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Building Innovation: A Guide For High-Performance Energy Efficient Buildings in India

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Building Innovation: A Guide for High-Performance Energy Efficient Buildings in India

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Lawrence Berkeley National Laboratory

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India launched the Energy Conservation Building Code (ECBC) in 2007, and a revised version in 2017 as ambitious first steps towards promoting energy efficiency in the building sector. Pioneering early adopters—building owners, architecture and engineering firms, and energy consultants—have taken the lead to design customized solutions for their energy-efficient buildings. *Building Innovation- A Guide for High-Performance Energy Efficient Indian Buildings* offers a synthesizing framework, critical lessons, and guidance to meet and exceed ECBC. Its whole-building lifecycle assurance framework provides a user-friendly methodology to achieve high performance in terms of energy, environmental, and societal benefits. Offices are selected as a target typology, being a high-growth sector, with significant opportunities for energy savings. The best practices may be extrapolated to other commercial building sectors, as well as extended to other regions with similar cultural, climatic, construction, and developmental contexts.

Our journey with energy efficiency in Indian buildings started with our collaborators, the Infosys' Green Initiatives Team and MetroValley Business Park Pvt. Limited. We gratefully acknowledge their collaboration, and pursuit of high performance and low energy impact buildings that has led to an integrated methodology and the creation of this *Guide*. We are grateful to Rob Sandoli, Sheila Moynihan, Sandra Dickison, and Elena Berger from U.S. Department of Energy for seeding and supporting the *Guide*. Our gratitude to Lauren Diekman from US India Business Council, Kartikeya Singh from Center for Strategic and International Studies, and Awinash Bawle from the California Governor's Office for their strategic guidance.

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Disclaimer

BUILDING INNOVATION

A Guide for High-Performance Energy Efficient Buildings in India

Reshma Singh, Baptiste Ravache, Dale Sartor

Lawrence Berkeley National Laboratory

This Guide empowers YOU to find innovative solutions

Developers/Owners/Builders:
What is a holistic decision framework for sustainability and energy-related investments?

A **Prioritization decision-making framework** to help prioritize investments for new construction and retrofits; **Proof-of-concept case studies** with strategies that reduce life cycle cost

Architects/Engineers:
What are effective building energy targets, technologies and software tools that enable me to design, model, and communicate better?

Specific technological approaches, metrics, and targets based on measured and modeled data to help drive better design that incorporates **energy efficiency and occupant comfort** across Indian climate zones

Sustainability/Facility Managers:
What building performance goals should I drive towards? How do I achieve operational efficiency in my building?

Energy information systems technology that enables data-driven actionable information and insights to reduce operational cost and wastage

Product and Service Industry:
What types of products and services are relevant for upcoming high-performance buildings?

Insights into integrated approaches and technologies recommended through R&D, effectively deployed in exemplary buildings, that can inform **product-to-market** fit

Academia, Researchers, Policymakers:
What is a best practice framework for both short and long term benefits?

Comprehensive **lifecycle design-build-operate approach** for high-performance buildings; **macro-level implications for building codes and policies**

HOW TO USE THE GUIDE

Goal: High-performance energy-efficient buildings

HOW TO DESIGN	CONSULT THE GUIDE
1. Design integrated, efficient architectural + electro-mechanical systems 2. Design for reduced envelope heat gain 3. Design for daylight autonomy without glare; lighting 4. Design low energy HVAC with optimized cooling 5. Design for meterability and low plug loads	❑ SECTION 1: WHOLE BUILDING APPROACH ❑ SECTION 2: BUILDING PHYSICAL SYSTEMS ❑ APPENDIX 3: LIST OF TECHNOLOGIES ❑ APPENDIX 4: LIST OF SIMULATION TOOLS ❑ APPENDIX 5: MODELING AND ANALYSIS

HOW TO BUILD	CONSULT THE GUIDE
1. Conduct integrated building stakeholder processes 2. Install sensors and controls for lighting, fans, HVAC, plugs 3. Integrate mixed mode operations 4. Install a robust building management system (BMS) 5. Commission the building and systems	❑ SECTION 1: WHOLE BUILDING APPROACH ❑ SECTION 2: BUILDING PHYSICAL SYSTEMS ❑ APPENDIX 3: LIST OF TECHNOLOGIES ❑ APPENDIX 4: LIST OF SIMULATION TOOLS

HOW TO OPERATE	CONSULT THE GUIDE
1. Implement an energy information infrastructure for efficient operations and maintenance 2. Train vigilant facility managers 3. Implement a green lease 4. Implement performance-based contracting 5. Engage occupants for enhanced building performance	❑ SECTION 1: WHOLE BUILDING APPROACH ❑ SECTION 3: BUILDING INFORMATION SYSTEMS ❑ APPENDIX 3: LIST OF TECHNOLOGIES

HOW TO FIND PROVIDERS	CONSULT THE GUIDE
1. Prioritize high-performance products and services 2. Utilize building energy simulation tools for energy-efficient design and communication	❑ APPENDIX 3: LIST OF TECHNOLOGIES ❑ APPENDIX 4: LIST OF SIMULATION TOOLS

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Executive Summary

India: Opportunities in Buildings

As India is poised to become the fifth-largest economy in the world, building stock is being added at a healthy rate of 8% per year, and building energy use is increasing exponentially. While U.S. buildings consume ~40%, or 38 Quads of the nation's 97 Quads of energy consumption (EIA 2018), Indian buildings already consume 30% of the nation's 24 Quads (IEA 2015) of energy consumption. India's power system needs to almost quadruple in size by 2040 to catch up and keep pace with electricity demand that—boosted by rising incomes and new connections to the grid—increases at almost 5% per year. Projections indicate that the Indian commercial sector footprint could *triple* to ~1.9 Billion sqm by 2030 over a baseline of 2010 (ECO III 2011). Although the buildings sector provides a challenge due to the extraordinary amount and pace of building construction, it also represents the most promising opportunities for fast and deep greenhouse gas emission mitigation.

With an active participation in the global economy, and influx of multi-national corporations, the Indian commercial building stock is becoming more international in form and function. Building energy use intensity is increasing at an unprecedented rate due to multiple factors including the rapid addition of a large, new construction footprint, increasing urban temperatures, trends towards mechanical space cooling, highly glazed facades, enhanced computing and service levels, high occupant density levels, and multiple shift operations. The energy intensity in high-end Indian buildings has started to parallel and even exceed that of western, conditioned buildings. This is unsustainable given India's energy supply limitations, the additional burden on a constrained electric grid, reliance on fossil fuel imports, and the massive environmental implications. Indeed, the cost of new office buildings in India is rising, not only from the perspective of economics of operations, but also due to environmental costs and associated productivity loss owing to unhealthy, polluted environments.

India has committed to an aggressive renewable energy target of 175 GW capacity by 2022 to provide equitable and clean energy access. This is coupled with recognition of energy efficiency as a primary resource, exemplified by the launch of the Energy Conservation Building Code (ECBC). India can continue its rapid buildings growth while taking advantage of regional opportunities such as passively cooled buildings with a wider occupant tolerance of heat, a ready supply of local, sustainable construction materials, inexpensive labor and craft costs, and a cultural ethos of careful resource use. Such approaches that have strong relevance, such as adaptive comfort and climate-suited construction, can also be suitable for transfer and transformation to other regions. These traditional opportunities, integrated with innovative building systems, information technology, and ecosystem processes, can enable a high-performance building stock.

Building Innovation: A Guide For High-Performance Energy-Efficient Buildings In India

This *Building innovation Guide* provides technical recommendations for achieving ***high-performance Indian office buildings that are smart, green, and energy efficient.*** The best practices recommended in the *Guide* are particularly ***suited to the climatic, cultural, and construction context of India, thereby offering localized solutions.***

Innovation occurs when new state-of-the-art is adopted into practice to create value. The key driver for building innovation in India is the emerging spatial aspiration of a growing, young workforce. There exist energy savings opportunities in the high-growth buildings sector.

Inspired by cellphone technology that leapfrogged landlines for millions who gained unprecedented access to communications, this *Guide* consolidates knowledge about state-of-the-art transformed into best practices, in order to help leapfrog over transitional building methods, technologies and models. The transformative tools, technologies and approaches suggested in the Guide are poised at the edge of innovation. They have been validated through simulations and expert opinion, and demonstrated in exemplary buildings, and hence can be recommended for adoption.

The *Building innovation Guide is* built on three core principles:

- ***Developing a triple bottom-line framework for energy-efficiency decision making***. High-performance buildings can be achieved through consideration of (1) social capital—enhanced working environments for occupants, (2) financial capital—an attractive return on investments, and (3) environmental capital—mitigated environmental impact of buildings.
- ***Adopting aggressive but achievable energy performance targets.*** These benchmarks are localized to the climate zones of India, and are based on a triangulation of monitored data from exemplary projects (presented as "Data Points"), modeled data from building energy simulations (presented as "Simulation Results"), and experts' inputs. Presented as "Tables of Metrics", the climate-specific benchmarks provide visibility into targets as well as best practice strategies that provide proof of concept of how real buildings are targeting and achieving high performance.
- ***Focusing on the entire building lifecycle i.e., design, construction, and operation*.** The Guide provides recommendations about the "why and how" of strategies to be employed through the building lifecycle**.** The design phase is when building energy modeling may be performed; the build phase is when construction using energy-efficient materials and systems may be done; and the longest operations phase is when commissioning, monitoring, and controls may be incorporated. (Embodied and demolition-based energy consumption are beyond the scope of this *Guide).*

The best practice recommendations are classified into three categories: whole-building design, physical building systems, and building information systems, as follows:

Best Practices for Multi-disciplinary, Whole-building Design. The *Guide* recommends that best practices strategies should be applied early at the whole-building design level. Optimum energy efficiency can be achieved through integrated stakeholder strategies that can be cost-effectively woven in as a "must-have" at the conceptual design phase, so they are not value-engineered out due to a later incorporation into the design process. The stakeholders should also focus on maximizing energy efficiency of the building as a whole, and not just on the efficiency of an individual building component or system. The multi-disciplinary interactions should explore synergies between otherwise inharmonious design strategies. For instance, increased glazing to enable daylighting needs to be balanced with the objectives of thermal comfort and glare-free visual comfort. Systems integration during design, and monitoring during operations, can help achieve verifiable, deeper levels of building energy efficiency and higher levels of performance. This requires critical integration between the building's physical systems and its information technologies, as described next.

Best Practices for Physical Building Systems. In this guide, the best practices are explored for the four intersecting physical building systems: envelope/passive systems, electrical equipment (plug loads), lighting, and mechanical systems for heating, ventilation, and air conditioning (HVAC).

1. Building Envelope. Planning best practice strategies for passive envelope systems at the beginning of the design process can help achieve large gains at relatively lower-cost. Envelope strategies constitute wall, windows, roof assemblies and shading to avoid exposures to solar heat gain and glare, and to support natural ventilation where possible. These strategies demonstrate even bigger savings for buildings with smaller floor plates that exhibit external load-dominance due to the larger surface-to-volume ratio. Strategies discussed in this guide include the following:

- Optimizing massing and orientation using building energy simulation
- Decreasing envelope heat gain through appropriate construction assemblies, passive construction, insulation, phase change materials, shading, and reflective ‘cool’ surfaces
- Optimizing fenestration and window-to-wall ratios
- Maximizing daylight autonomy without glare

2. Electrical Systems. Plug loads represent a significant 20%–40% of all electricity consumed in Indian office buildings. Strategies must cater to office electronics such as computers, monitors, and printers, and also include task lights, personal or ceiling fans, vertical transport (elevators/escalators), and other process loads. Best practices discussed in this guide for plug loads optimization include:

- Setting aggressive power management settings at the building and device level
- Providing an energy-efficient computing infrastructure
- Pursuing direct current power-based improvements
- Installing appropriate energy monitoring and control hardware
- Encouraging responsible occupant behavior
- Reducing the number, and increasing the efficiency, of plug-in devices

3. Lighting. Lighting represents approximately 10%–25% of all electricity consumed in Indian office buildings. Lighting load is greater for buildings with deeper floor plans or with operations that include evening or night shift hours. Strategies presented in the guide for reducing lighting loads include:

- Optimizing daylighting design
- Implementing highly efficient lighting equipment, luminaires, ballasts, and optimized lighting layouts
- Using lighting sensors and controls

4. Heating Ventilation and Air Conditioning Systems (HVAC). HVAC represents approximately 40%–60% of the electricity consumed in Indian office buildings and provides some of the largest opportunities for energy savings. Best practices detailed in this guide for HVAC energy optimization include:

- Separating the spaces that could be naturally ventilated and developing mixed-mode opportunities, rather than fully air conditioning all built spaces at all times
- Right-sizing equipment, and building-in modularity
- Leveraging opportunities such as district cooling to harness diversity and density
- Using non-compressor cooling or equipment with low greenhouse warming potential (low-GWP) refrigerants
- Considering low-energy cooling options such as night flush, displacement ventilation, under-floor air distribution (UFAD), radiant cooling and evaporative cooling
- Managing loads by decoupling ventilation and cooling
- Providing thermal storage options, both passive thermal mass and active ice storage solutions
- Considering progressive or hybrid mechanical systems
- Adopting flexible temperature setpoints with fans for adaptive comfort

Best Practices for Building Information Systems. Building information systems are critical to the “smartness” of buildings—they provide vital information to integrate the design and functioning of the building’s four physical systems as follows:

- First, by performing building energy simulation and modeling at the design phase, one can predict the building's energy performance and simulated code compliance.
- Second, by integrating building controls and sensors for communications at the build phase, one can manage real-time performance relative to the original design intent.
- Third, by conducting monitoring-based commissioning and benchmarking during the longest, operations phase, one can track building performance and provide feedback loops for better operations as well as insights for the design for the next generation of buildings.

In average buildings, 30% of the energy consumed is actually wasted because of operational inefficiencies (Energy Star 2010). Most commercial buildings *do not* operate and perform at levels intended during design. And this can only be known through measurement of building energy. Fortunately, it is possible to improve efficiencies and reduce costs by identifying whole-building, system-level, and component-level inefficiencies. This can done by installing sensors and meters that measure the energy consumption of a prioritized set of points of end-uses, equipment, zones, and other performance indicators. The collection and analysis of data through an energy management and information system (EMIS) can predict what end-uses or spaces consume how much energy and at what time. This also helps to identify excursions from predicted baselines, sources of energy waste, and inefficient equipment operations. Specific strategies for managing and optimizing energy-efficient operations of a building outlined in the guide include:

- Implementing component-level control strategies
- Implementing HVAC and lighting sensors, monitoring, and controls strategies.
- Designing for meterability and installing smart energy meters and system sub-meters
- Promoting energy data-driven decision-making across the building ecosystem, from the facilities staff to the corporate boardroom
- Promoting sequential energy-saving actions (i.e., schedule, control, repair, audit, and retrofit)
- Training vigilant building managers and facility operators
- Developing green leasing mechanisms.

