic conditions and their impact on energy demand in commercial buildings. These cities span across the Composite, Warm & Humid, Temperate, and Hot & Dry climatic zones, each showcasing unique cooling demand and energy consumption patterns driven by climatic variations.

In Delhi's composite climate, the significant temperature fluctuations between summer and winter require both cooling and heating strategies. The seasonal variations in humidity, especially during the monsoon, add further complexity, driving ventilation needs. Mumbai's warm and humid climate, characterized by high temperatures and moisture levels throughout the year, results in a constant need for cooling and dehumidification. Bangalore's temperate climate, with its mild and stable conditions, minimizes external energy loads, focusing primarily on internal heat gains for energy consumption. In contrast, Hyderabad's hot and dry climate experiences extreme summer temperatures, with its low humidity levels making it well-suited for evaporative cooling solutions that can efficiently meet peak cooling demands.

These cities, representing a diverse range of climatic conditions, highlight the need for tailored building designs, HVAC strategies, and energy-efficient solutions to address the specific cooling demands and enhance climate resilience across different regions of India. A detailed overview of the 4 cities, their climatic and other geographic and socio-economic conditions, the sample area chosen from each of them for the assessment have been provided here.

For this analysis, key commercial hubs were selected from four major Indian cities, based on their concentration of commercial buildings. OpenStreetMap (OSM) data was used to identify these areas, ensuring comprehensive coverage of each city’s primary commercial districts. The selected regions represent major economic and business centres known for their significant commercial infrastructure and high population density, making them ideal for evaluating energy consumption, cooling demand and GHG emissions.

2.2.1 Delhi (Composite Climatic Zone)

The city of Delhi lies in northern India between 28°24”17” and 28°53”0” North latitudes and between 76’50”24’” and 77’20”37’” longitudes. Covering an area of 1,483 sq. kms, it is surrounded by the states of Uttar Pradesh and Haryana. As per Census 2011, the total population of Delhi stands approximately 17 million. The city has been facing urbanization at a faster rate with a growth of about 25% in its urban areas between 2001 and 2011. With an increase in urbanization, economic activities have also diversified and the number of commercial spaces in the city is also on the rise.

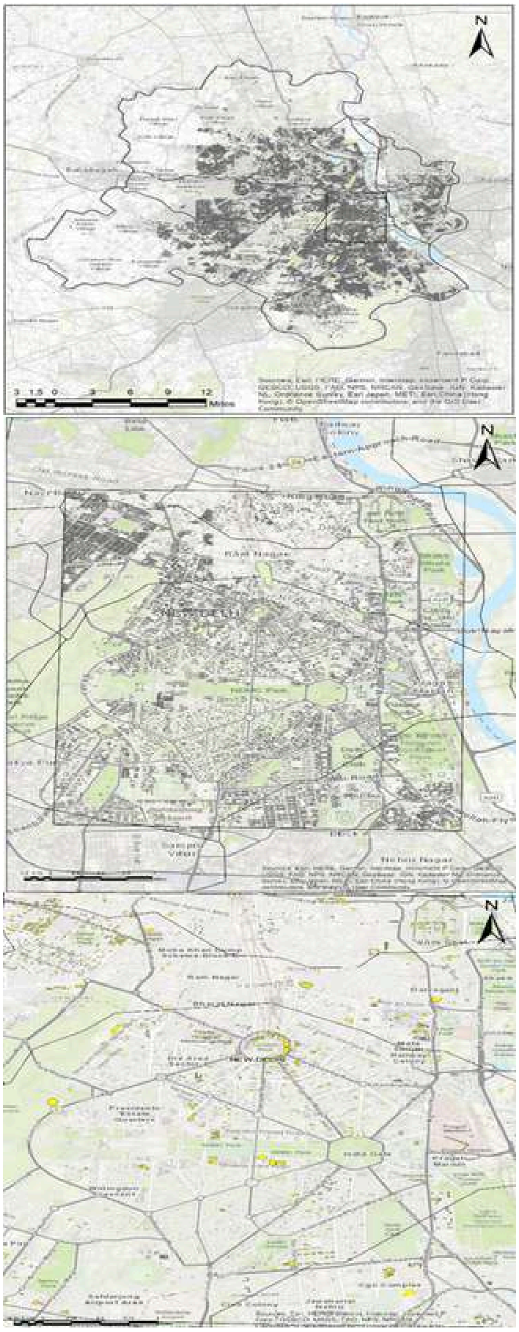


Figure 2: *Area selected for Delhi*

Delhi's composite climate, marked by scorching summers exceeding 40°C, cold winters dropping below 5°C, and a humid monsoon season, poses significant energy challenges for commercial buildings. Summers demand intensive cooling due to high temperatures and solar radiation, while winters shift energy needs to heating, particularly in poorly insulated buildings. The monsoon season adds dehumidification and ventilation requirements. Addressing these extremes requires energy-efficient HVAC systems, advanced insulation, energy-efficient glazing, and adaptive building designs. Strategies like solar shading, reflective roofing, and optimized natural ventilation can further enhance energy efficiency and occupant comfort, mitigating high annual energy consumption.

The central zone of Delhi including Connaught place, Janapath, Motilal Nehru place, Kamala Market, Karol Bagh has been taken as the sample area for the city’s electrical and cooling demand assessment. It is one of the oldest and most prominent commercial hubs in the city, and is the home to a wide array of office spaces, retail establishments, and financial institutions. A total of 391 buildings consisting of offices, schools, colleges, retail houses, hospitals, warehouses, government institutions and recreation centre have been taken into account for this exercise. Figure 2 represents the zones of Delhi taken as samples for this assessment.

2.2.2 Mumbai (Warm & Humid Climatic Zone)

The city of Mumbai lies on the western coast of India between 18°53' and 19°16' North latitudes and between 72°47' and 72°59' East longitudes. Spanning an area of 603 sq. km, it is bordered by the Arabian Sea to the west and the state of Maharashtra on other sides. As per Census 2011, Mumbai's population is approximately 12.4 million within the municipal limits, making it one of the most densely populated cities in the world. The city has experienced rapid urbanization, with significant growth in its suburban areas. Mumbai serves as India’s financial hub, hosting the Bombay Stock Exchange, major corporate headquarters, and a thriving services sector, including finance, IT, and entertainment industries. Its strategic location and its strategic coastal location, international air and sea connectivity, and extensive public transport network have supported the growth of commercial spaces and economic activity. However, the city also faces infrastructure-related challenges such as traffic congestion, seasonal flooding, and pressure on basic services, which require continuous planning and investment to ensure sustainable urban development.

The city falls in the warm and humid climatic zone, with year-round temperatures between 25°C and 35°C and humidity levels often exceeding 70-90%, poses significant energy challenges for commercial buildings. The persistent warmth creates a constant cooling demand, while high humidity, especially during the prolonged monsoon season, increases the latent cooling load for dehumidification, raising overall energy consumption. Unlike cities with distinct winters, Mumbai relies entirely on HVAC systems for cooling and moisture control throughout the year, straining energy resources. Advanced technologies like variable refrigerant flow (VRF) systems, heat recovery dehumidifiers, district cooling system (DCS) and passive strategies such as shading devices, reflective materials, and natural ventilation can optimize energy use. Additionally, building envelopes with moisture-resistant materials and effective drainage are critical to managing the impacts of humidity and water intrusion.

To assess the cooling demand and energy consumption of the city's commercial buildings for further policy recommendations, a total of 1,498 buildings have been selected from the areas consisting of Bandra Kurla Complex, Kalina, Dadar, Andheri, Powai and Santacruz. This zone is recognized as the city's premier financial and business district. It accounts for approximately 80% of the commercial area and serves as the headquarters for numerous multinational corporations and financial institutions. The figure 3 shows the snapshot of the areas in Mumbai selected for the assessment.

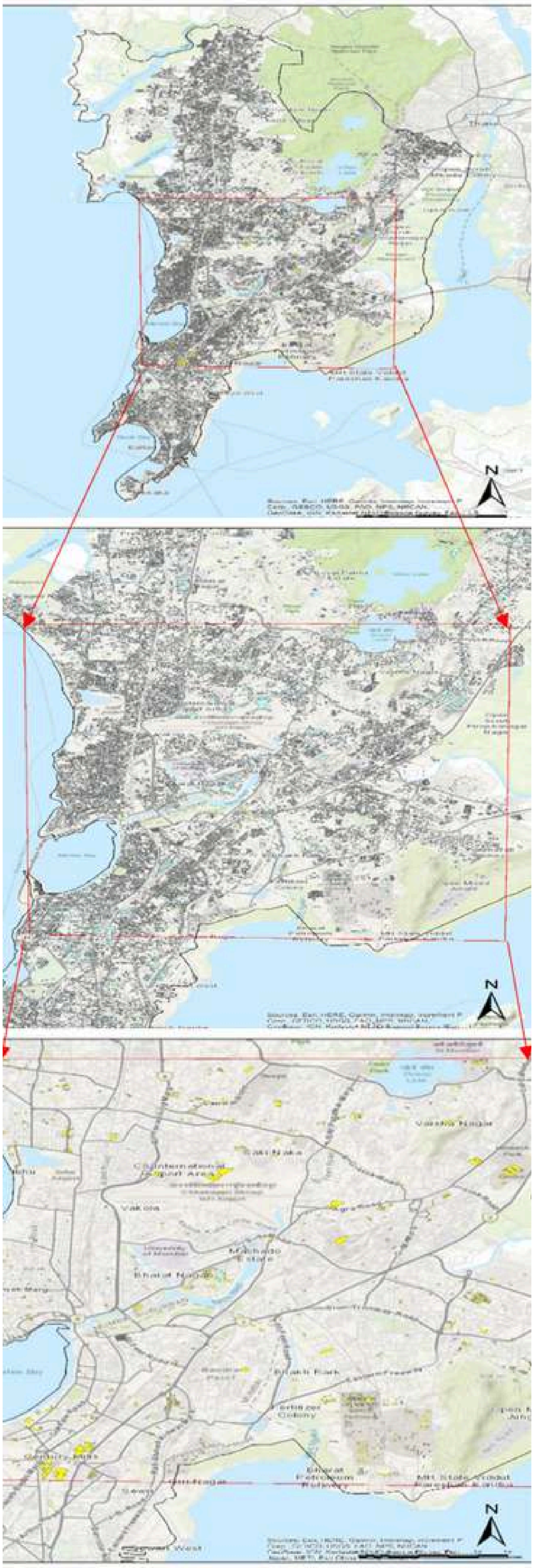


Figure 3: *Area selected for Mumbai*

2.2.3 Bangalore (Temperate Climatic Zone)

The city of Bangalore lies in southern India between 12°55' and 13°05' North latitudes and between 77°30' and 77°40' East longitudes. Spanning an area of 709 sq. km, it is situated on the Deccan Plateau at an average elevation of 920 meters above sea level. As per Census 2011, Bangalore's population is approximately 8.4 million within the municipal limits, making it one of the fastest-growing metropolitan cities in India. The city has undergone rapid urbanization, with significant expansion in its peripheral areas. Bangalore is renowned as India’s IT capital, hosting numerous technology parks, global IT companies, and start-ups. Its thriving tech ecosystem, along with a growing services sector and robust infrastructure, has driven substantial growth in commercial spaces, solidifying its status as a major economic hub in the country. Bangalore's temperate climate, with year-round temperatures between 15°C and 30°C, offers stable and moderate conditions, minimizing the need for mechanical heating or cooling. The city’s manageable humidity levels and absence of extreme weather make it one of the most energy-efficient cities for building energy demand. Commercial buildings primarily contend with internal heat gains from equipment, lighting, and occupant activities, which can be managed through passive cooling strategies like natural ventilation, shading devices, and thermally efficient materials. The moderate climate also supports energy-efficient designs that prioritize daylighting, energy recovery systems, and smart technologies like district cooling.