How to Use the *Building innovation Guide*

The Guide has five main segments, relevant for the various stakeholders to work together to achieve high-performance, as follows:

I. Introduction: This section discusses the challenges, opportunities, and goals for building energy efficiency in India. Context regarding U.S. and Indian commercial buildings is provided as background for diverse audiences.

II. Best Practices: This segment is the heart of the document, and presents best practice strategies for improving energy efficiency. It has three sections:

- Whole Building Approach,
- Building Physical Systems (Improve Envelope and Passive Design, Reduce Plugs and Process Loads, Optimize Lighting Design, Develop low-energy HVAC Strategies, Implement Climate Control Strategies),
- Building Information Systems (Install an Energy Information System).

The over-arching frameworks provided in the sub-section "Whole Building Approach" are relevant across the stakeholder groups– owner/developers, architects, engineers, operators, and building occupants– to define their whole building strategies and targets. The other sub-sections provide detailed information for various building team members e.g. mechanical, electrical, architectural, and energy consultants, but as they relate back to a shared set of metrics at the whole building level. It is worth noting that each of these sub-sections offers "Tables of Metrics" as benchmarks, using a triangulation of modeled data, monitored operational data from exemplary buildings, and expert opinion. These are benchmarks relevant across the office building typology, but a similar method can be adapted for broader application across other building typologies. Further details about modeled data are provided in "Simulation Results" (orange boxes), and about exemplary buildings are provided in "Data Points" (green boxes).

III. Conclusion: This segment provides a synthesizing framework for localization and prioritization of best practice strategies for specific buildings.

IV. Appendix: Glossary of Technical Terms (Appendix 1) provides definitions of terms and abbreviations used in the guide, in an effort to make technical information more accessible. A **List of Exemplary Buildings** and their locations is provided in Appendix 2. The **List of Technologies** (Appendix 3) provides information on potentially relevant technologies and services that can enable energy efficiency. The **List of Simulation Tools** (Appendix 4) provides information on software tools that may be helpful for various aspects of building design.

V. Climate Specific Modeling and Analysis (Appendix 5) provides methodology, assumptions, meta- analysis, and results of building energy simulations with results pertaining to building energy use and occupant thermal comfort. These are conducted in the EnergyPlus building energy software tool, and may be a helpful deep-dive for architects, engineers and energy consultants.

Potential Benefits of the *Building Innovation Guide*

This *Guide* provides a *structured methodology* to enable building stakeholders to deliver high performance throughout the building life cycle. Although these best practices are presented individually, they should not be thought of as an "a la carte" menu of options but recommendations towards a strategy of synthesis and integration. The guide also provides *tangible, quantitative, adoption-ready best performance metrics* for various climate zones in India. The metrics are concrete targets for stakeholder groups to achieve, by capitalizing on the synergies between systems through an integrated design process. These synergies can impel localized and customized solutions for high-performance commercial offices.

The Guide offers a *shared set of values and metrics across the building stakeholder ecosystem.* The primary audiences of the guide are building stakeholders, i.e., building owners, developers, energy modelers, architects, engineers, facility managers, operators, occupants, and auditors. These stakeholders may have questions such as: *How can I design, construct, and operate my building so that it is attractive and productive for the occupants while being economically and environmentally sustainable year after year?* Indirect audiences include building product industry experts with questions such as: "W*hat products will enable high performance and gain market share?"* and policy stakeholders with questions such as: "*How can we transform building stock to be high-performance?"*

The *Guide* provides a *framework for prioritizations* amongst best practice strategies that can empower building stakeholders to develop *lifecycle-based, triple-bottom-line-oriented decision-making processes*. Through adoption and validation of the qualitative and quantitative goals both at the building level, and across their office building portfolios, building stakeholders can also help influence regulations and policy towards a high-performance building stock. The set of best performance metrics can be an effective baseline in the absence of a formal benchmarking program. Energy-efficient processes, resources, and products across the building ecosystem can affect positive change and drive strong environmental and societal impact. These metrics and strategies may also be relevant to other economies across the world with similar contexts.

India is at an inflection point. We believe that this is a prime opportunity for building professionals to set ambitious building benchmarks, and accelerate high-performance in a new generation of buildings. And to propel India into the next frontier- a decarbonized, digitized, and innovative future.

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Introduction

Introduction

This guide provides best practice guidance and energy-efficiency recommendations for the design, construction, and operation of high-performance office buildings in India. The best practices strategies and targets are relevant for high-end office business buildings with primarily air-conditioned spaces and highly glazed facades that are becoming the trend in urban India. It provides recommendations that can help achieve best performance along the three axes of (1) financial efficiency, i.e. construction with faster payback and reduced operating and maintenance costs, (2) environmental sustainability with lowered energy use and reduced greenhouse gas (GHG) emissions, and (3) improved occupant comfort and well-being with enhanced working environments. It also provides ambitious (but achievable) energy performance benchmarks, both for building modeling (design phase) and measurement and verification (operations phase). These benchmarks have been derived from a set of representative best-in-class office buildings in India, building energy simulations from four (out of five) Indian climate zones, and expert opinion. Note that for granular targets, these best practices strategies and metrics should be normalized—that is, localized to account for building characteristics, diversity of operations, weather, and regional materials and construction methods.

Goals

The goal of the *Guide for High-Performance Energy Efficient Buildings in India* is to provide meaningful information on building energy efficiency and useful best performance guidelines throughout a building's lifecycle, from its conceptual design through its operations and maintenance. It focuses on solutions for high-performance air-conditioned offices (one/two/three shift; public/private sector; owner-occupied/tenanted), with spillover benefits to other building types. High-performance pertains to environmental, financial, and social cost, i.e., following a triple bottom-line framework described in Section II: Best Practices.

A previous version of the Guide (Singh, et al. 2013) initiated a set of technical guidelines for approaching building energy efficiency in Indian commercial buildings. This second version extends the previous work as follows:

1. **A set of climate-specific energy performance benchmarks suggested through unique tables of metrics** at both the whole-building and systems levels. This can help decision-makers set energy targets. These tables of metrics have been developed through analysis and synthesis of:
   i. *Extensive climate-specific building energy modeling and assessment,* specifically for Indian climate zones. The current guide presents primary modeled data for "standard," "better," and "best" performance that provides granularity across four (out of five) Indian climate zones.
   ii. *Data collection from additional case studies as further proofs of concept*. The guide includes several new 'data points' for high-performing buildings, including both new construction and retrofit projects.
   iii. *Expert opinion and knowledge* that has played an integral role, from vetting the assumptions for modeling, to identifying relevant market and construction contexts, and feedback on the interpretation of results.

2. **A methodology for a best-practice building life cycle:** This guide presents a structured approach using recommendations for energy conservation strategies, tools and technologies. Stakeholders can use this approach throughout the building life cycle: design, build, and operate, and develop informed decision-making through a triple-bottom-line framework.

3. **A prioritization framework:** This framework aims to help select appropriate localized energy-efficiency strategies and technologies for a custom building, drawing from the streamlined set of potential best practice options presented in this guide.

In a buildings ecosystem that is fragmented, this guide aims to develop a set of common values, vocabulary, and metrics across primary stakeholders (i.e., building owners, developers, energy modelers, architects, engineers, building facility managers, operators, occupants and

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auditors). These stakeholders have questions such as: *How can I design, construct, and operate my building so that it is attractive and productive for the occupants, while being economically and environmentally sustainable year after year?* Indirect audiences include building product industry professionals with questions such as: "W*hat products, technologies, and materials will enable high performance and garner market share?"* and policy stakeholders with questions such as: "H*ow can we transform Indian building stock to be high performance and attain national environmental goals?"*

Challenges

The guide addresses the following inherent challenges in delivering high-performance buildings, and sets objectives in order to overcome them:

1. **Meet the challenge of lifecycle assurance, i.e. ensuring that operations meet design intent.** Developers and builders typically consider project management constraints of first cost, schedule, and scope for a building project design. However the longest part of the lifecycle, i.e.operations, is often ignored in understanding the return on investment. In order to advance investments in energy efficiency, there is a need to move beyond first-least-cost decision-making to become financially and environmentally sustainable. Hence, it is important to incorporate, at the very least, the life-cycle costs from operational energy, waste, facility maintenance costs during decision-making.

Objective 1: *Provide a life-cycle performance assurance process that supports building system integration throughout the building's design, construction, and operation—a departure from the conventional approach. Also offer a triple-bottom-line framework, through which the operational, environmental, and human benefits can support the evaluation of high-performance energy-efficient building technologies and systems.*

2. **Meet the challenge of heterogeneity.** A wide diversity of building types, ownership, costs, services, and comfort levels exists even within the office building typology. As shown in Figure 1 and Figure 7, a portion of the office stock consists of largely non-air-conditioned, indigenous buildings, with lower-cost, low-energy use, that deliver arguable comfort levels. The bulk of the existing stock consists of mass-produced business-as-usual office buildings, referred to as BAU-1 (business as usual-1), and built with reinforced cement concrete construction and brick infill with operable, punched windows and external shade overhangs. These are typically fitted with *ad hoc*, decentralized air conditioning with occupant overrides to provide ostensibly higher levels of services. The character of the Indian economy is still BAU-1, i.e. lower grade office space, in smaller units (such as 1000 m^2 built up on 5000 m^2 plots). The construction cost of this BAU-1 building type is typically around INR 2000-3500/sqft. Lately, the trend is towards centrally air-conditioned, tenanted Class A office buildings or office-retail centers with higher level of service than BAU-1, a high percentage of single-glazed facades or curtain

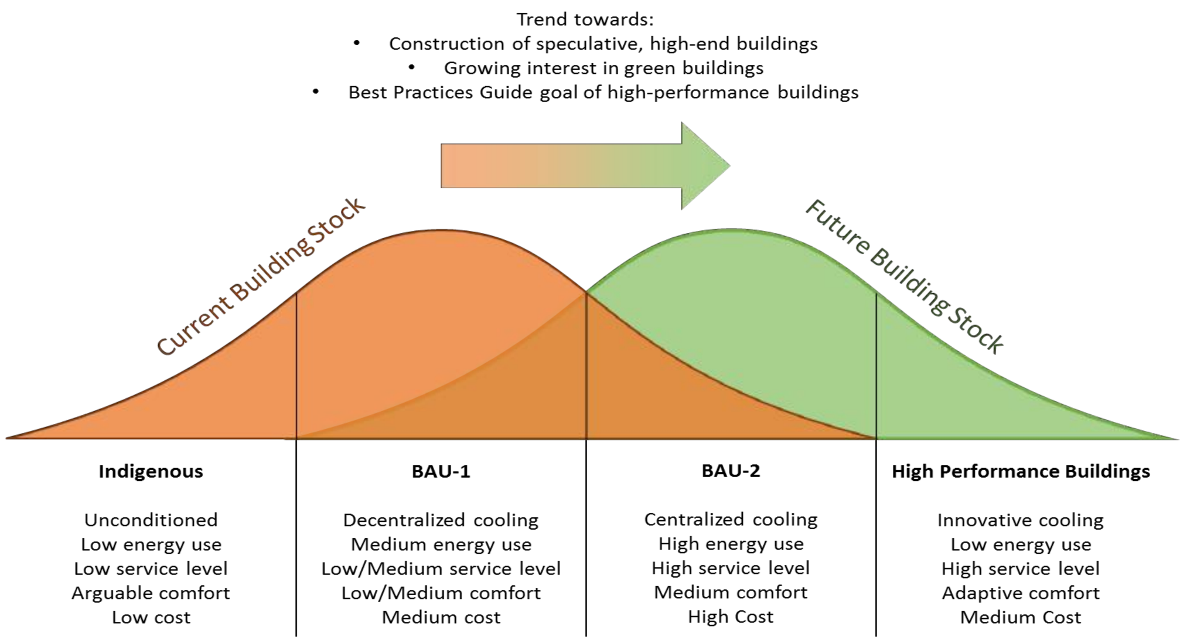

Figure 1: Evolution of the commercial office building stock in India

Introduction

glazing and high plug and lighting loads. We call this typology BAU-2 (business as usual-2). These buildings require more sophisticated systems to control and operate and tend to have higher energy use and waste. The cost of such BAU-2 buildings is typically INR 4000-7000/ sq ft. The market comprises of several smaller developers constructing BAU-1 and fewer larger developers constructing BAU-2 buildings. The market also exhibits a real issue of split incentives and energy billing between owners and tenants that often leaves little incentive for efficiency projects.

Objective 2: *Illustrate best practices across the heterogeneous buildings that provide superior energy performance without compromising on space quality, form, function, levels of comfort, and service. Identify benefits for both owners and tenants that can provide incentive for them to be on-board for energy efficiency.*

3. **Meet the challenge of regional transference, i.e. customizing building energy-efficiency technologies for local or regional needs.** Several building standards and physical systems have been transitioned from western applications without accounting for the regional, climatic, cultural, and economic context of India. Furthermore, de-rating of western equipment is seldom done to account for the Indian environment. On the other hand, several region-specific methods already exist in indigenous buildings that are able to offer higher performance for minimal cost. However, the knowledge and expertise for such methods is getting eroded due to a lack of scientific analysis and documentation. Building stakeholders should consider appropriate and localized energy-efficient strategies with respect to climate, standards, materials, construction, and technological maturity.

Objective 3: *Emphasize and provide empirical or scientific basis for regional, climate-specific solutions to leapfrog transitional systems. These solutions should include high-performance envelope design, daylighting, passive energy construction, mixed-mode operations, adaptive comfort, and low-energy innovative cooling. These 'low-tech' strategies, coupled with relevant novel tools and technologies can address energy efficiency needs.*

4. **Meet the challenge of fragmentation (segregation of buildings, trades, and professionals).** Buildings are typically designed, built, and operated with piece-meal or siloed consideration of various building systems like HVAC, lighting, plug-loads, and construction methods. The knowledge, processes, and applications of integrated technologies are sparsely available and are challenging to incorporate reliably.