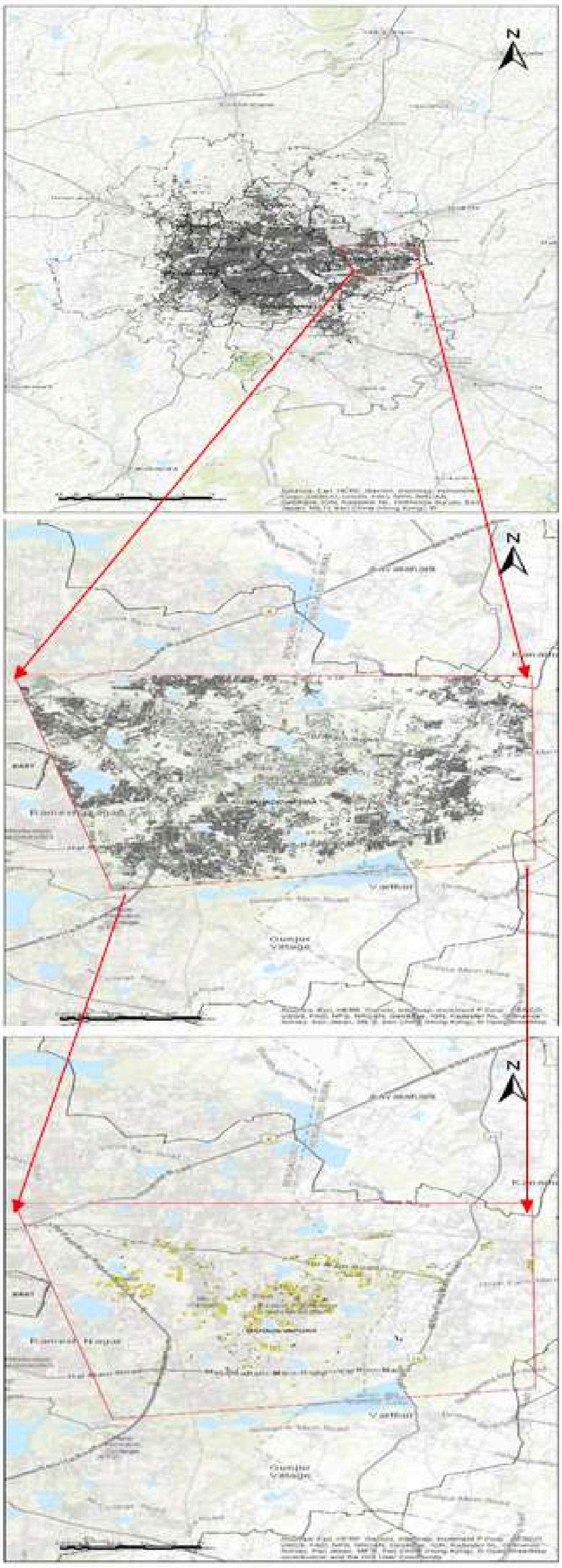


Figure 4: Area selected for Bangalore

Additionally, renewable solutions like rooftop solar panels can further enhance energy efficiency, aligning with sustainable urban development goals.

About 633 buildings from Bangalore's Whitefield, Madhupur and Mahadevpura areas have been taken into consideration for assessing this city's energy and cooling demand. In Bangalore, this area is identified as the focus area as it is a major IT hub and hosts many multinational IT companies, tech parks, and business centres. It has seen rapid growth in recent years, evolving into a key commercial zone. The figure 4 shows a representation of the study area.

2.2.4 Hyderabad (Hot & Dry Climate Zone)

The city of Hyderabad lies in southern India between 17°22' and 17°50' North latitudes and between 78°20' and 78°30' East longitudes. Spanning an area of 650 sq. km, it is situated on the Deccan Plateau at an average elevation of 542 meters above sea level. As per Census 2011, Hyderabad's population is approximately 6.8 million within the municipal limits, making it one of the largest metropolitan cities in India. The city has experienced rapid urbanization, with significant growth in its suburban and peripheral areas. Hyderabad is a major hub for the IT and pharmaceutical industries, hosting global IT companies, business parks, and research institutions. Its robust infrastructure, coupled with a thriving services sector and strategic location, has spurred significant growth in

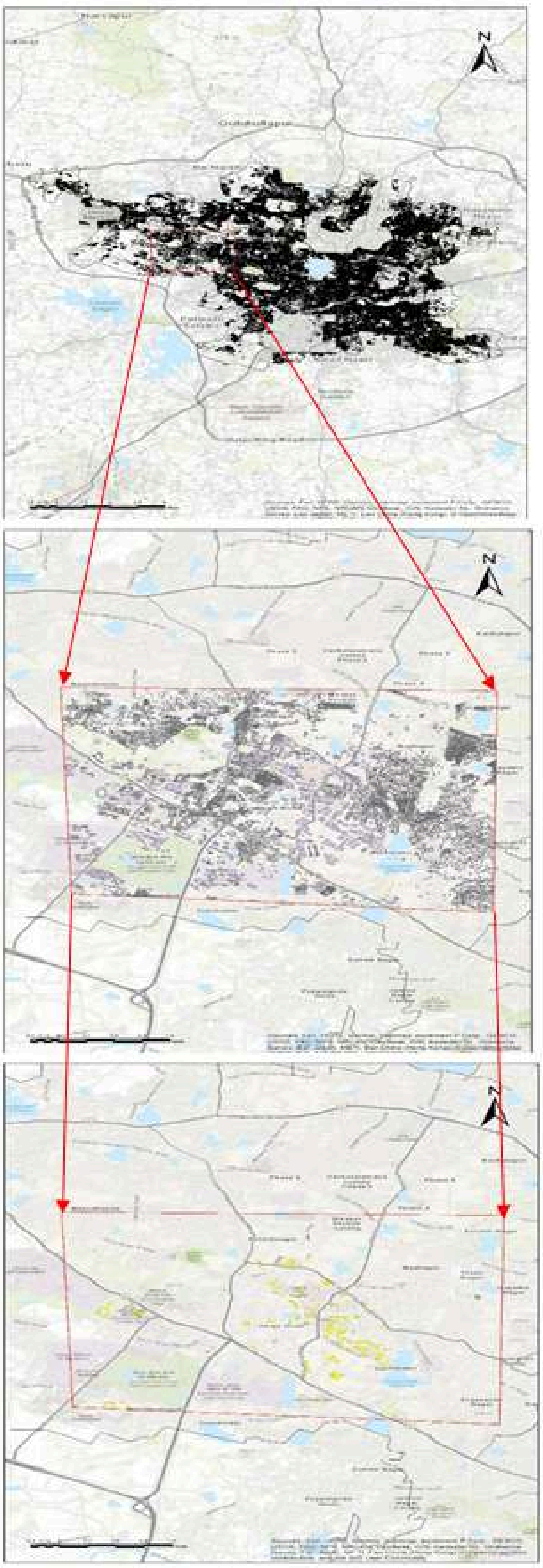
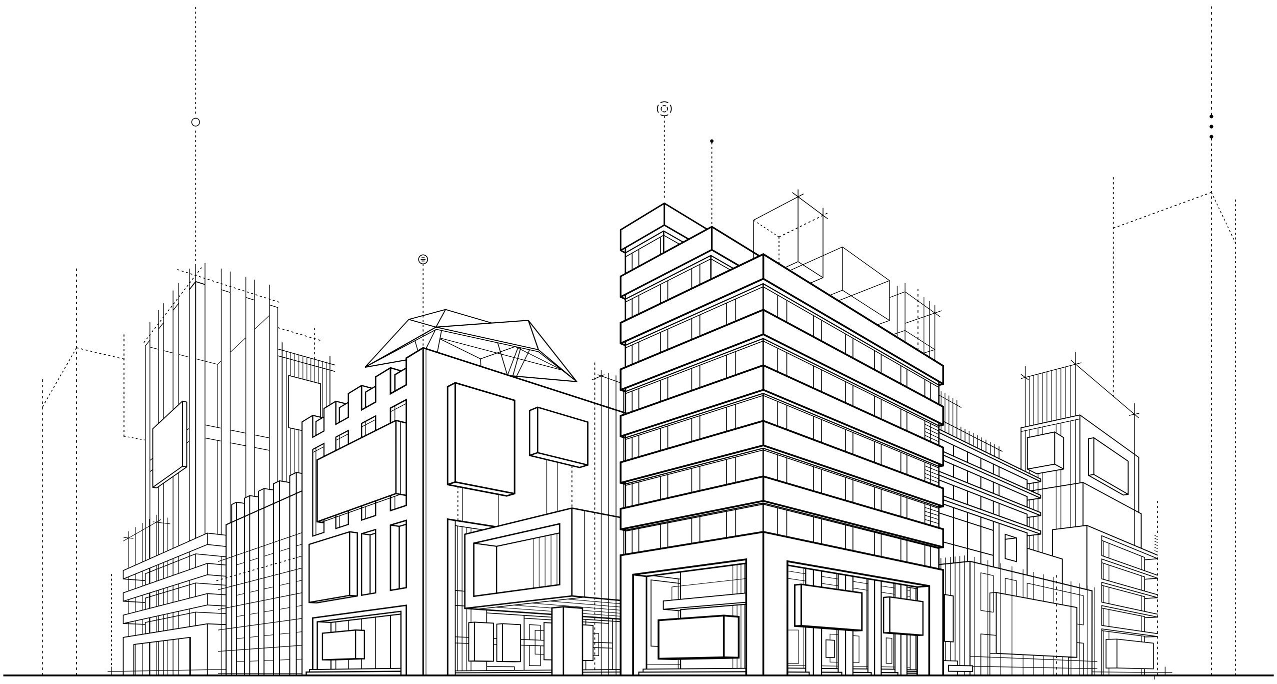


__Figure 5:__ Area selected for Hyderabad

commercial spaces. But simultaneously the city also grapples with urban challenges such as rising traffic congestion, flash floods during heavy monsoon events, and strain on civic amenities highlighting the need for comprehensive, climate-resilient, and inclusive urban planning. Hyderabad’s hot and dry climate, with summers reaching 35°C to 45°C and low humidity levels of 10-20%, presents unique energy challenges for commercial buildings. Cooling systems are heavily relied upon during peak summer months, while cooler nights and diurnal temperature variations offer opportunities for passive cooling, reducing energy demands. Unlike humid climates, the arid conditions minimize the need for dehumidification, focusing energy use on sensible cooling. Mild winters simplify HVAC design, with most energy demand concentrated in summer. Passive design strategies, such as reflective roofs, shaded windows, insulated walls, and high thermal mass materials, effectively mitigate heat gains. Night ventilation, greenery, and water features further enhance comfort and reduce heat loads. Optimized building orientation, efficient HVAC systems, and renewable energy integration are key to achieving energy efficiency and sustainability in Hyderabad’s climate.

Around 283 buildings from areas including Hightec City, Madhupur, Balanagar and Kondapur have been selected for getting a picture of energy consumption and cooling demand for different building categories of Hyderabad. This region is a major centre for IT and business process outsourcing (BPO) industries. The figure 5 shows the sample area selected for this city.



3 Methodology

To estimate the cooling and electrical demand of the cities of Delhi, Mumbai, Bangalore and Hyderabad, advanced data-driven tools have been integrated with innovative modeling techniques.

This approach ensures a comprehensive understanding of the cities' cooling dynamics, leveraging geospatial analysis, machine learning, and energy simulation tools.

For cooling demand and electrical load assessment, knowing the cooling space volume is important. However, there is no single point data source which can provide cooling space volume of a city or a region understudy. Currently, in India most of the cooling related studies are using per capital floor space requirement for living which ranges between 17~40m2/ person. Based on the population estate of the study area, the total floor space areas are generally calculated. However, this approach has certain limitations especially in the context of FAR (Floor Area Ratio) which varies widely across the regions. Therefore, per capita floor space area-based cooling space requirement estimate has significant level of uncertainty. It is estimated that in certain cases the margin of error could reach up to 30~50%. Total floor space area being the fundamental input for space cooling demand assessment, uncertainty of floor space area gets carried forward to the cooling demand estimate as well.

To overcome this problem specially

1. Advanced Data-Driven Methodology for Cooling Assessment

The study adopts an integrated approach combining geospatial analysis, machine learning, and energy simulation tools (SPIBEAT and CEA) to accurately estimate cooling demand, electricity consumption, and GHG emissions across different urban contexts.

2. SPIBEAT as a Key Innovation to Reduce Data Uncertainty

The Spatially Integrated Building Energy Assessment Tool (SPIBEAT) addresses limitations of conventional per-capita estimation methods by deriving building footprints, heights, and volume using open-source and ML-based techniques, significantly improving accuracy in cooling demand assessment.