Objective 4: *Provide a framework to support whole-building integration of building physical systems and building information technology systems. Also offer a set of common metrics across the building stakeholder ecosystem, enabling early integrated design decisions and deeper operational energy savings.*

5. **Meet the challenge of the grid and increasing renewables:** The Indian context is changing from "unreliable grids" with electricity thefts, blackouts, and brownouts as the norm, to an aspirational "smart grid" that can manage renewables and intermittency. New buildings need grid responsiveness to be future-ready.

Objective 5: *Provide a framework to support the smart grid that includes technologies such as smart metering, sub-metering, and data-driven decision-making. Given the increasing penetration of renewable energy, smart buildings could provide several valuable services to the grid including demand response and ancillary services. Smart building energy management and control systems can enable these services. Also recommend a sequence of strategies: first reducing energy demand; next, enhancing delivery efficiency of energy for active cooling, lighting and appliances; and finally replacing carbon-intensive grid energy sources.*

Contexts: Buildings' Energy Use in United States and India

In this section we compare typical buildings in India and the United States. Both countries have had differences in their construction, building systems, levels of controls and automation, metering and monitoring, and types of energy sources and systems (Table 1). But with globalization, these differences are starting to be blurred. Furthermore, both countries acknowledge the challenge of high building energy consumption and waste, have established aggressive targets for achieving building energy efficiency, and can benefit from bi-directional learning.

India enacted an Energy Conservation Act (ECA) in 2001, with the goal of reducing the energy intensity of the Indian economy. The ECA was coupled with the establishment of the Bureau of Energy Efficiency in 2002 and the rollout of the voluntary Energy Conservation and Building Code ECBC 2007. The recent updated code, ECBC 2017 has adopted a three-tier system comprising of the ECBC, ECBC+, and SuperECBC tiers, in ascending order of efficiency. Adherence to the minimum requirements stipulated for the

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ECBC tier of efficiency demonstrates compliance with the code, while the other two efficiency tiers are voluntary in nature. This feature was added to prepare the building industry for adapting to more aggressive energy-efficiency standards in coming years and to enable the market to adapt (BEE 2017). The ECBC provides specific targets for "Energy Performance Index" (EPI) levels. The EPI is the metric for site energy consumption per unit area, measured in kilowatt-hours per square meter per year [kWh/m^2/year]. This is similar to the term "Energy Use Intensity" (EUI) used in the United States, measured in thousand of British thermal units per square foot per year [kBtu/sqft/year]. India's building landscape has multiple codes (mandatory National Building Code or NBC, voluntary ECBC), green rating programs (IGBC, LEED, GRIHA), and green labeling (BEE Star Rating) with design energy targets.

On the other side of the ocean, the U.S. Department of Energy reported that U.S. residential and commercial buildings used 40% of the nation's total energy and 70% of the electrical energy, resulting in an estimated annual national energy bill of $430 billion in 2014. There is about 87 billion square feet of commercial space in the U.S., spread across more than 5 million commercial and institutional buildings (EIA, 2012). Commercial electricity consumption accounts for about 36% of total U.S. electricity demand. This sector is very diverse and includes office, retail, health care, education, warehouse and several other types of buildings, ranging in size from a few thousand to millions of square meters per building. Four types of commercial buildings account for more than 50% of total delivered electricity consumption—office, mercantile, education, and health care. From 2013 to 2040, commercial end-use intensity, measured in kWh per square foot, is projected to decrease by 8.8%. This decrease is led by a significant decline in the electricity intensity of lighting, but is also offset by a significant increase in miscellaneous electric loads. (Schwartz, et al 2017).

The state of California has also issued an aggressive goal for new commercial construction of zero net energy (ZNE) by 2030. In fact, the California Energy Commission (CEC) investments in building and appliance efficiency research have contributed to fifteen Title 24 building energy code changes between 2005 and 2016, which are expected to save more than $10 billion by 2025. The CEC adopted a tiered approach to enabling and encouraging ZNE construction—the base tier being the traditional mandatory standard that increases in stringency with each code cycle, and voluntary "reach" tiers for advanced levels of energy efficiency, increased self-generation capacity, and grid harmonization tools such as demand-response controls and energy storage (CEC 2015).

The Architecture 2030 challenge puts forward a goal of 69 kWh/m^2 (22 kBtu/sqft) for the building stock in 2030 (American Institute of Architects 2017), and net zero for new buildings. Energy retrofits and efficiency projects have helped best-in-class buildings achieve ambitious targets of 35–45 kWh/m^2 (11–15 kBtu/sqft)

In India, a study from a United States Agency for International Development USAID program (ECO-III 2011) shows that the average site energy performance index for an office building in India is 220–250 kWh/m^2 (70–80 kBtu/sqft). Best-in-class office buildings across the country are pursuing an aggressive range of targets between 65–90 kWh/m^2 (~20–29 kBtu/sqft) (Figure 2).

This guide considers the above targets, whereby air-conditioned buildings should provide superior levels of service and comfort, with ideally only a manageable increment of energy use as compared to unconditioned buildings. It presents robust climate-specific, whole-building, and system-level metrics that utilize building energy simulation modeling results and measured data from existing high-performance buildings as benchmarks. Building teams can consider these benchmarks for setting their own energy efficiency targets.

In both India and the United States, selecting and bundling the appropriate energy-efficiency measures to achieve these building energy performance targets depends on:

1. Know-how of materials, tools, and technologies
2. Cost of integration and implementation
3. Impact on energy savings

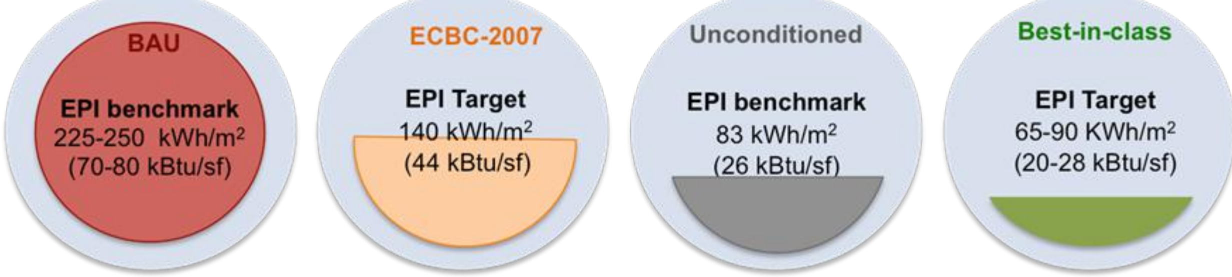

Figure 2: Comparative energy performance index (EPI) (annual) of an Indian business-as-usual (BAU) building, targets from ECBC-compliant, unconditioned and best-in-class air-conditioned office buildings (Sources: ECO-III 2011; ECBC-2007; Singh et al 2013).

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Table 1: Characterization of U.S. and Indian offices buildings

	United States	India
Commercial Construction	Primarily retrofit	Primarily new construction
Construction Type	Steel and glass	- Reinforced Cement Concrete (RCC) with masonry infill for stock buildings; - High percentage of glass facade for high-end buildings
Energy Source	- Natural gas; - Grid electricity; - Renewables or Green Power	- Electricity grid that is often unreliable; - Diesel generator as grid back up; -Renewables
Level of Control and Automation	Semi-automated or fully automated, using Building Management Systems (BMS)	- Primarily manual control for the building stock; - Semi-automated for new buildings - Automated using BMS for small percentage of high-end buildings
Energy Metering and Monitoring	At least one smart interval whole-building meter, some sub-meters	Manually read and recorded meters; manually read utility bills
Mechanical Systems	Fully air conditioned; centralized system; Heating is common using furnaces	Mix of natural and mechanical cooling and ventilation; or fully air-conditioned with centralized system in newer buildings; typically, no heating
Cost of Construction	Cost of labor similar to cost of construction materials/hardware	Lower cost of labor
Occupancy	18 m²/person	6 m²–10 m²/person (for Tier 1/2 city)

Targets need to be understood relative to building typologies in both countries. Buildings in India have been traditionally built with high thermal mass (brick, stone masonry) and have used natural ventilation as their principal ventilation and cooling strategy (Table 1). However, contemporary office buildings are energy intensive, increasingly being designed as aluminum and glass mid- to high-rise towers (Figure 3 and Figure 7). Their construction uses resource-intensive materials, and their processes and operations require a high level of fossil fuel use.

Moreover, a significant share of existing and upcoming Indian office space caters to high-density occupancy and multiple-shift operations. While the average U.S. government and private-sector offices have an occupant

Figure 3: Typical special economic zone buildings

Sears Holdings offices occupy three floors of a multi-tenant SEZ in Pune.
(Photo source: Sears Holdings India Facilities Team)

density of 20 m^2/occupant and 30 m²/occupant (215 and 323 sqft/occupant), respectively, Indian offices have a typical density of only ~6–8 m²/occupant (65–86 sqft/occupant) in Tier 1 cities that have high real estate costs and ~10 m²/occupant (108 sqft/occupant) in Tier 2 cities. Smaller non-speculative institutional buildings typically have an occupant density closer to U.S. standards, ~18 m²/occupant (194 sqft/occupant). At the other end of the spectrum, business processing office spaces have three-shift hot seats—a situation that, while conserving space because of its multiple shift usage, also leads to substantially higher EPI levels (See Figure 4 for comparison of EPIs across various building types). Additionally, with the increased demand for commercial office spaces from multinationals and IT hubs, and the current privileges being accorded to special economic zones (SEZs), the trend is towards larger buildings with fully conditioned spaces being operated using international ASHRAE standards, seldom transforming the applicability of these standards to be relevant for Indian climate and culture. These new buildings are dramatically increasing the energy footprint of the Indian office sector.

Paradigmatic Growth in India

U.S. buildings consume ~40% of the national energy use of 97 quads (EIA 2018), the highest of all sectors. Similarly, Indian buildings consume 30% of the national energy use of 24 quads and this is growing by 8% annually (MOSPI 2017).
India's commercial building footprint alone is projected to triple to ~1.7 billion m^2 (19 billion sqft) by 2030. In conjunction, projections also indicate that Indian building energy use will triple by 2030, fueled by explosive growth in building footprint and rising living standards that lead to

higher levels of building services *per capita* (e.g., lighting, plug loads, cooling). To give a historical perspective, in 2004–2005, the total commercial stock floor space was ~516 million sqm (5.6 billion sqft), and the average EPI across the entire commercial building stock was about 61 kWh/m^2. In comparison, in 2010, the total commercial stock floor space was ~660 million sqm (7.1 billion sqft) (Figure 5), and the average EPI across the entire commercial building stock almost tripled, to 202 kWh/m^2 (ECO III, 2011). Thus, there are two intertwined effects: an increase in total building area and an increase in the EPI that will cause explosive growth in energy use.

In the next Section II, Best Practices- the *Guide* offers recommendations to address and manage this growth at a per-building level.

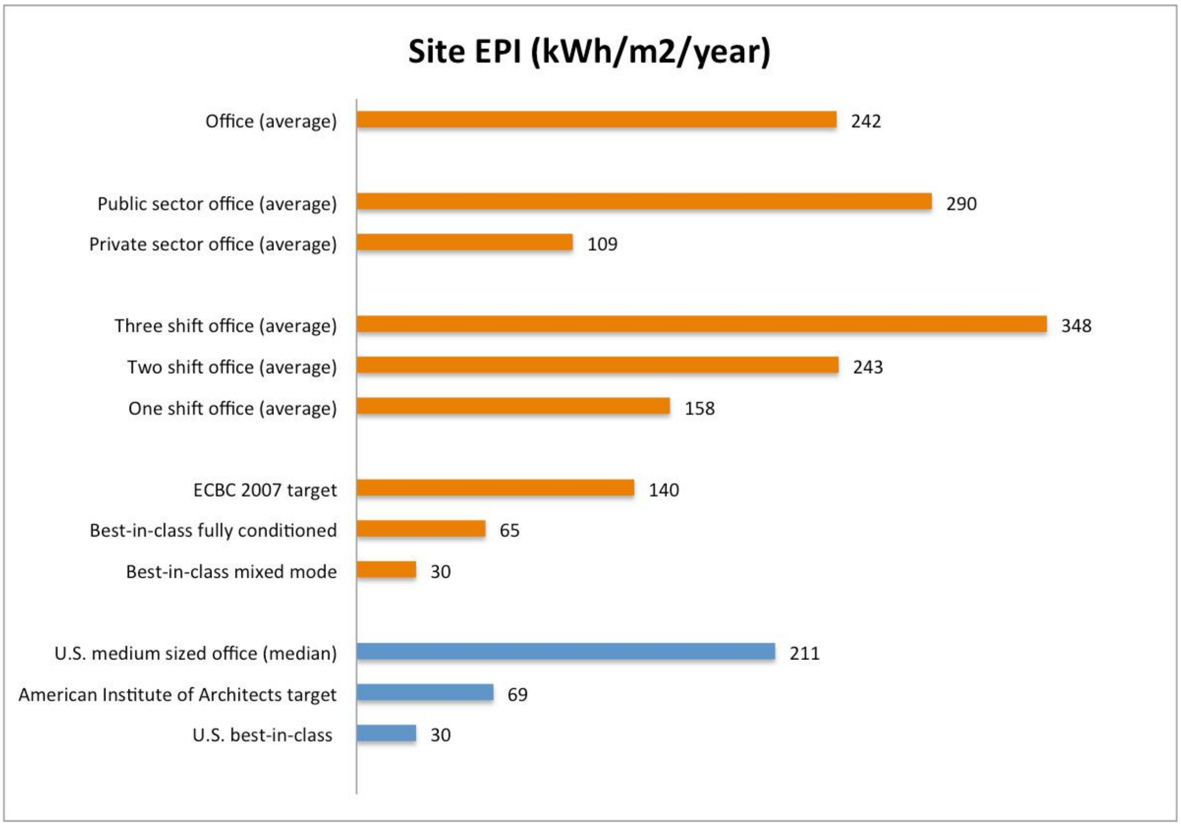


Figure 4: EPI (kWh/m2/year) of various types of office buildings in India and the U.S. (ECO-III, 2011; Energy Star, 2016; AIA, 2017).

Introduction

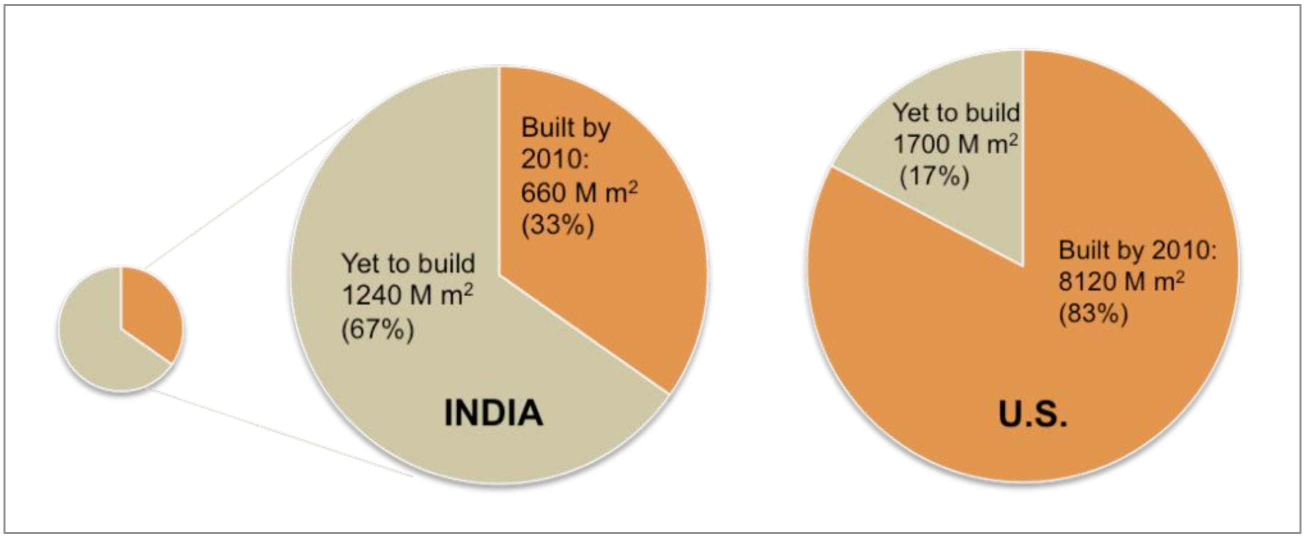


Figure 5: 2030 floor-space forecast for the commercial buildings sector (ECO-III 2011) (U.S. Energy Information Administration, 2012).

~3X

Explosive growth in commercial building footprint

100M m^2 added/year

(ECO III)

~3-5X

Energy Performance Index (EPI) of typical buildings

From 60 kWh/m^2 to up to 300kWh/m^2

~3X

Space use intensity

Multiple-shift buildings and high occupancy density

6-8 sq m/occupant

Figure 6: Drivers for the growth in office building energy footprint in India

Introduction

Figure 7: Examples of Indian office buildings.

Top left: typical BAU-1, older reinforced concrete building with deep shades, punched window openings, and *ad hoc* window split air-conditioning units (picture source: authors).

Top right: typical BAU-2, new high-end office building with international curtain wall esthetic (picture source: Zastavski).

Bottom left: typical business processing office space with dense occupancy and “hot seats” to accommodate multiple shifts at the same work station (picture source: Reuters).

Bottom right: levels of services are shifting to align with international practices (picture source: Glassdoor).

Best Practices

Best Practices

The best practices focus on guidelines for improving energy efficiency in commercial office buildings while achieving economic and environmental sustainability and occupant comfort. These guidelines leave plenty of freedom for the design team, rather than limiting them with rigorous requirements or prescriptive measures.

Discussion

Developers and builders can achieve typical project management constraints, below, while ensuring the design and operations of a high-performance building (Figure 8):

1. **Cost:** Return on investment (ROI) from energy-efficiency measures and technologies, and how economic value and profit can be maximized.
2. **Schedule:** Building, installing systems, and initiating occupancy, with an emphasis on speed of completion.
3. **Scope:** Optimum level of service expected by potential clients, and whether it is an owner-occupied or speculative, tenanted office building.

However, in order to advance investments in energy efficiency, there is a need to move beyond first-least-cost decision-making. Building project teams must embrace, at the very least, life-cycle costs including operational energy and facility management costs. Life-cycle economic cost accounting can be decisive for energy-efficient decision-making in new construction projects and low-cost retrofits. Particularly in retrofit projects with moderate- to high-cost implications, the added calculation of environmental and human cost benefits may be critical, especially in existing buildings where the economic benefits of cost differentials do not play a role. Known as triple-bottom-line accounting, the net present value calculations of operational, environmental, and human benefits can support customized evaluation of high-performance energy-efficient building technologies and systems.

A **triple-bottom-line sustainability framework** offers a comprehensive focus on a project's impact based on the financial cost (profit), environmental cost (planet), and social cost (people: i.e., occupant comfort and productivity). The first bottom line is pertinent to the economic cost, entailing simple paybacks for energy retrofit measures—with energy and facility management savings. When the second bottom-line, or environmental, benefits of reduced environmental pollution are included, simple paybacks are accelerated. Most strikingly, when human benefits are included—from reduced headaches and absenteeism to improved comfort, task performance, or productivity—paybacks for investments in energy efficiency are dramatically reduced (CBERD 2018).

Figure 8: Triple-bottom-line framework:
The intersection of the triple bottom line cost-benefit framework (people, planet, and profits) with the traditional project management framework (cost, schedule, and scope).

The introduction of triple-bottom-line accounting for decision-makers in the built environment may be the most critical catalyst for investments in building energy improvements.

This Guide offers an intersection between both the project management and triple-bottom-line (TBL) frameworks as the best practice approach between practical market dynamics and sustainability. The guide also focuses on hard, technical metrics based purely on the energy performance of the building pertaining to its physical systems, and, thereby, both its economic and environmental impact. **Tables of quantitative metrics** (Tables of Metrics) are provided throughout the guide to enable "apples-to-apples" comparisons and provide technical targets for whole buildings and physical systems across the board. Additionally, Appendix 5, *Climate-Specific Modeling and Analysis for High-Performance Indian Office Buildings,* provides simulation energy results that include occupant comfort, touching upon the third bottom line. Economic cost-benefit calculations are beyond the scope of the current guide and would be a driver for future research and analysis.

In the tables of metrics, the "standard data" references number from ECO-III (bilateral project agreement between the Government of India and the United States), benchmarking, and the National Building Code of India. These "standard" data are representative of the energy performance of the median (50th percentile) of commercial buildings in India. The BAU construction norm assumed across Indian commercial buildings is reinforced concrete construction (RCC), with 23-cm-thick brick or 20-cm-thick (autoclaved aerated) concrete block wall infill, minimal insulation, and a 30%–40% wall-to-window ratio using single-glazed units. This construction type is referred to as BAU-1 (Figure 1). BAU-2 buildings have larger glazed facades, fully air-conditioned spaces, and large computer loads, typology representing the Class A high-service private-sector office building. This typology is experiencing one of the highest growth rates in India and presents some of the greatest energy-efficiency opportunities.

For "better" practice, compliance with ECBC is referenced, and such "better" buildings are representative of the top quartile (i.e., the top 25th percentile). For the "best" practice (the highest level of efficiency that can be achieved in the building), the top fifth percentile, or best-in-class buildings, are referenced. The guide illustrates best-practice innovative strategies and technologies across office buildings in India. It focuses on cross-cutting, whole-building strategies, and system-level measures for each energy load breakdown (i.e., HVAC, plugs, lighting, and envelope heat gain).

Notes in reference to the tables of metrics provided in the guide that use monitored and modeled data, and expert opinion as a backbone for the metrics

1. Modeled data was developed using building energy simulations in different climate zones of India (detailed in Appendix 5. The simulations were conducted using a Indian office building archetype as a starting point, and best practices are layered. This approach allows the simulation results to be applicable across the office building sector. It also helps to streamline the custom strategies that would be custom-modeled that would be done on a per- building level.
2. The monitored data is from representative buildings are in four of India's five climate zones. Please refer to the exemplary buildings table in Appendix 2 for more details on each representative building.
3. The metrics have a baseline assumption of an average 8- to 10-hour working day, five days a week. These normalize the data for comparisons independent of the number of shifts and occupancy.
4. IT-intensive office spaces tend to have a higher EPI than buildings that house non-IT operations. Plug load management is critical in IT buildings. Metrics should be normalized to account for this fact.
5. Speculative commercial buildings (i.e., leased buildings) tend to have higher energy consumption since the building is not "owner-occupied" or "built-to-suit" for the occupant. Low first costs create direct benefits for the owner-developer, and low operating costs create direct benefits for the tenant. If developers and (anchor) tenants work together, energy and cost efficiencies can benefit both stakeholders.

In the following sections, the best practices are presented individually. However, they should not be thought of as an "a la carte" menu of options. Just as no two buildings are identical, no two owners will undertake the same energy management program. It is also not likely that all the listed best practices will be included, since some of them will conflict with each other. Rather, designers, engineers, developers, facility managers, and tenants need to work together to capitalize on the synergies between systems (e.g., a reduced lighting load can also reduce the building's cooling load), and curtail potential clashes between inharmonious systems and schedules.

Simulation

In addition to existing building data, energy simulation results offer a significant source of information that cannot be entirely acquired with measured data. One of the main advantages of using building energy simulation is the possibility of establishing robust baselines and incorporating strategies incrementally, thus evaluating their impact on energy consumption and comfort separately. Simulation can bridge the data gap for existing buildings when the savings offered by a particular solution have not been measured in every Indian climate zone. Simulation also helps to identify sweet spots through integrated parameters, to find the best possible clusters of i.e. best practices for each climate zone. On the other hand, building energy simulations should not be the sole source of data. Simulations rely on simplifying complex building systems and inherently involve a band of uncertainty in the results (Chong et al, 2015). Hence, this *Building Innovation Guide* attempts to balance simulated data with operational data from buildings and expert opinion. Further, the models in this Guide are built to be generic in order to have a broad applicability across the offices building typology. In reality, every building is a snowflake – being different in form, function, and loads. Hence, custom modeling may be required at the building level to get most benefit, but this effort can be effectively streamlined based on the broad principles and recommended strategies offered in this *Guide*.

A variety of tools can be used to simulate the performance of a building or a single piece of energy equipment. An extensive list of tools and their respective capabilities is outlined in work by Crawley, Hand, Kummert, and Griffith (2005) or on the U.S. Department of Energy repository of tools (http://www.buildingenergysoftwaretools.com/). A shorter list of the most relevant tools can be found in Appendix 4: *List of Simulation Tools*. This work used EnergyPlus 7.2 to create and simulate the models.

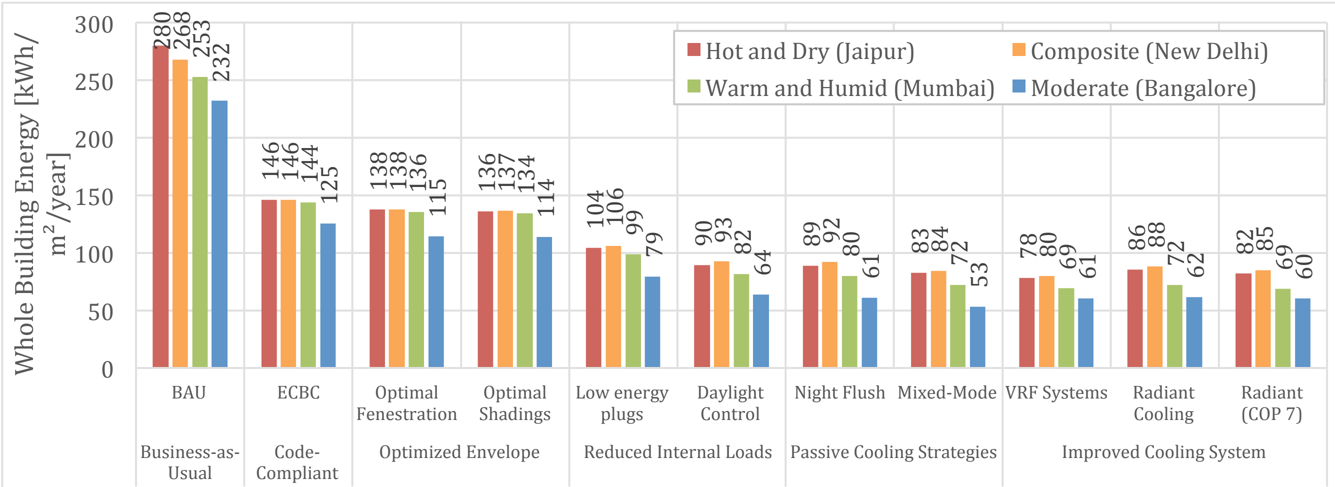
A total of 44 models were developed for this study, corresponding to one BAU baseline model, one ECBC 2007 code-compliant baseline, and nine independent best practice ECM models, each for four different climate zones represented by four major Indian cities: Bangalore (Temperate), Jaipur (Hot and Dry), Mumbai (Warm and Humid), and New Delhi (Composite). The parameters used in each model were chosen to be representative of common practice in India. These simulation results offer the possibility to compare the efficiency of solutions in different climate zones. The energy consumption of the buildings modeled is presented as a benchmark of theoretically achievable performances for medium-sized office buildings in India, with replicability across other building typologies.

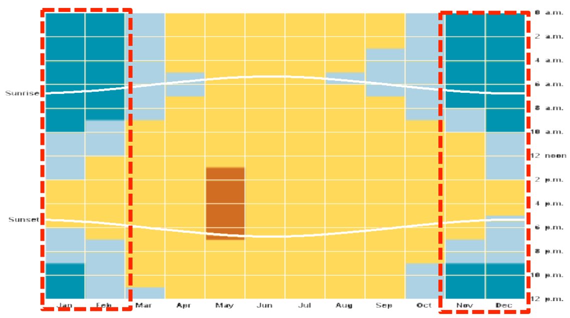
Figure 9 presents an overview of the simulation results and various meta-analyses conducted through this study, and their relevance to energy design and operations. The energy use results are congruent with the first version of the *Best Practices Guide for High-Performance Indian Office Buildings* (Singh, et al. 2013). The difference in energy use between the BAU models and ECBC models represents a reduction of 40%–50%, which compares well with the results of *ECBC User Guide* (ECBC 2007).

The modeling results use three primary metrics:
1. Total energy consumption per unit area, or Energy Performance Index (EPI).
For the Builder/Owner/Operator, a lower EPI represents lowered capital expenses, operations and maintenance cost, and replacement cost.
2. Total heat gains and losses of the building
For the Architect/Engineer, lower external heat gains can imply greater flexibility and efficiency for envelope and cooling systems.
3. Occupant thermal discomfort (predicted percent dissatisfied or PPD).
For the Facility Operator/ Occupant, better thermal comfort can imply fewer complaints, better occupant health and productivity, and enhanced tenant retention.