3. Scenario-Based Analysis for Future Energy and Climate Planning

The methodology enables scenario-based projections of cooling demand, energy consumption, and GHG emissions up to 2050, incorporating factors like climate change, population growth, and building design to support informed policy and resilient urban planning.

to reduce the margin of error while calculating the cooling space volume, The Celestial Earth has developed the special tool called ‘Spatially Integrated Building Energy Assessment Tool’ (SPIBEAT) which largely overcomes the issues of uncertainty of occupied building floor space areas in a particular area.

3.1. What is SPIBEAT?

SPIBEAT is a State-of-the-art Machine Learning Integrated Geospatial Analysis Tool to assess cooling demand of a region by assessing the building footprint and total living space volume. This is an open-source, user-friendly tool that overcomes long-standing technical difficulties in assessing a region's occupational building space and volume without manual measurement. It has been developed by integrating different open source tools – OSM, Blender, QGIS and City Energy Analyst (CEA) Model through ML code, thus integrating spatial analysis and Building Energy Estimator.

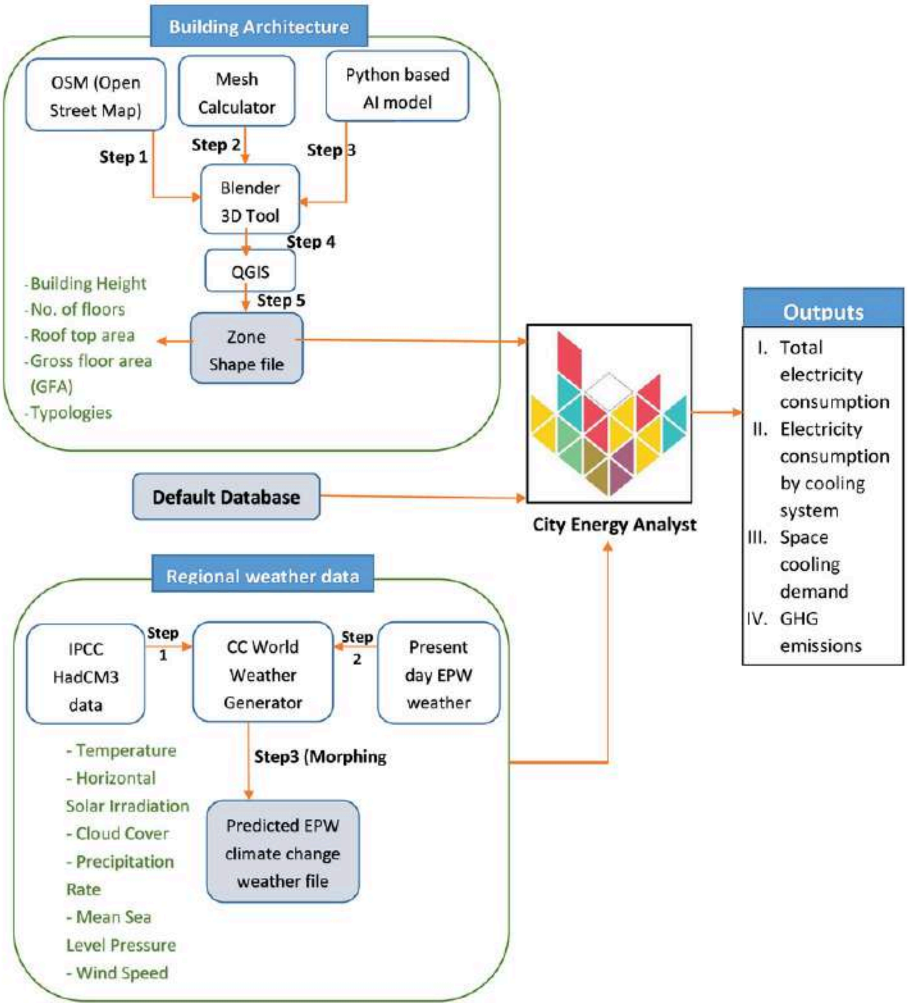


Figure 6: Cooling demand and energy consumption estimation using SPIBEAT

3.2. Step by step methodology

With the use of SPIBEAT the following tasks under this project has been accomplished:

1) Building Height Estimation and Footprint Extraction for Selected Study Areas:

This assessment had been done considering the existing building stock. While Open Street Map

(OSM) database module of SPIBEAT provided the comprehensive mapping information and detailed commercial building footprints of the 4 cities, its Blender and QGIS modules were used to extract building geometry information including building heights and roof areas. This data has been crucial for assessing the total space area of residential buildings and their respective cooling and electrical demand.

Steps followed for estimating residential building space area are explained in details below:

Step 1: Firstly, the initial dataset on building footprint of one of the selected study areas had been extracted from SPIBEAT's OSM module, which included building names but lacked building heights and their unique identifiers.

Step 2: This data had then been inputted into the second module of SPIBEAT, Blender, where there is a Mesh add-on, a type of 3D model, consisting of vertices, edges, and faces, thus used to define the shape and surface of buildings.

Step 3: A Python script utilising the 'bpy' add-on in Blender was used to extract the edge lengths of buildings from the mesh and export it as a CSV file. This CSV file contains unique building IDs, building heights, roof area, volume and other properties of buildings of the selected study area.

Step 4: The shapefile containing boundary of the concerned city was then imported into QGIS and the required study area had been selected and clipped.

Step 5: Then building footprint of the selected study area had been imported to QGIS.

Step 6: The CSV file produced in the previous step was imported to QGIS and the study area's building footprint shapefile had been merged with it using the joining function in QGIS.

This generates the building geometry shapefile (zone shapefile), which contained data in the form of the buildings' heights above and below ground and floors above and below ground with actual coordinates. The final output generated by SPIBEAT's QGIS module served as the primary input for SPIBEAT's last module, CEA. The same methodology had then been repeated for the 3 other cities.

2) Assessment of Total Electricity Consumption, Energy Consumption by Cooling System, Space Cooling Demand and GHG Emissions for baseline year (2023):

To assess the electricity consumption and space cooling demand for the baseline or recent year, the City Energy Analyst (CEA) software, the building simulator module of SPIBEAT, had been used. It is an advanced urban building energy modelling platform. CEA integrates urban design principles with energy systems engineering, offering a comprehensive analysis of building space cooling demands across the sub-national region.

CEA consists of default and input databases; the input databases are divided into primary and secondary databases. The primary inputs were derived from OpenStreetMap (OSM), Blender, and QGIS modules of SPIBEAT, which were generated in the form of zone shapefile. This database is useful to calculate the geometry and position of buildings, and serves as key elements in CEA. The default and secondary input databases in CEA were then generated as per the primary inputs given. However, a key feature of CEA is that its secondary-level input datasets can be customized by the user, providing flexibility to adjust fundamental cooling demand parameters such as HVAC system efficiencies, window-to-wall ratios, etc. A visual representation of CEA's inputs has been given below:

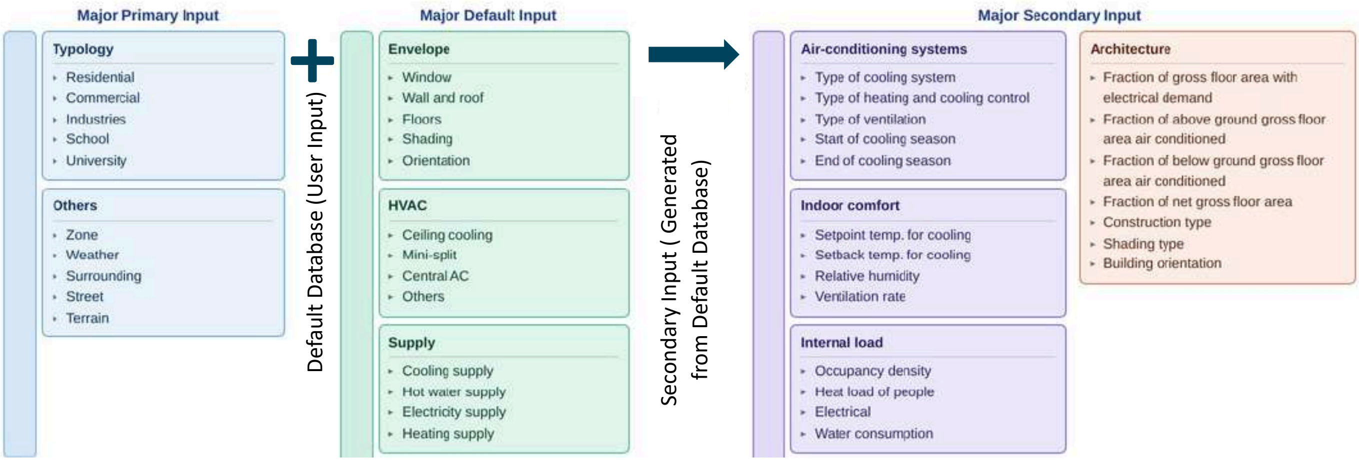


Figure 7: Inputs of the CEA model

The following are the parameters which can be customised by the user on the basis of the city's profile.

1) Building Properties:

- Typology: This encompasses various categories of buildings such as multi-residential, single residential, commercial, public utilities, and occupancy classifications.
- Architecture: This includes factors like weather conditions, construction type, construction year (assumed year: 2020), shading techniques, and building orientation.
- Indoor Comfort: This involves parameters like the set point temperature for cooling, setback temperature for cooling, relative humidity levels, and ventilation rates to ensure occupants' comfort.
- Internal load: This refers to factors affecting the building's internal load, including occupancy density, heat generated by occupants, as well as electrical and water consumption patterns.

2) Assemblies:

- Envelope: The envelope serves as the physical barrier separating the conditioned interior from the unconditioned exterior environment. It comprises elements such as windows, walls, roofs, floors, shading devices, and their orientations.
- HVAC (Heating, ventilation and air conditioning): HVAC systems

- are interconnected systems that provide heating, ventilation, and cooling services to various areas within the building. This may include ceiling cooling, mini-split systems, central air conditioning, among others.
- Supply: This pertains to the provision of various utilities to the building, including cooling, hot water, electricity, and heating supplies.

The outputs generated by CEA include detailed maps and charts depicting cooling demand distribution, energy usage patterns, and potential areas for intervention, thus enabling data-driven decision-making for sustainable urban development.

3) Estimation of building category wise energy insights:

To assess building-level energy performance and cooling demand across various climatic zones, a typology-based approach was adopted using the Energy Performance Index (EPI) as a central metric. The Energy Performance Index (EPI), expressed in kWh/m^2/year, serves as a standardized indicator of energy efficiency, enabling comparison across building types and climatic regions. The study focused on analyzing space cooling demand and cooling energy consumption for different building categories including residential, commercial, and mixed-use typologies within the selected cities.

The estimation process involved the following steps:

- Classification of building typologies based on their primary function and operational characteristics.
- Assignment of representative EPI values for each building typology, by using the total electrical consumption and gross floor area data provided by SPIBEAT. (Building's electrical consumption / Building's gross floor area = Building's EPI).
- Using the same approach, the cooling energy demand and thermal demand for the different categories of buildings of the 4 cities have been calculated for a comparative analysis.

4) Estimation of Energy Consumption by Cooling System, Space Cooling Demand and GHG Emissions under future scenarios (2050)

This user accessibility of CEA allows for scenario analysis, making it a powerful tool for urban planners and energy managers to evaluate different cooling strategies and their impacts on energy consumption and thermal comfort. In other words, not only the current cooling and energy consumption conditions, but SPIBEAT has also facilitated the projections of these cities' future cooling and overall electrical demand as well as GHG emissions under different scenarios. The process of scenario development begins with importing the necessary datasets into CEA, including building characteristics, and spatial information sourced OpenStreetMap (OSM) and Blender, as done while assessing the current cooling conditions. These datasets formed the foundation for the scenario analysis.

The next step involved identifying key factors that influence space cooling demand, such as population growth, temperature and precipitation trends until 2050, building architectural designs, HVAC systems, etc.These factors form a part of input database of the CEA software which were then changed as per scenario needs and inputted into the model.

Using CEA's advanced simulation capabilities, the impacts of these changes on building energy use and cooling demand have been assessed, thus aiding in the projections of future space cooling demands and GHG emissions of the concerned 4 cities till 2050 under different IPCC approved climate scenarios and development pathways.