For detailed results, see Appendix 5 *Climate-Specific Modeling and Analysis for High-Performance Indian Office Buildings.*

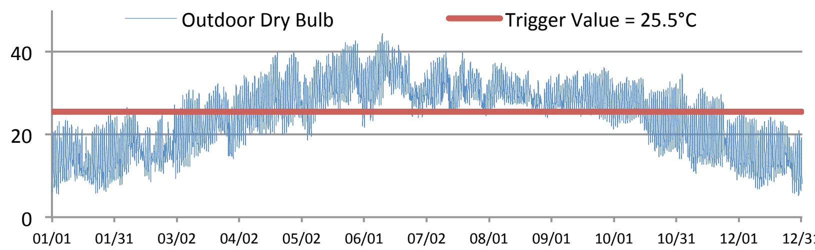
Best Practices





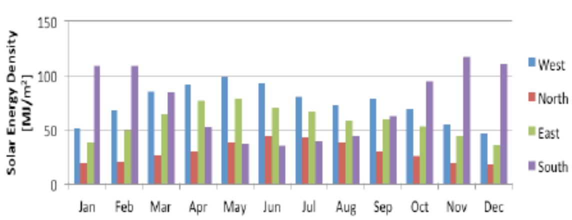
Meta-analysis 1, Thermal comfort analyses using Adaptive and Fanger comfort models.

Benefit: Flexible temperature setpoints and HVAC size reduction



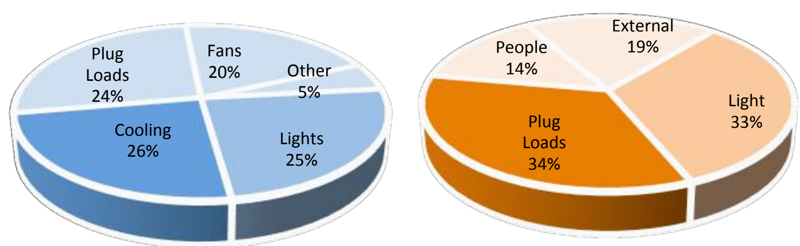
Meta-analysis 2, Night flush potential for the various climate zones.

Benefit: Can enable opex opportunity for HVAC system turndowns



Meta-analysis 3, Analysis of solar loads through windows per orientation.

Benefit: Enables capex opportunity for optimizing glazing and shading



Meta-analysis 4, Analysis of internal thermal loads: Proportion of lighting and plug loads in energy demand (left) and heat gains (right)

Benefit: Enables climate- independent strategies for lighting and plug load reduction – such as EPI reduction by 40% even in a BAU building

Figure 9: Highlights from building energy simulation study. Please see Appendix 5 for detailed results.

Figure 9a (top row): Simulation results per climate zone. These indicate baseline energy consumption and energy savings potential from best practices suites BP1 to BP7.

Figure 9b (middle and bottom row): Illustrative charts from meta- analysis studies that inform the overarching simulation study.

Notes: (1) ECBC 2007 is used for the code-compliance models. (2) All simulation results have an inherent band of uncertainty; numbers should not be considered absolute.

Section 1: Whole Building Framework

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Use a Whole-Building Approach

Early in the project, the focus should be on maximizing energy efficiency of the building as a whole, not just on the efficiency of an individual building component or system. Buildings are the most energy efficient when designers and operators, owners and tenants ensure that systems throughout the building are both efficient themselves and work together efficiently. Optimal energy efficiency can be achieved through an integrated design process (IDP), with stakeholder buy-in right from the beginning at the conceptual design phase.

Develop a Whole-Building Life-cycle Performance Assurance Framework

Whole-building system integration (Figure 10) throughout the building's **design, construction, and operation** can potentially ensure high performance, both in terms of energy efficiency and comfort/service levels. This is represented as the Lifecycle Performance Assurance Framework. Lawrence Berkeley National Laboratory, USA (LBNL) along with their partner institutions, conceptualized the Lifecycle Performance Assurance Framework through U.S. and Indian stakeholder engagements during the U.S.-India Joint Center for Building Energy Research and Development (CBERD) program, funded by the U.S. Department of Energy and the Government of India (cberd.org 2012).

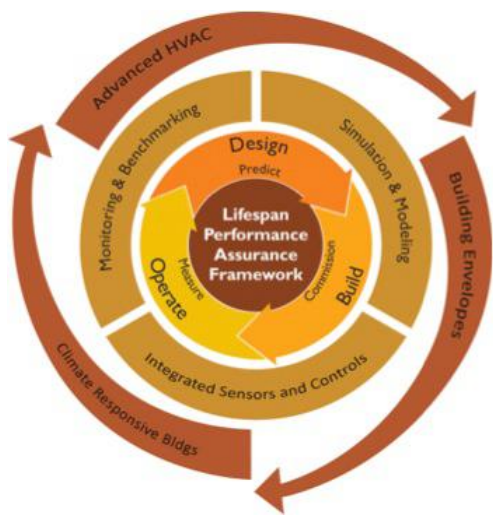


Figure 10: Lifecycle Performance Assurance Framework

At each stage of the life cycle, it is critical to ensure integration between the buildings' **physical systems** and **information technologies**. The building physical systems include envelope, HVAC, plugs, lighting, and comfort technology systems. The building information technologies provide information on the design and functioning of the building physical systems.

First, by performing **building energy simulation and modeling** at the design phase, a building's energy performance and code compliance can be estimated. This is especially relevant for certain strategies that may not be immediately attractive, but may become so through further analysis. Second, by building in **controls and sensors for communications,** real-time performance can be tracked at the building phase, relative to the original design intent. Third, by conducting **monitoring-based commissioning and benchmarking** during operations, building performance can be tracked, buildings can be compared to peer buildings, and operational feedback can be provided. Thus, the use of building IT provides indicators at all three stages of the life cycle to help predict, commission, and measure the building performance and its

Best Practices Use a Whole Building Approach

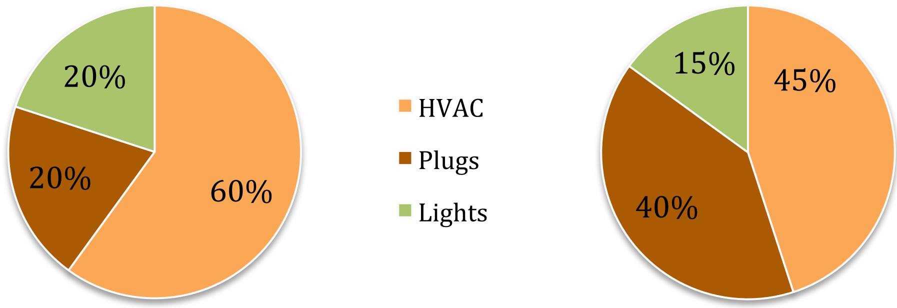


Figure 11: Electricity end-use consumption for a typical commercial office (left) and an IT office (right) in India

systems and components (see section on "**Implement an Energy Information and Management System**" for more information).

To design and operate an energy efficient building, a design team should focus on the energy performance based on modeled or monitored data, analyze what end uses are causing the largest consumption/waste, and apply a whole-building process to tackle the waste. For instance, peak demand in high-end commercial buildings is typically dominated by energy for air conditioning. However, for IT operations, the consumption pattern (and hence the "end-use pie") is different. In the latter, cooling and equipment plug loads are almost equally dominant loads. The equipment plug load is mostly comprised of uninterrupted power supply (UPS) load from IT services and computers, and a smaller load is from raw power for elevators and miscellaneous equipment. Figure 11 shows typical energy consumption end-use pies (baseline data from Greenspaces design team and monitored data from the Infosys Green Initiatives team)—energy conservation measures need to specifically target these end uses. A utility bill does not provide enough information to mine this potential: metering and monitoring at an end-use level (at a minimum) is necessary to understand and interpret the data at the necessary level of granularity. By doing so, one can tap into a substantial potential for financial savings through strategic energy management.

Use a Triple-bottom-line analysis framework for decision-making

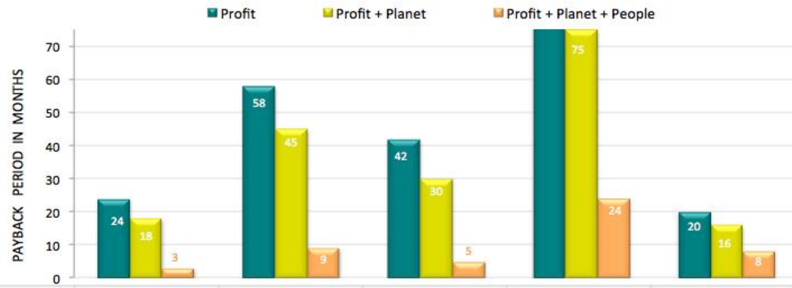
Energy represents 30% of operating expenses in a typical office building: it is the single largest (and most manageable) operating expense in offices. As a data point, in the United States, a 30% reduction in energy consumption can lower operating costs by $25,000 per year for every 5,000 square meters of office space (California Public Utilities Commission 2012). Another study of a national sample of U.S. buildings revealed that buildings with a "green rating" command, on average, 3% higher rent and a 16% higher selling price (Eichholtz, Kok, & Quigley 2009). Additionally, occupiers and investors use tools such as green rating systems as a guide for selecting properties for leasing or acquisition. In mature markets, the cost premium it takes to implement the ECMs ranges from 1%–6%. In India, the cost premium ranges from 6%–18%, with average payback of 3–7 years. In India, a cost-benefit analysis of a particular energy efficient building revealed a payback of 2–3 years on the cost (Jones Lang Lasalle JLL 2008).

Apart from tangible energy benefits, ECMs can enhance the comfort and attractiveness of the environment. Optimizing daylighting and lighting can provide better views and improve the visual acuity of the occupants. Well-designed mechanical systems can improve indoor air quality while reducing initial equipment costs and operating energy. Workplace productivity can be enhanced by providing individual light level controls for the task and direct access to daylight and views. Given that the bulk of working time is spent indoors, a better indoor environment can boost worker performance and reduce sick leave. Cost-benefit analyses indicate that improving indoor temperature control and increasing ventilation rates can be highly cost effective, with benefit-cost ratios as high as 80 and annual economic benefits ~$700 per person (Fisk 2007).

Green investments that increase employee wellness and productivity can have exponentially greater value. JLL offers a "3-30-300" rule of thumb that organizations typically spend approximately $3 per square foot per year for utilities, $30 for rent and $300 for payroll. While these figures are just archetypes, they are useful in providing an order of magnitude between the three areas of expenditure – A 2% energy efficiency improvement would result in savings of $.06 per square foot but a 2% improvement in productivity would result in $6 per square foot through increased employee performance. (JLL 2014)

A triple-bottom-line (TBL) analysis was conducted by the CBERD research team (Figure 12), wherein 15-year life-cycle calculations were done. Five energy-efficiency

Best Practices Use a Whole Building Approach



		High VLT Glass	Light Louvers	Dimming Ballasts	Awnings for shade	Operable Windows
Economic Consideration	**First cost per employee**	$45	$114	$70	$330*	$120
	Annual Energy savings:					
	Energy Savings (%)	35%*	35%*	30%*	20%**	35%**
	Energy savings per employee	$24	$23	$20	$40	$70
	ROI (Profit)	52%	20%	28%	12%	58%
Environmental Consideration	Given Annual Energy savings in kWh	130	130	113	224	392
	Annual Environmental Benefits:					
	Air pollution emissions	$6.7	$6.7	$5.8	$11.4	$20.0
	Water Savings	$0.3	$0.3	$0.2	$0.4	$0.8
	ROI (Profit + Planet)	68%	26%	38%	16%	76%
Social equity Consideration	**Annual Human Benefits**					
	Productivity increase (1- 4%)	$320	$240	$300	$100	$240
	Reduction in absenteeism (6 -14%)	$24	$24	$24	$24	$10
	ROI (Profit + Planet + People)	825%	258%	500%	54%	284%

* lighting energy savings **cooling energy savings

Figure 12: Triple-bottom-line calculations for investment in energy-efficient façades.

related façade investments were analyzed using Indian first costs, energy savings, and environmental benefits, and combined with international (due to lack of availability of Indian data) findings on health and productivity benefits. This analysis revealed that the return on investment ranged from 52% to more than 500% (Loftness, et al. 2014).

Develop a sequential approach

Whether in the United States or India, a certain minimum level of improvements to energy efficiency often can be attained through no-cost or low-cost ECMs that lower the first costs of construction and equipment.

Start with a careful selection of regional, low-embodied energy that *use* less energy and fewer resources to make, transport and build—this reduces first cost and environmental cost.

Next, target operational energy savings. All best practices begin with reducing conditioning and plug-load energy demands before pursuing innovative conditioning and plug-load strategies. This process essentially follows a best practice sequential approach (Figure 13): implementing a suite of measures that reduce internal loads (e.g., optimizing cooling levels, latent loads, lighting, and equipment loads) as well as external heat gains (e.g., optimizing envelope for insulation, reduced infiltration, and optimized glazing). Only when the demand load is reduced to an optimum level, should other ECMs be considered (systems efficiency, controls, and plant design improvement).

Finally, the design team can then add value by the provision of renewables, waste heat recovery, and other “supply side” measures that are beyond this guide’s scope.

In addition to operational cost savings, optimizing building loads can also lead to lower first costs. By targeting low-hanging fruit through early-stage ECMs, the first costs saved through these can be applied toward more expensive technology solutions like high-quality glazing or sensors that can further the energy and cost benefits later in the building life cycle.

For example, cost saving gained by reducing the number of lighting fixtures and increasing daylight levels in a space can be used to install daylight sensors. The latter can provide a large cost benefit with a relatively short payback time by driving down the operational hours for artificial lighting.

Using systems integration to apply ECMs at the whole-building level using systems integration can greatly benefit the EPI of a building. Figure 14 shows whole-building energy use metrics for: Standard (business-as-usual), Better (from ECBC/better-performing buildings), and Best practices (from best-in-class Indian commercial buildings)

Data Point

Development Alternatives Headquarters, New Delhi: Lower Embodied Energy (Data Point 1) at the whole-building level.

The three metrics: annual energy use per square meter, peak energy use per square meter, and annual energy use per occupant are each significant for decision-makers. Annual energy use per square meter, also known as EPI, is valuable since it provides a view into the running energy consumption of the building normalized to the size. Peak energy use per square meter is critical to understand a building's requirement for power supply, backup power supply, mechanical system sizing, and design of thermal storage. Blackouts and brownouts are related to peak loads of buildings—peaks directly influence grid responsiveness, and ultimately sustainable grid design. The annual energy use per full time equivalent is important as it takes into account the energy consumption per person, which normalizes the energy to the density of occupancy.

This process is illustrated through the best practice strategies and data points that follow in the subsequent sections. **Data points** provide examples of Indian high-performance office buildings where a best practice strategy or cluster of strategies has been used: from the selection of appropriate building materials to the reduction of embodied energy during new construction to the implementation of high-priority operational strategies.

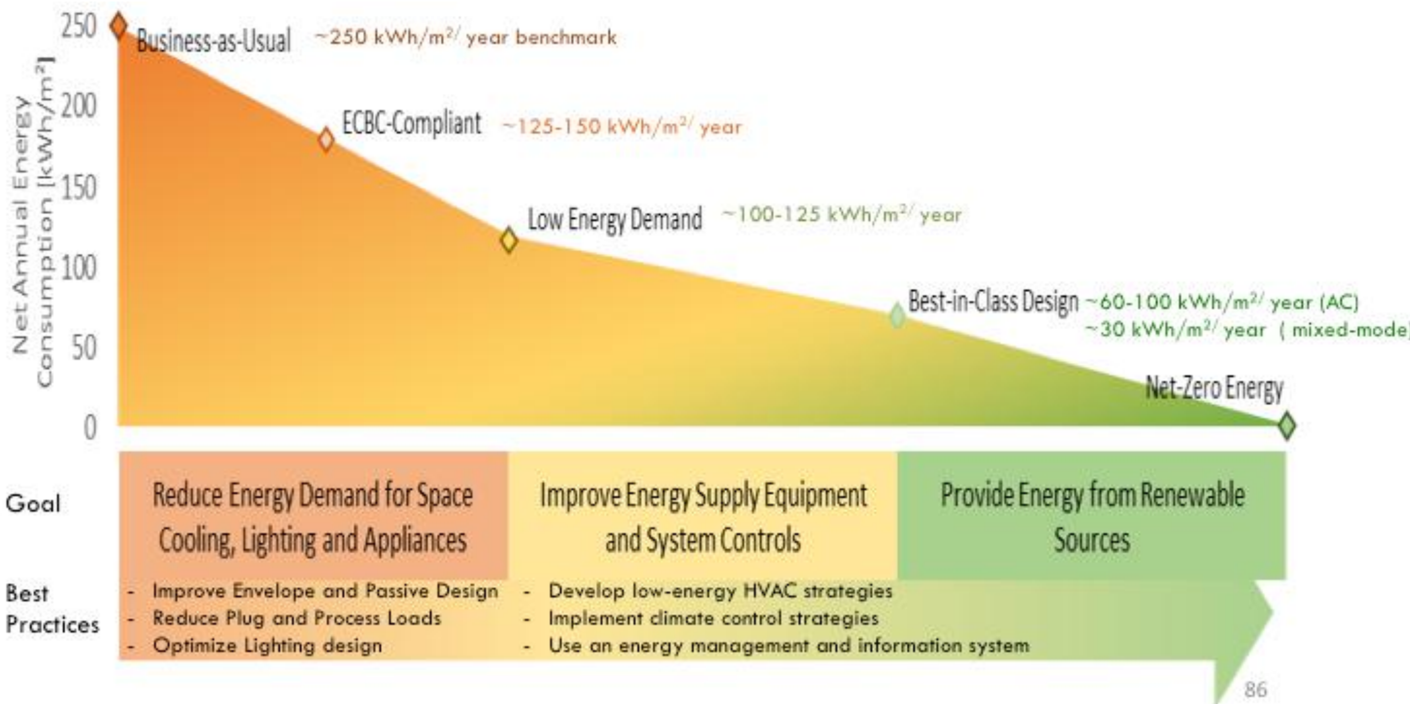


Figure 13: Sequence of approaches to create a set of integrated energy conservation strategies

Table 2: Table of Whole-Building Metrics. Measured: average across climate zones; Simulated: per climate zone

Whole-Building Metric		Measured	Simulation			
			Temperate *(Bangalore)*	Hot Dry *(Jaipur)*	Warm Humid *(Mumbai)*	Composite *(New Delhi)*
Annual energy use EPI [kWh/m²/year]	**Standard**	250	232	280	253	268
	Better	150	125	146	144	146
	Best	64 (30)	53	78	69	80
		-74%	**-77%**	**-72%**	**-73%**	**-70%**
Peak energy use [W/m²]	**Standard**	90	100	123	95	110
	Better	40	39	56	45	56
	Best	19	16	29	22	30
Annual energy use/occupant [kWh/person/year]	**Standard**	2,250	2,320	2,800	2,530	2,680
	Better	1,460	1,250	1,460	1,440	1,460
	Best	620	540	780	690	800

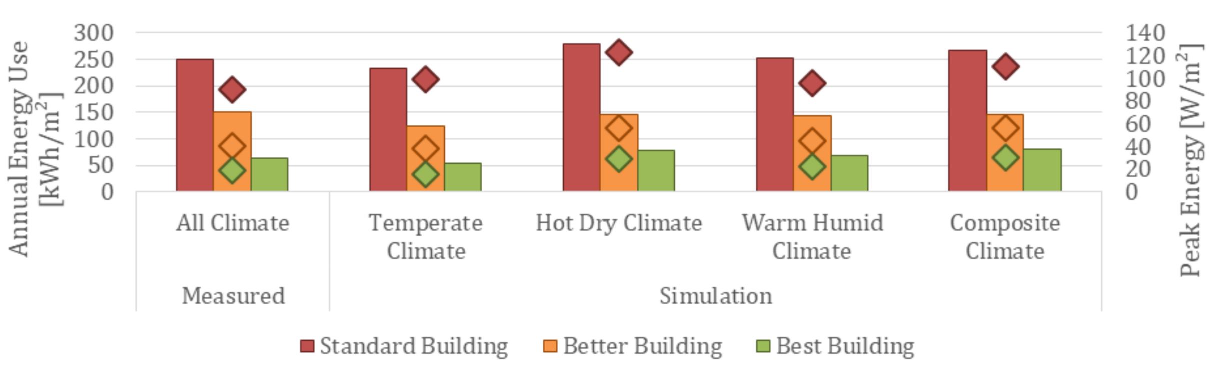


Figure 14: Charts for whole-building metrics. The energy metrics are derived from measured data from buildings, expert opinion, and building energy simulation results.

Data Point 1: Development Alternatives Headquarters, New Delhi: Lower embodied energy

and deliver materials and products. Reducing the embodied energy necessitates the use of local, low-processing materials. At the Development Alternatives Headquarters in New Delhi, the materials used for the building envelope, result in a 30% reduction of total embodied energy in comparison to a conventional building. The building envelope features mud and fly ash blocks to replace burnt brick, timber for doors and windows, and a conscious choice to use no aluminum or polyvinyl chloride (PVC).

Figure: Development Alternatives Headquarters, New Delhi, showing the low-embodied-energy mud and fly ash blocks used for the envelope (source: turenscape.com, Ashok B. Lall and Associates).

Best Practices

Section 2: Building Physical Systems

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Improve Envelope and Passive Design

Plan energy conservation measures (ECMs) for passive envelope systems at the beginning of the design process to help achieve large savings at relatively lower-cost. Envelope ECMs constitute wall, windows, roof assemblies and shading to avoid exposures to solar heat gain, and to support daylighting with visual comfort, and natural ventilation where possible. These practices demonstrate even bigger savings for buildings with smaller floor plates that exhibit external load-dominance due to the larger surface-to-volume ratio

Optimize massing, orientation, and envelope using building performance simulation

Design teams should model the effects of shading elements, especially external and self-shading, to maximize views and minimize heat gain. See Appendix 5 for details.

Simulation Results
Improving building aspect ratio and fenestration (Simulation Result 1)

Decrease envelope heat gain

a. Treat opaque surfaces as "cool" surfaces, by providing cool roofs and cool paints. Cool roofs reflect heat and are most effective during the hottest part of the day and the hottest time of year, coinciding with peak energy demand. Therefore, cool roofs help to reduce peak loads and reduce the sizing requirement and first cost for air-conditioning equipment. Cool roofs can save up to 25% of roofing energy loads, or roughly up to 5%–10% of air-conditioning loads at the top floor. However, care should be taken to control reflection so that glare and heat do not increase the energy use of neighboring buildings.

b. Provide adequate wall and roof insulation to shield the building from external heat gains. This can be done by adding an air gap in the wall construction or another insulation layer balanced with the provision of cool surfaces. Vegetated roofs can be used for insulation and for a co-benefit of water collection.

c. Provide shading for windows, regardless of whether they are punched windows or curtain walls.

d. Conduct annual simulation for a deeper dive into building envelope heat gain that combines the thermal gains and losses (measured as U-factor), and solar gains (measured as solar heat gain coefficient or SHGC). This simulation is possible in a tool such as COMFEN (See Appendix 3, List of Simulation Tools) that provides results for specific building geometry with windows in specific location and climate zone. See the Glossary for explanation of these terms.

Data Points
Godrej Bhavan, Mumbai: Retrofit, vegetated roof (Data Point 2)
ITC Green Center, Gurgaon: Reduced external heat gains (Data Point 3)
Paharpur Business Center, New Delhi: High albedo building surfaces (Data Point 4)
SDB-1, Infosys, Pocharam: Second skin, insulated envelope (Data Point 5)

Optimize fenestration and window-to-wall ratio (WWR)

a. Maximize north and south exposures and fenestration; minimize east and west exposures.
b. Limit the WWR to an optimum level, as shown in Table 3.
c. Design windows with thermal breaks in the aluminum frame to reduce the heat conduction through frames that occupy a significant percentage of surface area.
d. Carefully design the shape of window cross-sections (tall and thin versus short and wide). Select the appropriate glazing to minimize solar heat gain and maximize visible transmission level. Glazing should be carefully selected (per orientation of the building) for cost and performance, using the following four attributes: (1) single or double-glazing, (2) visible light transmittance (VLT) (higher is generally better, as long

as glare is controlled), (3) SHGC (lower is better in cooling dominant climates), and (4) U-value of the assembly (lower is better). See the Glossary for explanation of these terms.

Data Points
Dev. Alternatives, New Delhi: Aesthetic and functional envelope (Data Point 6)
SMSF, Gurgaon: Optimal solar shadings (Data Point 7)

Simulation analysis shows that the impact of a modified longer, thinner floorplan, and the addition of appropriate shading devices on optimized north-south fenestration of 40% and 30% WWR, led to an EPI reduction of 7%–10%. These savings were derived from a reduction in the cooling coil consumption and fan demand, driven by a 31%–44% reduction in solar heat gain transmitted into the building.

Maximize daylight autonomy without solar glare

a. Design a shallow floorplan, about 16 meters (m) to 18 m wide with windows on both sides.

b. Provide lightshelves to improve the distribution of daylight in the interior space. A lightshelf is a horizontal structure that divides a window into a 'vision panel' below the lightshelf, and a 'daylight panel' between the lightshelf and ceiling, and reflects light onto the ceiling surface. A lightshelf also enables continuous provision of daylight even when shades are lowered over the vision panel. The ceiling and top of lightsheves should be of the brightest practical color, as long as the contrast with other room surfaces is not excessive to cause visual discomfort. Lightshelves can be interior, or exterior, or a combination. The exterior portion can double-duty as an overhang.

c. Provide shading to mitigate glare. According to Illuminating Engineering Society, glare implies too much light, or excessive contrast, meaning the range of luminance in the field of view is too great – causing visual discomfort. Start with exterior shading to control brightness and install sun baffles (brise soleil) outside the windows (Touma, 2017). Next, use manual or automated window blinds as glare-mitigating devices. Finally in conjunction, improve thermal comfort by using low-SHGC glass with low-emissivity coating and high transmittance.

d. To maximize the spread of daylight, plan intermittently occupied cabins and conference rooms in the core zones and open floorplan workstations in the perimeter zones. In terms of the interior space planning, provide low partitions and light colors to maximize the effect of daylighting.

e. For advanced design and detailed analysis, conduct annual simulations for location-based dynamic energy metrics, to help maximize daylight performance without causing problems of glare or increased cooling loads. For instance, the Sefaira tool (See Appendix 3, *List of Simulation Tools*) combines spatial daylight autonomy (sDA), or percentage of the space that receives sufficient daylight (300 lux for 50% occupied hours), with annual sun exposure (ASE), to provide the amount of space that has too much direct sunlight (over 1000 lux for 250 occupied hours).

f. Monitor and control operable shading and windows. See Section on *Climate Control Strategies*.

Data Points
Suzlon One Earth, Pune: Daylight-oriented envelope (Data Point 8)
SDB-1, Infosys, Pocharam: Shading and Lightshelves (Data Point 9)

Table 3 provides best practices for passive design and envelope parameters.

Best Practices Improve Envelope and Passive Design

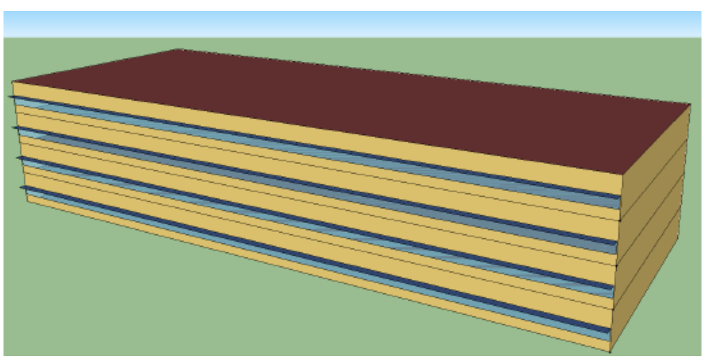
Table 2: Best practices for passive design and envelope parameters

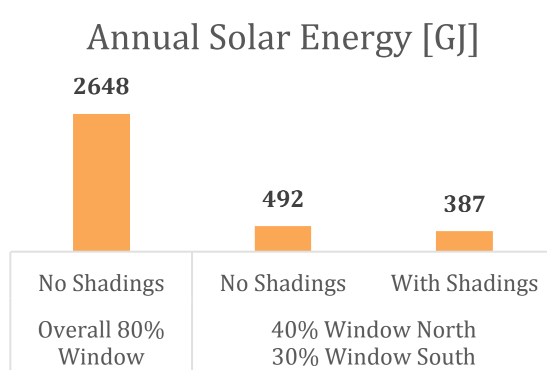
Building Attribute	Best
Orientation	North-south maximized perimeter; locate services like staircases and mechanical and electrical rooms on the east-west perimeter
Massing/Stories	Minimize surface area prone to envelope heat gain; increase self-shading potential
Floorplate Depth	9 m for a single-sided window space, 18 m for double-sided window space (assuming interior light shelves)
Shading Strategies	Overhangs for south façade windows; small fins on north; both fins and overhangs for east and west façade windows
Window-to-Wall Ratio	25%–30% (ECBC code, WWR < 40%)* Consider 30-45%, with careful design to address thermal and visual comfort
Vertical Fenestration	Meet or exceed ECBC values
Area Serviced by Daylight	90%
Wall U-Value	Meet or exceed ECBC values

*Note here that the ECBC Prescriptive Compliance (ECBC 2007) approach does not allow WWR to exceed 40%; whereas, 80% WWR is the ratio that more closely represents the full-glazed façade type of construction that has begun to dominate commercial building design and practice in India.