3.3 Limitations of the Methodology

While the methodology adopted in this study ensures a comprehensive and data-driven approach for estimating city-scale cooling demand, electrical consumption, and GHG emissions, it is important to acknowledge the inherent limitations and uncertainties associated with the tools, data sources, and modelling assumptions. The following are the limitations:

While the methodology adopted under this study ensures a robust and data-driven approach for estimating city-scale cooling demand, electrical consumption, and GHG emissions, it is important to acknowledge the inherent limitations and uncertainties associated with the tools, data sources, and modelling assumptions. These are as follows:

I. Typology Classification and Mixed-Use Buildings:

Buildings are categorized based on predominant use using available spatial data and assumptions. Mixed-use structures pose classification challenges and are addressed through proportional splits, which may not fully capture actual operational patterns or energy consumption.

II. Use of Image-Based and Open-Source Data:

SPIBEAT relies on open-source datasets such as OSM for building footprints and Blender for height estimation. However, incomplete or inconsistent data especially for informal settlements, peri-urban areas, older buildings, or newly developed zones may affect the accuracy of building geometry and cooling volume estimates.

III. Simplified Energy Performance Metrics:

EPI is estimated as electrical consumption per unit floor area. While useful for comparison, it does not account for factors such as building age, construction quality, HVAC efficiency, or occupancy patterns, which influence actual performance.

IV. Absence of Real-Time Data:

The lack of real-time electricity or cooling load data leads to reliance on proxy values and assumptions. This limits the accuracy of demand estimation and localized energy efficiency planning.

4

Cooling and Electrical Demand Assessment of 4 cities

The comparative analysis of electricity consumption, cooling demand, and greenhouse gas (GHG) emissions across Delhi, Mumbai, Bangalore, and Hyderabad in 2023 reveals significant variations influenced by climate conditions, urban development, population density, and energy efficiency practices. These four major Indian cities, each with distinct climatic and infrastructural characteristics, exhibit unique energy consumption patterns that highlights how important it is to have unique energy management strategies.

With the use of CEA model, the baseline year's (2023) space cooling demand, energy consumption of cooling systems and emissions for each commercial building within the selected sample areas of these cities have been estimated. Apart from the primary, default and secondary inputs, the simulations in this model were based on a weather file that we uploaded.

The weather data used in this analysis were the baseline year weather files of the respective cities,

1. Climate-Driven Differences in Cooling Demand and Emissions
Cooling demand, electricity consumption, and GHG emissions vary significantly across Delhi, Mumbai, Bangalore, and Hyderabad, primarily influenced by differences in climatic conditions, urban density, and building characteristics, highlighting the need for climate-sensitive analysis.

2. High Energy and Emission Pressure in Delhi and Mumbai
Delhi records the highest per-building electricity consumption and emissions due to extreme temperatures and dense urbanization, while Mumbai exhibits high per capita cooling demand driven by persistent heat and humidity, placing continuous pressure on energy systems.

3. Need for Tailored, Climate-Responsive Cooling Strategies
The findings emphasize that city-specific interventions are essential, including energy-efficient HVAC systems, passive cooling techniques, renewable energy integration, and improved building design to manage rising cooling demand and reduce environmental impact.

sourced from the Indian Society of Heating, Refrigerating, and Air Conditioning Engineers (ISHRAE) section on the EnergyPlus website. This weather data, representing present-day climatic conditions, was provided in the form of an EPW (EnergyPlus Weather) file for the year 2020. To make the data compatible with the City Energy Analyst (CEA) model, it was morphed using CCWorldWeatherGen.

The City Energy Analyst (CEA) model was employed to estimate the population and gross floor area (GFA) of the commercial buildings in each study area. These estimates formed the basis for calculating key parameters, including per building, per capita, and per square meter. Further, the city wise per capita, per square meter, and per building space cooling demand, energy consumption and associated GHG emissions have been assessed for baseline year. For calculating per capita space cooling demand and emissions, one of the required data was current year population of the study areas which have been provided by the CEA model. The CEA model also supplied the total building space area for each of the sample areas, which facilitated calculations for per square meter cooling and energy demand and emissions. Further, the building footprint shapefile provided the total number of commercial buildings considered for assessment in each city, enabling estimations of baseline per-building cooling demand and GHG emissions. The tables below show the city wise per capita and per building space cooling demand and GHG emissions for 2023:

Table 1: *City wise per commercial building results for baseline year (2023)*

Parameters (2023)	Delhi	Mumbai	Bangalore	Hyderabad
Per commercial building total electricity consumption (million units)	2.24	1.31	2.10	1.93
Per commercial building energy consumption of cooling system (million units)	1.59	1.07	1.41	1.49
Per commercial building cooling demand (million units)	4.36	2.94	3.88	4.10
Per commercial building GHG emission (tonsCO2)	1945	1205	1790	1731

Delhi emerges as the city with the highest total electricity consumption per building, driven largely by its substantial cooling requirements due to its hot, semi-arid climate and high population density. The cooling systems in Delhi contribute significantly to its energy use, consuming more electricity than those in any other city analysed. Consequently, Delhi also records the highest GHG emissions among the four cities, underscoring the environmental impact of its energy-intensive cooling practices. These findings point to an urgent need for Delhi to enhance energy efficiency in its cooling systems and to explore (innovative) solutions such as district cooling, passive cooling technologies, and the integration of renewable energy sources.

Mumbai, characterized by a humid tropical climate, shows the highest per capita cooling energy use and GHG emissions, reflecting the high cooling demand necessitated by its coastal environment. This indicates a heavy reliance on cooling systems to combat the effects of heat and humidity, which contributes to higher per capita emissions. To address these challenges, Mumbai must focus on enhancing the efficiency of its cooling systems and increasing the adoption of renewable energy sources, such as solar power. Additionally, urban planning measures like the implementation of cool roofs, increased vegetation cover, and water-based cooling systems could help mitigate the heat and reduce the cooling demand.

Bangalore demonstrates the lowest energy use and emissions, which can be attributed to its relatively mild climate and more efficient energy usage patterns. The city records the lowest per building and per capita electricity consumption, as well as the lowest GHG emissions, highlighting its leadership in energy efficiency. Bangalore's favourable climatic conditions, combined with proactive energy policies, have resulted in reduced cooling demand and overall electricity use. To maintain its status as a model for energy efficiency, Bangalore should continue to strengthen its building codes, promote the use of energy-efficient appliances, and encourage green building practices to further optimize energy consumption and minimize environmental impact.

Hyderabad presents a moderate profile in overall electricity consumption but stands out with the highest per capita electricity use. This suggests rising energy demand as the city continues to grow, driven by urbanization and economic development. While its total building-level energy consumption and GHG emissions are not as high as Delhi’s, Hyderabad’s growing energy needs signal future challenges in managing its environmental footprint. To address these concerns, the city should prioritize investments in energy-efficient infrastructure and cooling technologies, and explore alternative energy sources to reduce its dependency on conventional power.

These findings highlight the need for targeted interventions, including improving energy efficiency in Delhi and Hyderabad, integrating renewable energy in Mumbai, and sustaining Bangalore’s efficiency. Strategies such as green roofs and improved building codes can help reduce cooling demand. A comparative matrix of cooling load, energy efficiency, best practices, and challenges is presented in Table 4.

Table 2: *Matrix comparing the energy efficiency and cooling load performance of buildings across the different climatic zones*

Climatic Zone	City	Cooling Load	Energy Efficiency	Best Practices	Challenges
Composite	Delhi	High in summer (40°C+), moderate in monsoon, low in winter	Moderate to Low due to dual heating and cooling demands.	• Use of flexible HVAC systems. • Solar shading and reflective roofing. • Insulated building envelopes. • Consider District Cooling Systems (DCS) for large buildings or campuses.	• Dual demand for cooling (summer) and heating (winter). • Poor insulation in older structures adds inefficiency.
Warm & Humid	Mumbai	Consistently High year-round (25°C-35°C with 70-90% humidity)	Low due to constant cooling and dehumidification.	• Advanced HVAC systems with integrated dehumidifiers. • Natural ventilation and shading. • Reflective materials to reduce heat gain. • Explore DCS for commercial zones in high-density areas.	• Persistent high latent cooling loads due to humidity. • High energy costs from continuous HVAC operation.
Temperate	Bangalore	Low year-round (15°C-30°C with mild humidity	High due to minimal HVAC dependency.	• Passive cooling strategies like cross-ventilation. • Optimized natural daylighting. • Energy-efficient lighting systems.	• Internal heat gains dominate energy use. • Lower demand for HVAC upgrades may slow adoption of new technologies.
Hot & Dry	Hyderabad	High during summer days (35°C-45°C), low at night and in winter	Moderate depending on passive design implementation.	• Evaporative cooling for energy-efficient cooling. • Night ventilation to leverage diurnal temperature drops. • Reflective or cool roofing and high thermal mass.	• Intense daytime heat during summer spikes cooling demand. • Lack of reflective or insulated materials in older buildings.

5

Building Category Wise Energy Insights:

Cooling Efficiency and Space Cooling Demand

1. Climate and Building Typology Strongly Influence Energy Performance
Energy Performance Index (EPI), cooling demand, and overall energy consumption vary significantly across building types and cities, driven by climatic conditions, building functions, and operational factors such as occupancy and internal loads.

2. Higher Cooling Demand in Mumbai and Hyderabad Across Building Types
Buildings in Mumbai (warm-humid) and Hyderabad (hot-dry) consistently show higher EPI values and cooling energy demand across most typologies, due to continuous humidity and extreme heat, leading to greater dependence on mechanical cooling systems.

3. Bangalore as a Benchmark for Energy Efficiency
Bangalore records the lowest EPI and cooling demand across most building categories, reflecting the advantages of its temperate climate and effective use of passive cooling strategies, making it a model for energy-efficient urban development.

5.1 Comparative analysis of Energy Performance Indicators (EPI) for various building typologies across different Climatic Zones

The Energy Performance Index (EPI) is a key metric used to evaluate the energy efficiency of buildings. It represents the total annual energy consumption per unit area, typically expressed in kilowatt-hours per square meter per year ($kWh/m^2/year$). EPI serves as a standardized measure, enabling a comprehensive assessment of how efficiently energy is utilized within buildings. This metric is invaluable for benchmarking energy performance, facilitating meaningful comparisons between buildings of similar types or functions, and identifying areas for improvement. Calculating the EPI aids in recognizing inefficiencies and implementing targeted interventions to reduce energy consumption and enhance operational performance. Furthermore, EPI plays a significant role in complying with energy efficiency policies and achieving certifications such as LEED and BEE's STAR ratings in India. A lower EPI reflects improved energy efficiency, which not only reduces operational costs but also minimizes carbon footprints, contributing to global sustainability goals.

The variation in Energy Performance Indicators, cooling energy demand, and space cooling requirements across diverse building typologies is influenced by multiple factors, including climatic differences, functional characteristics of buildings, and operational needs. This study focuses on variations across four distinct climatic zones in India: Delhi (Composite Zone), Mumbai (Warm and Humid Zone), Bangalore (Temperate Zone), and Hyderabad (Hot and Dry Zone). Each climatic zone presents unique conditions, such as temperature profiles, humidity levels, and solar radiation intensities, which directly influence the energy demand for space cooling. Building functions, ranging from residential to commercial and industrial applications, further add to the complexity of energy performance variations. Operational parameters, including occupancy patterns, internal heat loads, and the efficiency of HVAC systems, also play a vital role in determining energy consumption and EPI values.

Through a detailed analysis of these factors, this research provides a thorough understanding of how climate-specific and building-specific attributes shape energy performance and cooling demand.

By offering insights into these dynamics, the results contribute to the development of targeted energy efficiency strategies specific to the distinct requirements of each climatic zone. Such strategies aim to optimize energy use in buildings, reduce costs, and promote sustainable practices, ultimately supporting broader environmental and energy conservation goals. The tables below show different EPIs, cooling energy demand and space cooling demand values for different building types in different climatic zones.

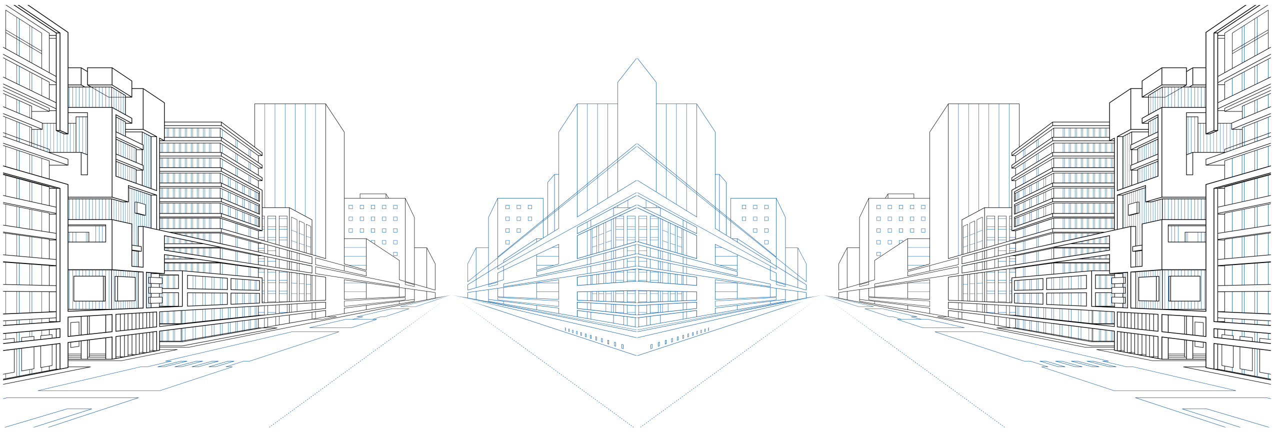


Table 3: *Matrix comparing the energy efficiency and cooling load performance of buildings across the different climatic zones*

Building categories	EPI (kWh/sqm)			
	Delhi (Composite)	Mumbai (Warm & Humid)	Bangalore (Temperate)	Hyderabad (Hot & Dry)
I) Office buildings (corporate office buildings, government offices, commercial office buildings, etc.)	144	155	96	158
II) Educational institutions (Schools, colleges, universities, research centres)	145	159	101	155
III) Transportation facilities (train and metro stations)	145	150	115	158
IV) Retail (Shopping malls, shopping complexes, super markets, show rooms, garments store, book store, food store, etc.)	151	160	130	162
V) Hospitality and leisure (hotel, guest house, restaurants)	148	152	120	153
VI) Recreation (cinema, sports activities area, museum, stadium, planetarium)	144	150	115	135
VII) Hospitals	148	154	105	156
VIII) Residential commercial (PGs, hostels)	132	155	98	167

Building categories	EPI (kWh/sqm)			
	Delhi (Composite)	Mumbai (Warm & Humid)	Bangalore (Temperate)	Hyderabad (Hot & Dry)
IX) Special purpose buildings (auditorium, banquet hall, club, community centre, exhibition hall, library, data centres)	145	168	110	150
X) Industrial	131	172	102	157
XI) Other commercial buildings (with mixed-use developments)	148	170	95	173
XII) Global Capability Centre	155	154	150	162

5.1.1 Statistical Analysis of Energy Performance Index (EPI)

In addition to the comparative analysis of Energy Performance Indicators (EPI) across building typologies and climatic zones, a detailed statistical assessment was undertaken to better understand the distribution of EPI values across the selected cities. Specifically, mean and median values of EPI were computed at both the building-type level and city-level, providing further insights into central tendencies and patterns in energy performance.

1. *Delhi (Composite Climate)*

The EPI distribution for Delhi is moderately skewed, with the mean EPI slightly higher than the median, indicating the presence of a subset of buildings with relatively high energy use that pull up the average. The cumulative distribution plots confirm that a significant proportion of buildings in Delhi achieve EPIs between 90–120 kWh/m^2/year, reflecting relatively average energy efficiency across the city.

Table 4: *Building-wise average values of the EPI for Delhi*

Building Type	Min EPI	Max EPI	Mean EPI	Median EPI
Office	96	185	144	148
Educational Institution	100	166	145	150
Transportation	95	176	145	153
Retail	94	181	151	152
Hotel & Restaurant	98	181	148	153
Recreation	85	213	144	149
Religious Institution	90	177	147	153
Hospital	100	186	148	158
Residential Commercial	95	178	132	133
Special Purpose	80	172	145	149
Industrial	95	158	131	138
Commercial	95	191	148	151
BPO	145	169	155	152

2. Mumbai (Warm & Humid Climate)

Mumbai shows a consistently higher mean and median EPI, reflecting the persistent cooling demand driven by humidity and temperature. The narrow gap between the two values indicates a more uniform distribution of energy use across buildings. This highlights Mumbai's structural reliance on mechanical cooling and dehumidification, making it critical to address through efficient HVAC systems and envelope improvements.

Table 5: *Building-wise average values of the EPI for Mumbai*

Building Type	Min EPI	Max EPI	Mean EPI	Median EPI
Office	100	192	155	158
Educational Institution	100	234	159	158
Transportation	95	189	150	150
Retail	98	217	160	158
Hotel & Restaurant	100	182	152	157
Recreation	102	179	150	158
Religious Institution	105	186	146	146
Hospital	100	171	154	160
Residential Commercial	98	177	155	156
Special Purpose	95	229	168	165

Building Type	Min EPI	Max EPI	Mean EPI	Median EPI
Industrial	98	228	172	172
Commercial	95	225	170	169
BPO	144	161	154	156

3. Bangalore (Temperate Climate)

Bangalore demonstrates the lowest mean and median EPI values among all four cities. Both indicators are closely aligned, suggesting limited variation across its building stock and reflecting the city's climatic advantage and better passive design opportunities. The results reinforce Bangalore's position as the most energy-efficient city in this assessment.

Table 6: *Building-wise average values of the EPI for Bangalore*

Building Type	Min EPI	Max EPI	Mean EPI	Median EPI
Office	95	193	141	140
Educational Institution	98	164	141	143
Transportation	82	139	115	120
Retail	90	182	149	149
Hotel & Restaurant	95	173	149	151
Recreation	90	150	136	144
Religious Institution	90	152	121	121

Building Type	Min EPI	Max EPI	Mean EPI	Median EPI
Hospital	95	200	145	144
Residential Commercial	90	166	145	147
Special Purpose	90	160	139	139
Industrial	92	178	146	147
Commercial	80	187	149	147
BPO	144	175	151	149

4. Hyderabad (Hot & Dry Climate)

Hyderabad exhibits a wider spread of EPI values, with the mean EPI slightly higher than the median, indicating variability in building design and system efficiency. While many buildings fall into moderate ranges (95–110 kWh/m²/year), the presence of high-intensity users (e.g., IT parks, data centres) elevates the overall mean. This suggests the need for targeted interventions for high-energy consuming buildings while promoting passive cooling strategies in conventional commercial facilities.

Table 7: *Building-wise average values of the EPI for Hyderabad*

Building Type	Min EPI	Max EPI	Mean EPI	Median EPI
Office	102	198	158	160
Educational Institution	102	178	155	164
Transportation	100	192	158	159
Retail	100	201	162	163
Hotel & Restaurant	110	181	153	156
Recreation	100	156	135	150
Religious Institution	90	152	143	143
Hospital	102	200	156	159
Residential Commercial	110	185	167	179
Special Purpose	105	180	150	150
Industrial	100	200	157	161
Commercial	100	218	173	175
BPO	144	199	162	158

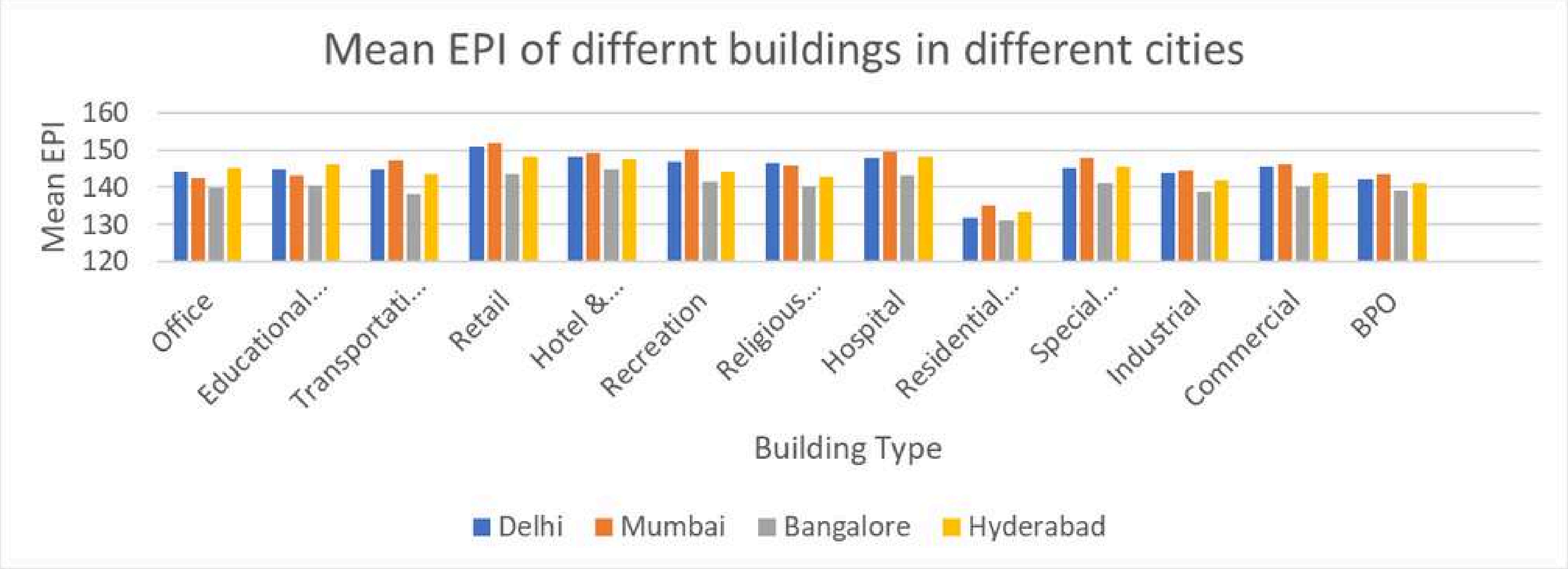


Figure 8: *Mean EPI of different buildings across the four cities*

Figure 9: *EPI range distribution percentages across the four cities*

Table 8: *EPI range across various building types in different climatic zones with BEE star rating*

	Delhi (Composite)		Mumbai (Warm & Humid)		Bangalore (Temperate)		Hyderabad (Hot & Dry)	
Typology	**EPI**	**Star Rating (Acc. To BEE*)**	**EPI**	**Star Rating (Acc. To BEE*)**	**EPI**	**Star Rating (Acc. To BEE*)**	**EPI**	**Star Rating (Acc. To BEE*)**
Office buildings (corporate office buildings, government offices, commercial office buildings, etc.)	96-185	**1-4 star**	100-192	**1-4 star**	95-193		102-198	**1-4 star**
Educational institutions (Schools, colleges, universities, research centres)	100-184		100-234		98-164		102-178	
BPO (IT parks)	17-19 (AAhEPI)	**5 star**	16-18 (AAhEPI)	**5 star**	16-20 (AAhEPI)	5 star	16-23 (AAhEPI)	**3-4 star**
Transportation facilities (train and metro stations)	95-176		95-189		82-139		100-192	
Retail (Shopping malls, shopping complexes, super markets, show rooms, garments store, book store, food store, etc.)	94-181	**4-5 star**	98-217	**5 star**	90-182	4-5 star	100-201	**3-4 star**
Hospitality and leisure (hotel, guest house, restaurants)	98-181		100-182		95-173		110-181	
Recreation (cinema, sports activities area, museum, stadium, planetarium)	85-213		102-179		90-150		100-156	
Religious Institutions (temple, mosque, gurudwara, church, synagogue)	90-177		105-186		90-152		110-175	
Hospitals	100-186		100-171		95-200		102-200	
Residential commercial (PGs, hostels)	95-178		98-168		90-166		110-199	
Special purpose buildings (auditorium, banquet hall, club, community centre, exhibition hall, library, data centres)	80-172		95-178		90-160		105-180	
Industrial	95-158		98-228		92-178		100-200	
Other commercial buildings (with mixed-use developments)	95-160		95-210		80-187		100-218	