Data Points and Simulation Results

Simulation Result 1: Improving building aspect ratio and fenestration





Building energy simulation revealed that, while conserving an equivalent floor space, the best performing envelope has large north and south facades. Walls facing east and west have no windows, to prevent undesirable summer solar heat gains. Windows placed on south walls can be shaded efficiently with horizontal overhangs that block high midday sun. Windows placed on north walls can be shaded efficiently with vertical fins to block morning and evening summer sun coming from the side. By reducing the window-to-wall ratio from 80% to only 40% on the north and 30% on the south, solar heat gains are greatly reduced, and so are cooling demand and HVAC energy consumption. Shading provided a 40% reduction of solar gains. The impact of this fenestration strategy resulted in a modeling result of 7%–10% whole-building energy reduction from ECBC levels, and 50%–54% reduction from BAU levels, with maximum impact in a hot and dry climate. For a medium-sized office building, this translates to an energy savings of 63–90 megawatt-hours (MWh), or a cost savings of INR 4.5–6.3 Lakh per year (assuming an INR 7/kWh unit cost of electricity).

Best Practices Improve Envelope and Passive Design

Data Point 2: Godrej Bhavan, Mumbai: Retrofit and vegetated roof

The Godrej Bhavan building in Mumbai was retrofitted in 2010 to adopt a more energy-efficient design. This retrofit included replacing the original HVAC system and lighting, and updating the envelope. The original terrace roof, covered in “tandoor” roof clay tiles, was replaced by a green, vegetated roof. Another remarkable measure implemented was a planting of trees atop and around the building that reduces the heat island effect and maintains a cooler microclimate. That change resulted in a decrease of the surface temperature by 10°C, and therefore a decrease of the heat transferred to the building top floors that house the management offices, reducing peak load for the HVAC equipment.

Figures: (Left) Retrofitted green roof. (Right) New operable windows at Godrej Bhavan, Mumbai.

Data Point 3: ITC Green Center, Gurgaon: Reduced external heat gains

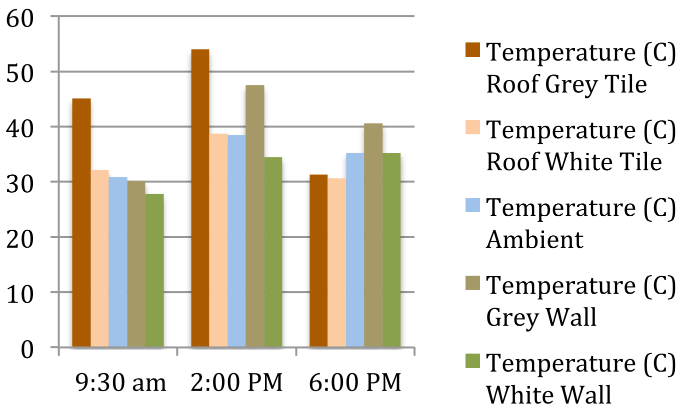
At the ITC Green Center, Gurgaon, a low-rise (ground plus three) structure with narrow floor plan was designed to minimize external envelope heat gain, with the longer axis oriented northeast-north. The configuration and orientation of the L-shaped building ensures self-façade shading for the entrance areas and foyer. A high-albedo coating chosen for the roof has reduced the roof surface temperature by 30°C, and brought down the air conditioning loads at the top floor by 10%–15%. Low-E 6 mm double-glazing with 12 mm air gap (6-12-6) was selected such that the northern glazing has a higher level of visual transmittance (T-vis) without compromising on the uniformity of the visual esthetic. The WWR has been limited at 33%, compared to the ECBC standard of 40%. Mutual shading and window shading was designed such that the SHGC is 0.26. The envelope heat gain was reduced from the base case by about 65%. Additionally, roof and wall cross sections were designed for the assembly to have low U-values; the wall assembly has a U-value of 0.6 W/(m^2.K) (sources: TERI, ITC). Also, see Datapoint 15.

Figures: ITC Green Center, Gurgaon, showing the daylit atrium and façade with low-E windows (photos: ITC).

Best Practices Improve Envelope and Passive Design

Data Point 4: Paharpur Business Center, New Delhi: High albedo building surfaces

"The color of green is white." At the Paharpur Business Center in New Delhi, high albedo paint was applied on the southwest façade and roof of the building to reduce the solar heat gain into the building. The roof also houses a greenhouse that shades the roof, doubles as a terrace café, and substantially reduces envelope heat gain and provides a pleasant rooftop garden experience in the densely polluted central business district.



Figures: (Left) At the Paharpur Business Center (PBC), Delhi, light-colored tiles on the roof and cool wall paints were used to decrease envelope heat gain. (Right) The chart shows a drop in surface temperatures using cool materials and paints on a typical April day (Source: PBC).

Data Point 5: SDB-1 at Infosys, Pocharam: Second skin and insulated envelope

At Infosys, Pocharam, an envelope with a second skin (i.e., cladding of aerated clay Weinerberger tiles) was used, with an air gap providing isolation of the façade from the structure. This creates a thermal break and a time lag to keep the heat absorbed by the skin away from the structure. The exterior wall also has R-10 insulation (extruded 2" polystyrene), with U-value of 0.4 W/(m^2.K) for the wall assembly. The massing and orientation was designed to maximize the north-south orientation and minimize the east-west orientation. While there is virtually no fenestration on the east and west facades, the north and south WWRs are optimized to about 30%. Spectrally selective double-glazed low-e windows filled with argon, with a low U-value and a light-to-solar-gain ratio of 2.0, were used to maximize visual transmittance and optimize solar heat gain. All windows are shaded as detailed in Data Point 9.

Figures: Envelope with second skin/cladding at Infosys, Pocharam.

Best Practices Improve Envelope and Passive Design

Data Point 6: Development Alternatives, New Delhi: Esthetic and functional envelope

The Development Alternatives Headquarters building, New Delhi, uses an esthetic and functional envelope design featuring vertical planting on the building façade and cavity walls that use air as an effective insulating layer. The air acts as a moderate insulation layer that keeps heat dissipation costs low. Additional advantage is gained from the high thermal mass using stone cladding and strategically angled windows with built-in shading devices to minimize heat gain and maximize daylighting. The WWR is limited below 20%, and the punched openings on east and west facades are shaded by overhangs or by the building structure itself. The cost of the double-glazed units (DGUs) was kept to a minimum by using plain glass rather than low-e glass. The logic being that shading the glass and having a second layer of glazing reduces heat conduction to create a thermal effect that is within 10% of using expensive glazing at double the cost. Second, the DGUs have an air infill, rather than argon or vacuum, to keep the costs almost half that of "high-performance" window assemblies (source: Holcim report). The double clear air-filled units must be well made with good edge seals and desiccant.

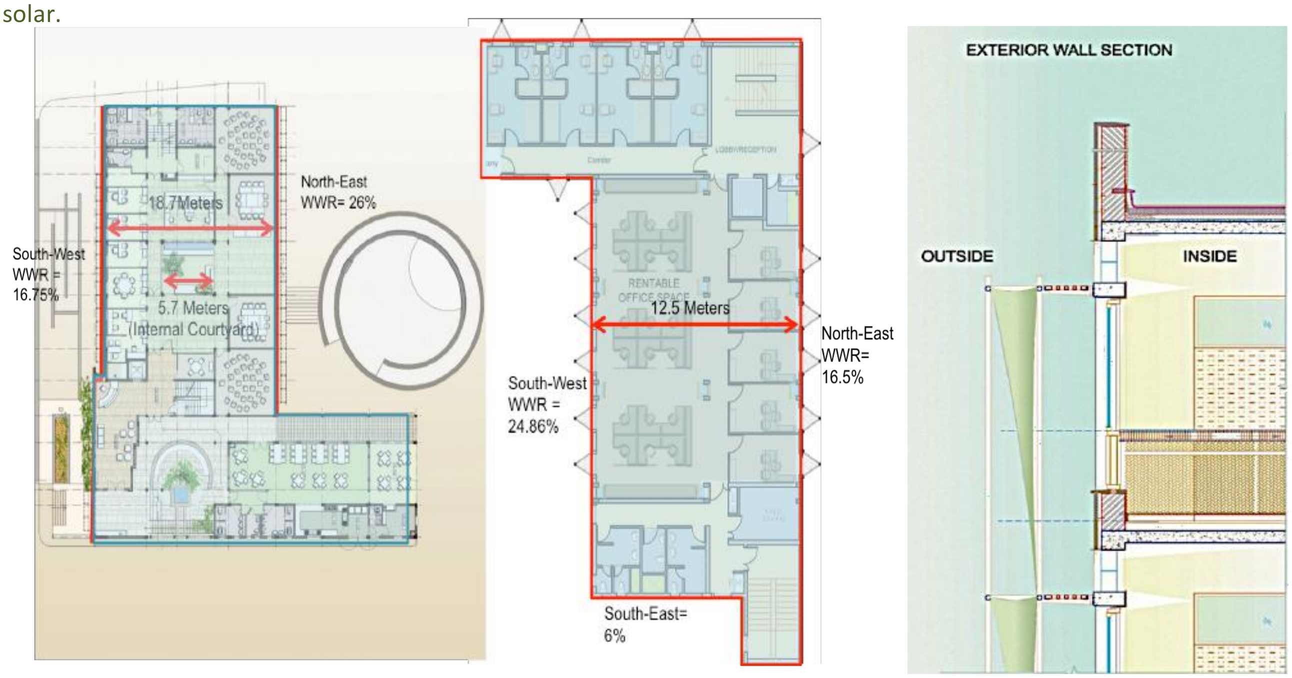
Figures: (Left) The high thermal mass of the Development Alternatives Headquarters contrasts with neighboring BAU-2 building with a curtain wall façade.
(Center) The WWR was kept to a minimum, while vertical green provides visual and thermal relief.
(Right) The operable windows on the western façade are innovatively angled to catch the gentler northern and southern solar exposures.

Best Practices Improve Envelope and Passive Design

Data Point 7: SMSF, Gurgaon: Optimal solar shading

At the SMSF building in Gurgaon, sail-shaped, semi-opaque shades made of replaceable fabric are installed to block direct high-altitude solar radiation while diffusing beneficial daylight into the office spaces and allowing views out of the building. The orientation and size of the shades have been designed based on the location's latitude, by using the Ecotect® tool such that the summer sun is blocked and allowed to enter when beneficial (during cold winter days). The entire shading structure is minimally connected to the envelope to avoid negative thermal bridge. The WWR ranges between 15%–26% only, yet the building gets adequate daylight owing to the narrow floorplan. The large walkway pergolas and rooftop solar photovoltaic installation also act as a giant shade while an internal courtyard allows diffuse daylight into the building, avoiding unwanted glare and heat gain from the incident sunlight.

(Left): The windows at SMSF, Gurgaon, are shaded by sails that are oriented to optimally reduce solar radiation. (Right) A gentler microclimate is created using large shading devices such as garden pergolas and rooftop solar.



The shallow floorplan and courtyard allow daylight to penetrate the building optimally, despite a low window to wall ratio. (source: AB Lall and Associates).

Best Practices Improve Envelope and Passive Design

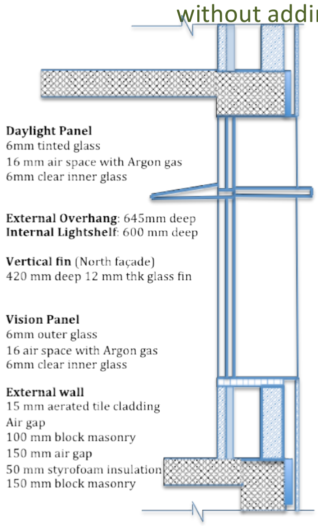
Data Point 8: Suzlon One Earth, Pune: Daylight-oriented envelope

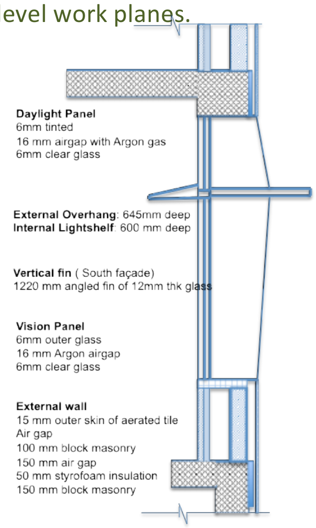
At the Suzlon One Earth campus in Pune, the orientation of blocks is such that the majority of building façades face north, south, northwest, and southeast. Daylight is harnessed through curtain walls, but the massing is such that the curtain walls are kept shaded, either through self-shading, from the upper blocks massing, or with extensive louvers that provide a distinct architectural vocabulary at the lower floors. Many of the building blocks have narrow floorplans, ~ 17 m wide, such that 90% of the occupants' spaces benefit from daylight.

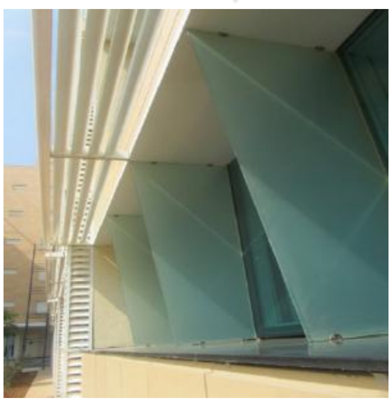
Use of louvers and internal movable shades, and the mass of the building's blocks to shade the large glazed façade areas at Suzlon One Earth, Pune. The glazing has low-e glass; extensive over-deck insulation is provided and the height of the buildings is kept deliberately low—all factors that substantially reduce the envelope heat gain (source: Synefra).