***Table 9:** Cooling energy demand across various building types in different climatic zones*

Building categories	Cooling Energy Demand (Per sq. m energy consumption by cooling system) (kWh/ sqm)			
	Delhi (Composite)	Mumbai (Warm & Humid)	Bangalore (Temperate)	Hyderabad (Hot & Dry)
I) Office buildings (corporate office buildings, government offices, commercial office buildings, etc.)	71	84	65	82
II) Educational institutions (Schools, colleges, universities, research centres)	72	87	65	82
III) Transportation facilities (train and metro stations)	68	80	62	75
IV) Retail (Shopping malls, shopping complexes, super markets, show rooms, garments store, book store, food store, etc.)	74	81	63	77
V) Hospitality and leisure (hotel, guest house, restaurants)	73	86	68	96
VI) Recreation (cinema, sports activities area, museum, stadium, planetarium)	68	89	62	75
VII) Religious Institutions (temple, mosque, gurudwara, church, synagogue)	67	95	68	99
VIII) Hospitals	73	85	66	80
IX) Residential commercial (PGs, hostels)	68	87	68	99
X) Special purpose buildings (auditorium, banquet hall, club, community centre, exhibition hall, library, data centres)	68	84	63	91
XI) Industrial	65	80	63	74
XII) Other commercial buildings (with mixed-use developments)	68	77	66	79

***Table 10:** Space cooling demand across various building types in different climatic zones*

Building categories	Thermal demand (Per sq. m end use space cooling demand) (GJ/sqm)			
	Delhi (Composite)	Mumbai (Warm & Humid)	Bangalore (Temperate)	Hyderabad (Hot & Dry)
I) Office buildings (corporate office buildings, government offices, commercial office buildings, etc.)	0.7	0.83	0.64	0.81
II) Educational institutions (Schools, colleges, universities, research centres)	0.72	0.86	0.63	0.81
III) Transportation facilities (train and metro stations)	0.62	0.79	0.62	0.74
IV) Retail (Shopping malls, shopping complexes, super markets, show rooms, garments store, book store, food store, etc.)	0.74	0.8	0.62	0.76
V) Hospitality and leisure (hotel, guest house, restaurants)	0.73	0.85	0.67	0.95
VI) Recreation (cinema, sports activities area, museum, stadium, planetarium)	0.67	0.87	0.62	0.74
VII) Religious Institutions (temple, mosque, gurudwara, church, synagogue**)**	0.66	0.94	0.67	0.98
VIII) Hospitals	0.72	0.84	0.65	0.82
IX) Residential commercial (PGs, hostels)	0.67	0.86	0.68	0.98
X) Special purpose buildings (auditorium, banquet hall, club, community centre, exhibition hall, library, data centres)	0.67	0.83	0.62	0.9
XI) Industrial	0.64	0.79	0.62	0.73
XII) Other commercial buildings (with mixed-use developments)	0.67	0.76	0.66	0.78

5.2 Analysis of electrical and cooling demand of different building categories in the 4 cities

5.2.1 Office Buildings

Office buildings in Mumbai and Hyderabad generally exhibit higher EPIs and cooling energy demands compared to Delhi and Bangalore. The warm and humid climate of Mumbai leads to continuous cooling needs throughout the year, with higher moisture levels requiring dehumidification systems that contribute to increased energy consumption. In Hyderabad, the hot and dry climate also creates significant cooling demands, especially during peak summer months when temperatures soar, necessitating more space cooling. Conversely, Bangalore, with its temperate climate, enjoys a cooler environment and lower humidity, translating to reduced cooling requirements and energy consumption. Delhi, being in a composite climatic zone, lies in between, experiencing moderate demands influenced by seasonal shifts.

5.2.2 Educational Institutions

The energy performance of educational institutions follows a similar trend, where Mumbai and Hyderabad display higher energy requirements due to climatic factors. Mumbai's humid conditions necessitate year-round operation of cooling systems in classrooms and auditoriums to maintain a comfortable indoor environment. Hyderabad experiences seasonal temperature extremes, which lead to increased cooling energy use. In Delhi, the moderate seasonal variation results in average energy needs, while Bangalore demonstrates efficient energy use due to its milder climate.

5.2.3 Transportation Facilities

Transportation facilities, such as airports, metro stations, and railway terminals, show higher cooling and energy demands in Mumbai and Hyderabad compared to Bangalore and Delhi. In Mumbai, high humidity levels, coupled with the continuous flow of passengers, drive up energy needs for cooling and ventilation systems. In Hyderabad, the arid climate with intense heat necessitates significant cooling efforts to maintain comfort. Bangalore, with its favourable climate, typically experiences much lower energy usage, while Delhi again falls in the middle range due to its composite climate.

5.2.4 Retail Buildings

Retail spaces, such as shopping malls and commercial complexes, tend to have some of the highest cooling energy demands across all climatic zones, driven by high footfall and internal heat loads from lighting and equipment. Mumbai's warm and humid conditions increase the burden on cooling systems, making energy performance higher. Hyderabad also shows elevated demands due to the dry heat, which requires cooling to ensure a pleasant shopping experience. Delhi sees relatively moderate demands, while Bangalore enjoys the lowest energy needs due to naturally cooler ambient conditions, requiring less air conditioning.

5.2.5 Hospitality and Leisure Buildings

Hotels, resorts, and leisure facilities show stark differences in energy requirements across regions. Mumbai and Hyderabad top the charts, with significant energy usage driven by their challenging climatic conditions. In Mumbai, maintaining guest comfort amid high humidity calls for extensive use of air conditioning and ventilation systems. Hyderabad faces high cooling loads due to its extremely hot climate, especially during peak summers. Bangalore’s temperate climate, combined with its reputation as a tech hub, helps hospitality buildings optimize energy usage. Delhi, with its seasonal variations, shows moderate energy requirements in this category.

5.2.6 Residential Commercial Buildings

Buildings such as hostels and paying guest accommodations exhibit higher energy consumption in Hyderabad and Mumbai. In Mumbai, the combination of warm temperatures and high humidity makes cooling systems essential for maintaining comfortable living spaces. Hyderabad’s hot summers create similar demands for cooling systems. Delhi, with a mix of hot summers and cool winters, experiences more balanced energy consumption, while Bangalore again displays the lowest demands due to its mild weather, resulting in reduced operational energy for cooling.

5.2.7 Special Purpose Buildings

Buildings like auditoriums, data centres, and laboratories, classified as special purpose buildings, also highlight significant differences. Mumbai’s humid climate and round-the-clock operation of specialized equipment create high cooling needs. Hyderabad, with its extreme temperatures, shows similar energy demands, particularly in data centres that require efficient cooling systems to maintain equipment functionality. Delhi faces moderate challenges based on seasonal shifts, and Bangalore continues to demonstrate the lowest energy demands due to its favourable conditions.

5.2.8 Industrial Buildings

Industrial buildings reflect energy performance differences that align with regional climatic demands. Hyderabad and Mumbai lead with higher energy needs due to harsh climatic conditions affecting both operations and employee comfort. In Mumbai, the combined challenges of humidity and continuous industrial activity increase cooling and dehumidification requirements. Hyderabad sees significant energy demands due to prolonged hot periods. Delhi’s industrial spaces see moderate energy consumption, with variations based on the season. Bangalore, as expected, experiences minimal energy demands due to cooler temperatures throughout the year.

6

Future Cooling Scenarios of the 4 Cities (2050)

✓ **1. Business-as-Usual Leads to Sharp Rise in Cooling Demand and Emissions**
Under BAU conditions, all four cities are projected to experience significant increases in electricity consumption, cooling demand, and GHG emissions by 2050, driven by urbanization, rising temperatures, and expanding commercial infrastructure.

✓ **2. Sustainable Scenarios Significantly Reduce Future Energy Burden**
Scenario-based analysis shows that passive design strategies and high-efficiency HVAC systems can substantially reduce cooling demand, electricity use, and emissions by up to 40–46% in some cases, demonstrating the effectiveness of targeted interventions.

✓ **3. Strong Need for City-Specific Cooling Strategies**
Each city exhibits distinct trends; Delhi faces the highest future demand, Mumbai and Hyderabad show strong reduction potential, while Bangalore remains relatively efficient highlighting the need for climate-responsive, location-specific energy strategies.

6.1 Creating long-term scenarios of space cooling for energy demand forecasts

To estimate the future cooling and electricity demand of commercial buildings in Delhi, Mumbai, Bangalore, and Hyderabad, scenario-based assessments have been conducted for the period up to 2050. These cities, spanning diverse climatic zones, are grappling with rapid urbanization, population growth, and climate change impacts such as rising temperatures and altered precipitation patterns. Delhi has been witnessing rising heatwave intensity and erratic rainfall trends which will be coinciding with rapid urbanization, adding to cooling demands (Delhi Heat Action Plan 2024-25; NASA, 2018). Bangalore has been seeing the growth of urban heat islands causing higher night temperatures in commercial zones, alongside increased heavy rainfall days (TERI; CEEW, 2024). In Mumbai, the diurnal temperatures are climbing, with frequent flooding and reduced vegetation due to urban expansion (Rana et al., 2014; Ramachandra et al., 2014). In Hyderabad, night time urban heat islands and increased northeast monsoon rainfall are the key challenges, alongside urban sprawl (Shrikant and Swain, 2022; Venkatesh et al., 2018).

These climate and urbanization trends will likely drive higher electricity and cooling demands, exacerbating GHG emissions. Hence, scenario-based assessments incorporating climate change and future population growth conditions will help policymakers plan the necessary sustainable infrastructure, explore equitable solutions and energy efficient technologies and anticipate energy demand. Two additional future scenarios, one incorporating building architectural change as per Energy Conservation Building Code and another one incorporating implementation of a more efficient HVAC system have been explored under this study.

To develop long-term scenarios for space cooling, our own SPIBEAT tool has been used. The process began with importing the necessary datasets into CEA, including building characteristics, and spatial information sourced from platforms like OpenStreetMap (OSM) and Blender. These datasets formed the foundation for the scenario analysis. The next step involved identifying key factors that influence space cooling demand, such as population growth, temperature and precipitation trends until 2050, urban development patterns, building architectural designs, HVAC systems, etc. These factors form a part of input database of the CEA software which were then changed as per scenario needs and inputted into the model.

6.2 Description of future cooling demand scenarios

6.2.1 Business-As-Usual (BAU) and B1 scenarios

Firstly, using the CCWorldWeatherGen tool which utilized climate model summary data from the IPCC Third Assessment Report (TAR), specifically from the HadCM3 A2 (~RCP 8.5) and B1 (~RCP 4.5) scenarios, two distinct weather files for the year 2050 were generated. The tool allowed us to modify 'present-day' EPW (EnergyPlus Weather) files to generate the two climate change weather files suitable for building performance simulation programs. The EPW parameters considered in this analysis include:

- Daily mean temperature
- Maximum temperature
- Minimum temperature
- Horizontal solar irradiation
- Total cloud cover
- Total precipitation rate
- Relative humidity
- Mean sea level pressure
- Wind speed

These two future weather files — HadCM3 A2 and B1 correspond to BAU and B1 scenarios respectively for year 2050. The key differences between these scenarios, based on the Special Report on Emissions Scenarios (SRES) by the IPCC DDC, are as follows:

- **BAU Scenario (A2 Scenario):** This scenario assumes a continuation of current policies, technological trends, and socio-economic patterns without significant new interventions in the buildings sector. This means that building codes and energy efficiency

- standards remain largely unchanged, with limited adoption of green construction practices or retrofitting of existing infrastructure. Urban development continues to follow conventional patterns, relying heavily on resource-intensive materials and fossil fuel-based energy systems. As population growth in cities steadily increases due to migration and converging fertility rates, demand for residential and commercial space rises, further straining urban infrastructure. Economic development remains regionally focused, with slower growth in income and technological progress. The scenario aligns with severe global warming, drastic shifts in precipitation patterns, and widespread ecosystem collapse, leading to catastrophic impacts on biodiversity, food security, and human well-being.
- **B1 Scenario:** The B1 describes a convergent world with the same global population that peaks in mid-century (roughly by 2050) and declines thereafter, driven by global trends such as improved education and healthcare, not local interventions. While population changes are not directly influenced at the national or city level, the scenario remains relevant through actions taken by governments, industries, and communities to shift toward service- and knowledge-based economies, reduce material intensity, and adopt clean, resource-efficient technologies. The focus is on integrated solutions for economic, social,
- and environmental sustainability with improved equity but no additional climate initiatives beyond current commitments. Key transitions are expected between 2020 and 2050, with local and national actions playing a vital role in aligning with the scenario's goals.

6.2.2 Active and Passive Cooling Scenarios

While the BAU and B1 scenarios reflect extreme and moderate climate change impacts, they lack significant policy interventions or energy efficiency strategies. To address this, the project incorporates three key scenarios from the Indian Cooling Action Plan (ICAP): comfortable cooling, sustainable cooling, and smart cooling. These scenarios aim to reduce cooling demand, energy consumption, and the use of high-impact refrigerants. Two sub-scenarios passive and active cooling have been developed. The passive scenario focuses on energy-efficient building designs leveraging natural elements, while the active scenario emphasizes advanced high-efficiency HVAC systems to reduce energy use, cooling demand, and emissions. Both scenarios use 2050 BAU (A2) climate conditions as a baseline for comparison, providing a robust framework for sustainable and resilient cooling strategies tailored to the unique challenges of the four project cities.

The table below outlines the key scenario descriptions for 2050, providing a framework to estimate and manage future electrical load and cooling demand across the four cities.

Table 11: *Descriptions of future space cooling demand scenarios*

S.No.	Scenario	Description and basic assumptions	Active/Passive Cooling	ICAP Cooling Category
1.	BAU Scenario (Baseline 2050 Scenario)	• Population continues to grow steadily due to limited intervention. • No major policy changes; sustainability goals delayed or ignored. • Fragmented growth; traditional sectors dominate with low innovation. • Slow and limited adoption of clean technologies. • Severe climate change effects, high heat stress, and ecological degradation. • Driven by inaction; weak local and global coordination.		
2.	B1 Scenario	• Population peaks mid-century, then declines due to better health, education, and planning. • Strong, proactive policies focused on sustainability at all levels. • Shift to service and knowledge-based economy with high innovation. • Widespread use of clean, resource-efficient technologies. • Moderate climate change impact due to strong mitigation efforts. • Enabled by local/national governments, private sector, and civic participation.	Active/Passive Cooling	
3.	Efficient building design scenario	• Reduction of reliance on mechanical cooling systems • Focus on natural processes and architectural design strategies: a) Changes in building tightness, construction type, shading, roofs, windows and walls b) Construction of buildings with heavy materials to enhance thermal mass c) Increase in tightness of buildings to a highly tight level, minimizing air leakage d) Upgradation of windows to triple glazing with two selective low-emissivity coatings to limit heat transfer e) Reduction in window-to-wall ratio is reduced to 0.1, minimizing window surface area to reduce heat gain f) Coating of roof with white paint over plaster to reflect sunlight and reduce heat absorption g) Applying dark blue paint over clay bricks on walls for improved insulation h) For shading, use of venetian blinds to block direct sunlight and reduce indoor temperatures These changes collectively create a more energy-efficient environment by optimizing passive cooling methods.	Passive Cooling	Sustainable Cooling

S.No.	Scenario	Description and basic assumptions	Active/Passive Cooling	ICAP Cooling Category
4.	HVAC High Energy Efficiency Scenario	• Reduction in cooling demand by changing mechanical cooling demand. • The following changes are made in the HVAC systems: a. Change in HVAC system by switching to ceiling cooling technology as it is more energy efficient and provides improved thermal comfort b. Modifications in the efficiency of cooling supply system c. Switch to mechanical ventilation equipped with demand control and an economizer for optimizing energy use d. Adjustment of cooling set point temperature to 26°C, ensuring comfortable cooling e. Regulation of relative humidity (RH) levels with a minimum of 30% and a maximum of 50%, preventing excessive dryness or humidity	Active Cooling	Comfortable & Sustainable Cooling

Following the same methodology, involving the use of SPIBEAT tool, the BAU, B1 and the above mentioned active and passive cooling scenarios have been run for the four concerned Indian cities. This analysis forecasts their cooling load and electrical demand how the implementation of architectural or technological interventions can reduce the building wise electrical load, space cooling demand and GHG emissions in these cities and acts as a guidance for policymakers for future urban resilience planning of the city.

6.3 City Wise Future Electrical and Cooling Demand Forecasts

6.3.1 Future Electrical Load and Cooling Demand Scenarios for Delhi

In case of Delhi, as mentioned earlier, the Connaught Place which is majorly a commercial hub, has been selected as the city's representative study area for this project. If BAU conditions (high population growth and a lack of sustainability interventions) continue till 2050 in Delhi, it will lead to drastic heat stress conditions and shifts in precipitation patterns, causing a substantial increase in electrical load, cooling demand and consequent greenhouse gas (GHG) emissions, compared to that of 2023. Conversely, under the B1 scenario, lesser extreme climatic conditions due to a focus on environmental and economic sustainability, clean energy interventions, along with slower population growth, the rise in cooling demand, electricity consumption, and emissions is significantly moderated relative to the baseline year.

However, implementing the described active and passive cooling techniques significantly reduces the total electrical consumption of commercial buildings, their space cooling demand, and GHG emissions till 2050 compared under the same climatic conditions as in the BAU scenario. The most significant reductions in electrical load and space cooling demand in Delhi's commercial buildings occur when decentralized or centralized air-conditioning systems are replaced with ceiling cooling systems, supported by vapor compression chillers and dry cooling towers which serve as cooling supply systems and mechanical ventilation is installed along with adjustments in the setpoint temperatures and relative humidity. Improving the efficiency of the cooling supply system further enhances energy savings. Significant decrease in electrical load, space cooling demand and GHG emissions also occur in the selected commercial buildings when passive design strategies or architectural changes such as applying reflective paints in roofs and walls, installing low emissivity windows or lowering the Window-to-Wall ratio, etc. are made in them (as per the efficient building design scenario) to enhance their thermal performance or energy efficiency. This analysis demonstrates that, even with the same climatic conditions in 2050 as in the BAU scenario, energy-efficient interventions and architectural upgrades can substantially lower electrical and space cooling demand as well as GHG emissions of the commercial buildings in Delhi.

The table below presents percentage reductions in the total electrical load, cooling demand and GHG emissions in the concerned active and passive cooling scenarios relative to the BAU scenario for the selected sample area of Delhi for year 2050.

Table 12: *Percentage change in electricity consumption, space cooling demand and GHG emissions from BAU scenario to other scenarios for year 2050 in Delhi's selected commercial buildings*

	Percentage change in space cooling demand from BAU scenario to other scenarios		
	BAU scenario – B1 scenario	BAU scenario – Efficient building design scenario	BAU scenario – HVAC high energy efficiency scenario
Total electricity consumption (Mwhyr)	-1%	-5%	-19%
End-use space cooling demand (Mwhyr)	-2%	-13%	-44%
GHG emissions (tonsCO2)	-1%	-8%	-29%

6.3.2 Future Electrical Load and Cooling Demand Scenarios for Bangalore

For Bangalore, the representative area of the city selected for the analysis, Whitefield is a major commercial hub consisting of multinational companies, start-ups, retail hubs, top healthcare facilities, educational institutions, and shopping malls. If current conditions continue without implementing any change in current policy or interventions, practices or behaviour in this study area, the total electricity consumption, end use space cooling demand and associated greenhouse gas emissions will witness significant increase. However, with behavioural and systemic changes—such as the adoption of clean energy technologies, a shift to renewable energy, reduced reliance on fossil fuels, and the transition to a service-based economy as exemplified in the B1 scenario—GHG emissions are substantially reduced. This leads to a slower rate of temperature increase, which in turn lowers space cooling demand and electricity consumption compared to Business-As-Usual (BAU) conditions.

The concerned parameters including building electrical and cooling demand also lowers by 2050 if further changes in the building envelope or the installation of ceiling cooling system and mechanical ventilation as described in the efficient building design or HVAC high energy efficiency scenarios are made in the buildings.

The table below shows the percentage reductions in electrical load, cooling demand and GHG emissions across scenarios for the selected sample area of Bangalore till 2050 for different scenarios relative to the BAU scenario.

__Table 13:__ Percentage change in space cooling demand from BAU scenario to other scenarios for year 2050 in Bangalore's selected commercial buildings

	Percentage change in space cooling demand from BAU scenario to other scenarios		
	BAU scenario – B1 scenario	BAU scenario – Efficient building design scenario	BAU scenario – HVAC high energy efficiency scenario
Total electricity consumption (Mwhyr)	-1%	-4%	-16%
End-use space cooling demand (Mwhyr)	-2%	-14%	-41%
GHG emissions (tonsCO2)	-1%	-8%	-25%

6.3.3 Future Electrical Load and Cooling Demand Scenarios for Mumbai

In case of Bandra Kurla Complex (study area of Mumbai city), the electrical load, space cooling demand and GHG emissions till 2050 under BAU and B1 scenarios follow the same pattern as Delhi and Bangalore. Under BAU conditions, these parameters go on increasing as compared to 2023 levels while in B1 scenario, they witness slight reductions, but still higher than current levels, due to the introduction of measures such as use of clean or renewable technologies.

The commercial buildings in the study area can encounter very high reductions in electrical consumption, space cooling demand and GHG emissions by 2050 if the HVAC and ventilation systems are changed to ceiling cooling and mechanical ventilation technologies respectively and adjustments are made in the room set point temperature and relative humidity.

Furthermore, passive cooling strategies including application of reflective paints in roofs or walls of buildings or changing the shading devices, etc. under the efficient building design scenario will also be successful in reducing the buildings' electrical load and cooling demand without implementing any mechanical changes.

The table below shows the proportion by which the electrical load, cooling demand and GHG emissions reduce when different sustainable measures are implemented till 2050 against BAU for the city of Mumbai.

Table 14: *Percentage change in space cooling demand from BAU scenario to other scenarios for year 2050 in Mumbai's selected commercial buildings*

	Percentage change in space cooling demand from BAU scenario to other scenarios		
	BAU scenario – B1 scenario	BAU scenario – Efficient building design scenario	BAU scenario – HVAC high energy efficiency scenario
Total electricity consumption (Mwhyr)	-1%	-6%	-21%
End-use space cooling demand (Mwhyr)	-1%	-15%	-46%
GHG emissions (tonsCO2)	-1%	-9%	-31%

6.3.4 Future Electrical Load and Cooling Demand Scenarios for Hyderabad

For Hyderabad's study area, Hitec City, too, if conditions remain unchanged until 2050, as projected in the BAU scenario, electrical load, space cooling demand and GHG emissions are expected to increase significantly. However, with the adoption of sustainability measures, as outlined in the B1 scenario, these metrics are projected to show a moderate reduction.

The introduction of both active and passive cooling techniques further helps to reduce electrical load, space cooling demand and GHG emissions till 2050. The most substantial decrease occurs with the combined implementation of ceiling cooling system technology and mechanical ventilation along with improved indoor comfort by regulation of set point temperature and relative humidity.

Apart from such mechanical changes, architectural changes in roofs, windows, walls, etc. of the commercial buildings as given in table, can also reduce their electrical and cooling demand but comparatively to a lesser extent.

The table below presents percentage decrease in the electrical load, cooling demand and GHG emissions across scenarios if BAU conditions do not continue.

Table 14: *Percentage change in space cooling demand from BAU scenario to other scenarios for year 2050 in Hyderabad's selected commercial buildings*

	Percentage change in space cooling demand from BAU scenario to other scenarios		
	BAU scenario – B1 scenario	BAU scenario – Efficient building design scenario	BAU scenario – HVAC high energy efficiency scenario
Total electricity consumption (Mwhyr)	-1%	-7%	-22%
End-use space cooling demand (Mwhyr)	-2%	-17%	-40%
GHG emissions (tonsCO2)	-1%	-11%	-29%

The scenario-based assessment of future cooling and electricity demand for commercial buildings in Delhi, Bangalore, Mumbai, and Hyderabad highlights the critical impact of urbanization, climate change, and policy interventions on energy consumption and GHG emissions. The findings reveal that under Business-As-Usual (BAU) conditions, significant increases in electricity consumption, space cooling demand, and emissions are expected across all cities due to rising temperatures, urban heat island effects, and population growth. However, implementing sustainable cooling strategies and energy-efficient interventions, such as efficient building designs, passive cooling techniques, and high-efficiency HVAC systems, can drastically reduce these parameters. Delhi exhibits the highest projected cooling and electricity demand under the Business-As-Usual (BAU) scenario, driven by its extreme temperature variations and dense urban fabric. Mumbai, with its humid tropical climate, shows high demand as well, but the adoption of passive cooling measures can yield significant reductions. Bangalore, benefiting from its moderate climate, shows relatively lower demand across scenarios, highlighting the advantage of natural climatic conditions in reducing energy requirements. Hyderabad, with its semi-arid climate, demonstrates intermediate trends, where targeted interventions such as efficient building designs and advanced HVAC systems can lead to notable energy savings. Across all cities, implementing sustainable cooling strategies proves most effective in mitigating the projected surge in energy consumption, cooling demand and GHG emissions. Mumbai and Hyderabad, in particular, stand out for their potential to achieve substantial reductions through rooftop solar integration and cool roof technologies. Delhi requires a more aggressive policy push due to its higher baseline energy needs, while Bangalore's focus should be on maintaining its low demand trajectory through proactive measures. These city-specific insights emphasize the need for tailored strategies that align with regional climates and urban contexts to achieve sustainable energy use and climate resilience. These insights provide a robust foundation for policymakers to design resilient infrastructure and prioritize energy efficiency in the commercial sector to support long-term climate goals.

7 Conclusions

1. Rising Cooling Demand Driving Energy and Emission Pressures
Cooling demand in commercial buildings is rapidly increasing due to climate change, urbanization, and expanding built-up areas, leading to higher electricity consumption and GHG emissions, especially in cities like Delhi and Mumbai.

2. Climate-Specific Variations Across Cities and Building Types
Energy performance and cooling needs vary significantly across cities and building categories, with Mumbai and Hyderabad showing higher demand, while Bangalore remains the most energy-efficient due to its favourable climate.

3. Need for Integrated, Future-Oriented Cooling Strategies
Scenario analysis highlights that passive cooling, efficient HVAC systems, renewable energy integration, and district cooling systems can significantly reduce future energy demand and emissions, making them essential for sustainable urban development.

The assessment of cooling and electrical demand in commercial buildings across Delhi, Mumbai, Bangalore, and Hyderabad highlights the growing energy burden driven by climate change, rapid urbanization, and increasing cooling requirements. The findings of this study underscore that without strategic interventions, the energy demand for space cooling will continue to rise, placing immense pressure on electricity grids and exacerbating greenhouse gas emissions. Among the four cities, Delhi shows the highest projected increase in cooling demand due to extreme seasonal variations, whereas Mumbai experiences persistently high cooling needs throughout the year due to its warm and humid climate. Bangalore, with its temperate climate, remains the most energy-efficient, while Hyderabad’s hot and dry conditions necessitate intensive cooling, especially during peak summer months.

The study further reveals that commercial building categories such as office spaces, retail centres, hospitality facilities, and industrial structures exhibit significant variations in energy performance based on climatic zones. Retail malls and hospitality buildings in Mumbai and Hyderabad require the most energy due to high humidity and occupant density, whereas educational and office buildings in Bangalore display lower energy consumption due to favourable climatic conditions. Without effective energy efficiency measures, the rise in demand for cooling across all commercial sectors will lead to a steep increase in electricity consumption and emissions, making it crucial to implement targeted energy management strategies. Future projections indicate that under a Business-As-Usual (BAU) scenario, the electricity consumption and space cooling load in all four cities will rise dramatically by 2050, exacerbated by rising urban temperatures and the expansion of built-up commercial spaces. However, scenario-based assessments show that implementing strategic interventions, such as passive cooling strategies and high-efficiency cooling technologies, can significantly mitigate the anticipated surge in energy demand. Passive cooling techniques such as improved building envelope design, reflective and green roofing, optimized shading, and natural ventilation can effectively lower cooling demand without requiring major infrastructure modifications. At the same time, high-efficiency active cooling solutions, such as advanced HVAC systems, demand-controlled ventilation, and ceiling cooling technologies, offer substantial reductions in energy consumption and emissions. These strategies have the potential to reduce cooling loads by over 40% in certain cases, demonstrating the critical role of innovative and sustainable cooling approaches in urban planning.

In addition to building-level strategies, the study recommends conducting feasibility assessments for District Cooling Systems (DCS) in high-density commercial zones across these cities. DCS, which centralizes the production and distribution of cooling energy, can significantly enhance energy efficiency and reduce peak electricity loads when deployed at scale. Feasibility studies should evaluate factors such as thermal load density, infrastructure availability, investment requirements, and regulatory frameworks to determine the suitability and cost-effectiveness of DCS implementation. Successful adoption of DCS in appropriate zones such as business districts, commercial hubs, and mixed-use developments can play a transformative role in achieving energy-efficient urban cooling while reducing reliance on individual energy-intensive systems.

To address the projected challenges, it is essential to integrate policy-driven solutions that strengthen compliance with the Energy Conservation Building Code (ECBC) and encourage the adoption of high-efficiency cooling systems in commercial buildings. Expanding the use of renewable energy, particularly through rooftop solar installations, can help offset the increasing electricity demand. Furthermore, urban cooling strategies, such as integrating green spaces, implementing cool roof initiatives, and adopting climate-responsive building designs, can play a crucial role in mitigating the urban heat island effect while reducing dependency on active cooling systems. Encouraging smart, automated cooling technologies can also lead to optimized energy use, ensuring both occupant comfort and efficiency.

The findings of this study reinforce the need for city-specific interventions to align with regional climatic conditions and urbanization trends. Given the rapid expansion of commercial spaces and the increasing strain on energy resources, a combination of building design optimization, advanced cooling technologies, and renewable energy integration will be necessary to create a more sustainable and resilient urban landscape. The transition toward energy-efficient cooling in commercial buildings not only supports climate mitigation efforts but also ensures long-term economic and environmental sustainability. Proactive planning and investment in sustainable cooling infrastructure will be critical in shaping India's urban energy landscape for the future.

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References

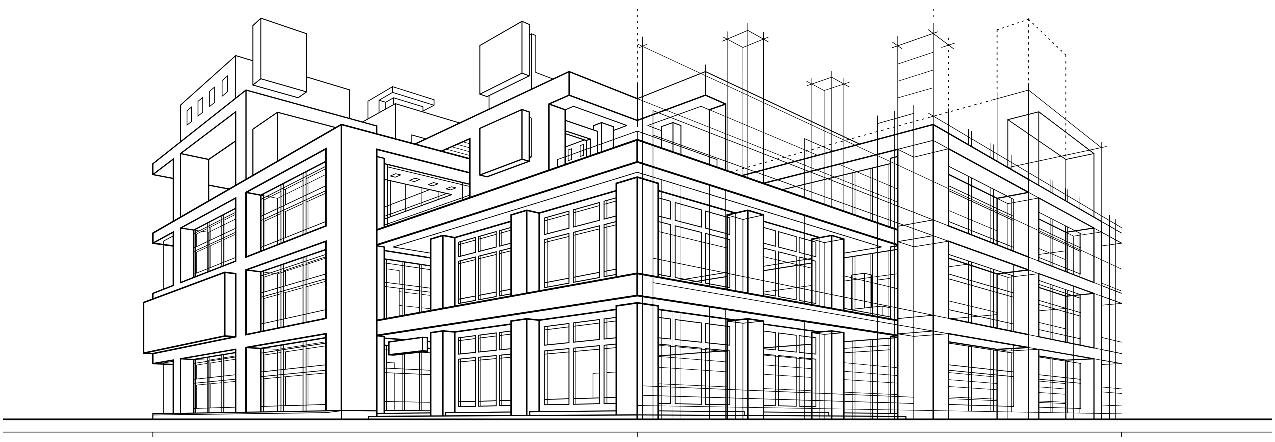
1. *Alliance, G. C. C. (2012). A Practical guide to cool roofs and cool pavements.*
2. *Bhattacharya, A. (2020). Optimal cooling pathways: An implementation framework for the India cooling action plan.*
3. *Blender Development Team. (2022). Blender (Version 3.1.0) [Computer software]. https://www.blender.org*
4. *Bureau of Energy Efficiency. (n.d.). Schedule - Residential building labelling. Government of India. https://beeindia.gov.in/sites/default/files/Schedule%20-%20Residential%20building%20labelling.pdf*
5. *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.*
6. *de Bont, J., Nori-Sarma, A., Stafoggia, M., Banerjee, T., Ingole, V., Jaganathan, S., ... & Ljungman, P. (2024). Impact of heatwaves on all-cause mortality in India: A comprehensive multi-city study. Environment international, 184, 108461.*
7. *Delhi Planning Department. (n.d.). Demography. Government of Delhi. https://delhiplanning.delhi.gov.in/sites/default/files/Planning/19._demography.pdf*
8. *Directorate of Economics and Statistics, Telangana. (n.d.). District statistical handbook: Hyderabad. Government of Telangana. https://ecostat.telangana.gov.in/districts/03-Hyderabad.pdf*
9. *District Energy in Cities Initiative, National District Cooling Potential for India (2021). Empower, EESL, UNEP, Global Environment Facility. https://eeslindia.org/wp-content/uploads/2021/03/Final-Report_National-District-Cooling-Potential-Study-for-India.pdf*
10. *Energy Conservation Building Code (2017). Bureau of Energy Efficiency, Ministry of Power, Government of India. https://beeindia.gov.in/sites/default/files/BEE_ECBC%202017.pdf*
11. *Energy Sector Management Assistance Program (ESMAP) Annual Report (2020). Retrieved from https://www.esmap.org/energy-sector-management-assistance-program-%28esmap%29-annual-*
12. *Frayssinet, L., Merlier, L., Kuznik, F., Hubert, J. L., Milliez, M., & Roux, J. J. (2018). Modeling the heating and cooling energy demand of urban buildings at city scale. Renewable and Sustainable Energy Reviews, 81, 2318-2327.*
13. *Kandya, A., & Mohan, M. (2018). Mitigating the Urban Heat Island effect through building envelope modifications. Energy and Buildings, 164, 266-277.*
14. *Ministry of Environment, Forest & Climate Change (2019). India Cooling Action Plan. New Delhi: Ministry of Environment, Forest & Climate Change*
15. *Municipal Corporation of Greater Mumbai. (n.d.). City profile. Municipal Corporation of Greater Mumbai. https://dm.mcgm.gov.in/assets/pdf/city_profile.pdf*
16. *Office of the Registrar General & Census Commissioner, India. (n.d.). District Census Handbook: Bangalore (Part A). Government of India. https://karnataka.census.gov.in/DCHB-PART-A/572.Bangalore.pdf*
17. *OpenStreetMap contributors. (2015) Planet dump [Data file from $date of database dump$]. Retrieved from https://planet.openstreetmap.org*
18. *QGIS Development Team, 2009. QGIS Geographic Information System. Open Source Geospatial Foundation. URL http://qgis.org*
19. *Singh, C., Vyas, D., Patil, S., Ranjit, N., Poonacha, P., & Surampally, S. (2024). How are Indian cities adapting to extreme heat? Insights on heat risk governance and incremental adaptation from ten urban Heat Action Plans. PLOS Climate, 3(11), e0000484.*
20. *The CEA Team. (2024). City Energy Analyst (v3.35.5). Zenodo. https://doi.org/10.5281/zenodo.1084777*
21. *Vishwanathan, S. S., & Garg, A. (2020). Energy system transformation to meet NDC, 2 C, and well below 2 C targets for India. Climatic Change, 162(4), 1877-1891.*
22. *World Economic Forum. (2019). How India is solving its cooling challenge.*

Annexure

City-wise per capita results for baseline year (2023)

kWh=1 unit

Parameters (2023)	**Delhi**	**Mumbai**	**Bangalore**	**Hyderabad**
Per capita total electricity consumption (kWh/yr) for commercial buildings	595	614	581	627
Per capita energy consumption of cooling system (kWh/yr) in commercial buildings	421	500	390	483
Per capita cooling demand (kWh/yr) for commercial buildings	156	373	72	125
Per capita GHG emissions (tonsCO2) for energy consumption in commercial buildings	0.515	0.562	0.494	0.56



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