Data Point 9: SDB-1 at Infosys, Pocharam: Shading and lightshelves

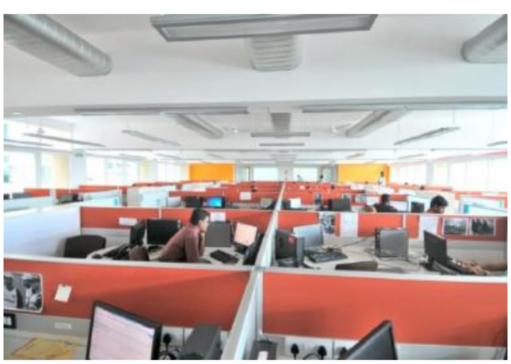
At SDB-1 at Infosys, Pocharam, the windows only cover 20%–30% of each façade and are sectioned into two parts. The window section includes a light shelf, a vision panel, and a daylight panel (the building is oriented with bigger facades facing north and south, and minimum wall area facing east and west). A light shelf is installed to distribute the light deeper into the floorplan and to reduce glare by bouncing the light off the ceiling to provide diffused daylight. The glazing was selected such that the VLT is higher for the daylight panel above the light shelves, and lower for the vision panel below the light shelves. This allows for brighter light to enter at higher wall levels and gain deeper penetration, without adding glare at the lower vision-level work planes.

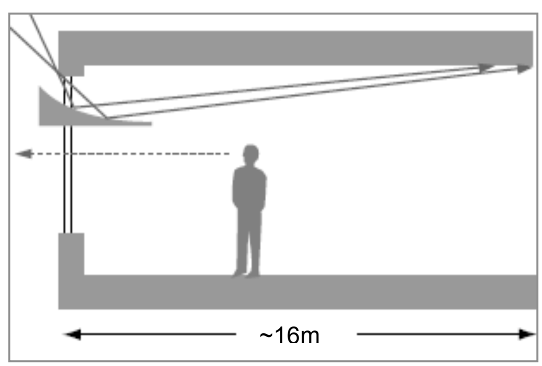






Figures: SDB-1 at Infosys, Pocharam. (Left) Cross section and picture of the north façade. (Right) Cross section and picture of the south façade.





Figures: The combination of a narrow floorplan and light shelves increases the penetration of glare-free daylight (source: Infosys Green Initiatives Team).

Reduce Plug and Process Loads

Plug loads represent approximately 20%–40% of all electricity consumed in commercial office buildings. Outlined below are strategies to reduce plug loads in an office that caters to office appliances or devices such as computers, monitors, photocopiers, faxes, and printers—and may include task lights, personal or ceiling fans, vertical transport, or similar loads.

Set aggressive power management settings

Provide these settings on all equipment or use power management software controlled by the IT departments.

Provide a computing infrastructure

Provide computing infrastructure to tenants with thin clients, i.e., networked, secure monitors and terminals with access to a virtual machine infrastructure, separated from building electricity loads. The IT recommendations need to be balanced with the computing needs for the organization. (the above recommendation is relevant for a call center or bank, but may be less suited to a software development or engineering enterprise) (Monga 2012).

Pursue direct-current-based improvements

Provide DC office equipment to avoid power loss due to DC-to-AC power conversions at UPS and back to DC conversion at the equipment. Consider providing DC for lighting, computers, and larger equipment. A simplified AC/DC hybrid coupled power network can provide the opportunity to use up to 30% less energy for 15% less capital cost while maintaining 200% of the reliability of an AC system (Patterson, et al. 2011). This strategy is starting to be under consideration for a few projects in India.

Install smart hardware

Hardware solutions such as smart power strips that monitor and control the loads intelligently based on rules or optimized for occupant requirements, timers, and efficient (ENERGY STAR-rated) office equipment are a new trend in India.

Encourage responsible occupant behavior

Encourage energy reductions by increasing occupant awareness of efficiency settings and providing incentive programs to reduce plug loads (e.g., the tenant that practices the highest levels sustainability receives a 1% rent rebate) and tenant guidelines for energy use. Monitor the schedule and device shut-off such that the nighttime load is only a fraction of the daytime load. Have occupants use laptops rather than desktop computers. The use of laptops with peripherals like ergonomic keyboards and mice in lieu of desktops reduces energy consumption.

Data Points
SDB-1 at Infosys, Pocharam: Low plug load consumption (Data point 10)

Reduce the number of plug-in devices

Share printers, microwaves, refrigerators, coffeemakers, and other appliances across office occupants.

Data Points
Sears Holdings Offices, Pune: Shared equipment (Data point 11)
Simulation Results
Plug load reduction (Simulation result 2)

Table 4 provides plug load metrics for standard-, better-, and best-performing buildings.

Table 3: Table of Metrics: Plug Loads

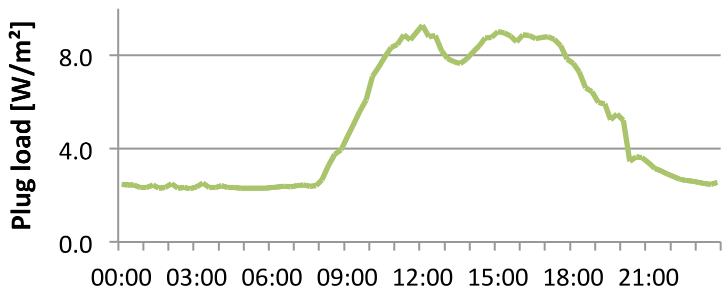
Plug Load Metrics (includes UPS and Raw Power)		Measured	Simulation (All climate zones)
Plug Annual Consumption [kWh/m²/year]	**Standard**	100	35
	Better	55	32
	Best	30	24
Plug Peak Load [W/m²]	**Standard**	20	10.8
	Better	15	10
	Best	7	7.5

Best Practices Reduce Plug and Process Loads

Data Points and Simulation Results

Data Point 10: SDB-1 at Infosys, Pocharam: Low plug load consumption

At Infosys buildings, peaks for plug loads are 10–11W/m^2, based on 8 W/m^2 for computers and 2–3 W/m^2 for other equipment. An occupant behavior and plug load survey revealed that nighttime computer plug loads were still substantial (~60% of daytime loads), which indicated that desktops were not turned off during unoccupied hours. This was then managed through behavioral and technology solutions (source: Infosys).

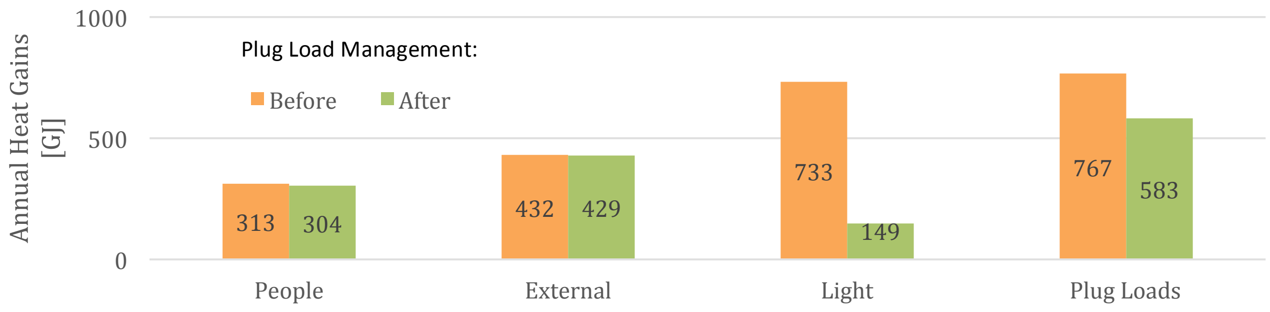


Figures: (Left) Plug loads in offices at Infosys, Pocharam. (Right) Shared Office Equipment.

Data Point 11: Sears Holdings Offices, Pune: Shared equipment

At the Sears Holdings Offices in Pune, equipment is shared: one projector and one printer is provided per floor, occupants use LCD screens for projection instead of having projectors in all meeting rooms, and staff members use laptops rather than desktops: all of these measures suffice for their operations. Another example of frugal operations is that the average paper consumption has been significantly reduced to 35 sheets per month per employee. Most seats are shared "hot seats" used by different staff over multiple shifts, leading to efficient space utilization that aligns well to the type of operations required.

Simulation Results 2: Plug load reduction



Plug loads and lighting have a double effect on energy consumption: they directly consume electricity and convert that energy into heat, increasing the cooling load and, therefore, HVAC system energy consumption. Simulations showed that, in Bangalore, where the external heat gain is not as high as in other climates, reducing the power density by 55% could reduce HVAC electrical consumption by 44%. The chart above shows that lighting and plug loads were the main source of heat gain before reducing the power density, and energy use from these sources was considerably reduced after proposing energy savings strategies for lighting and plug loads.

Optimize Lighting Design

Lighting represents approximately 10%–25% of all electricity consumed in office buildings. The lighting load is greater for a building with a deeper floor plate or one that operates for evening or night shift hours. The following section offers strategies for reducing lighting loads.

Optimize daylighting design

Provide glare-free daylighting using optimized glazing and reflecting light shelves. The energy conservation measures done during design and construction can mitigate the requirement for internal shading and artificial lighting during daytime (see Section *Envelope and Passive Design*).

Data Points
SDB-1 at Infosys, Pocharam: Optimized daylight design (Data point 12)

Implement a highly efficient equipment and optimized lighting layout

a. Consider designing for lower ambient lighting levels (e.g., 300 lux compared to 500 lux) in office spaces, and provide light-emitting diode (LED) task lights for occupants who require higher levels of lighting. Design lighting power to match the space requirements (see Table 5)

b. Provide LED or T5 fluorescent luminaires. At the very least, provide T8 rather than T12 lights for retrofits.

c. Provide electronic ballasts (e.g., DALI) rather than magnetic ballasts for workstations, meeting rooms, cabins, restrooms. Electronic ballasts can save a minimum of 12% of energy consumed, and even more if premium electronic ballasts are used.

Table 4: Lighting power density (LPD in W/m²) for various space types in ECBC-compliant and best practice buildings

Space Type	ECBC	Best Practice
Offices	10.0	4.5
Meeting room	11.5	5
Restroom	7.7	3
Common areas/lobby	9.1	3
Parking areas	3.0	1

Data Points
Making the case for LED retrofits (Data point 13)
Suzlon One Earth, Pune: Reduced lighting power density (Data point 13)
ITC Green Center, Gurgaon: Low LPD example (Data point 14)

Provide lighting sensors and controls

a. Install photosensor controls that dim or shut off lights when adequate levels of natural light are detected.

b. Install occupancy controls that shut off lights in unoccupied areas. These are high-resolution sensors that detect tiny movements and are useful in occupied spaces such as offices with sedentary workers or in unoccupied storage spaces.

c. Install motion sensors that detect walking movement, specifically for circulation spaces and restrooms.

d. Install dimmers, for example, in meeting rooms.

e. Install sensors to continually monitor light levels in the space to ensure that visual comfort is maintained irrespective of conditions outside.

f. Group the luminaires in layers, where the luminaires closest to the windows (perimeter zone) are controlled separately from those in the center (core zone).

g. Use timers concurrently to switch off the lights once all users have left the space. The control system can be equipped with a timer for additional benefits. If the building reaches a high degree of daylight autonomy, the daylight sensor and timer can be coupled together. It is only when the timer indicates that it is past daylight hours that the sensors get triggered to power themselves on and start sensing for occupancy, leading to enhanced energy savings.

Data Points
Sears Holdings, Pune: Alternate lighting aisles (Data point 16)

Simulation Results
Daylight and lighting consumption (Simulation result 3)

Best Practices Optimize Lighting Design

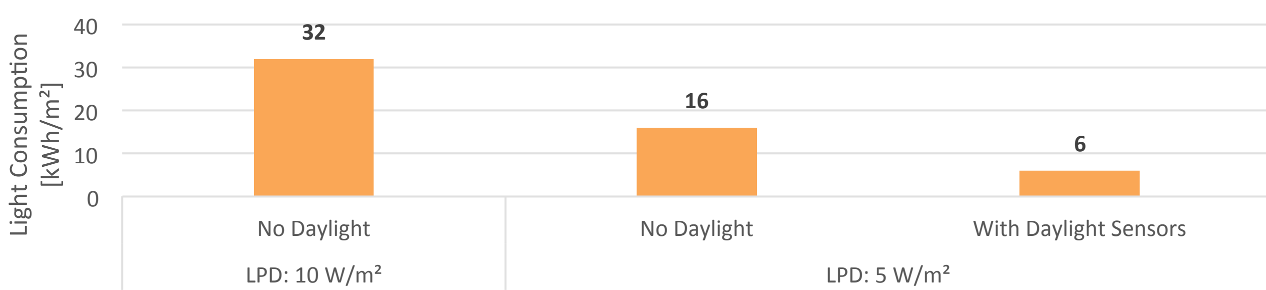
Table 6 provides lighting metrics for standard-, better-, and best-performing buildings with respect to lighting system operations.

Table 5: Table of Metrics: Lighting Loads

Lighting Metrics		**Measured/ Expert Opinion**	**Simulation (All Climate)**
Lighting Annual Energy Consumption [kWh/m²/a]	**Standard**	40	32
	Better	15	32
	Best	8	6
Lighting Peak Energy Use [W/m²]	**Standard**	15	10
	Better	10	10
	Best	2	5

Data Points and Simulation Results

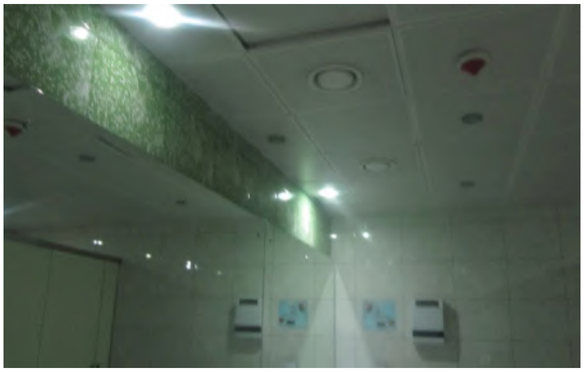
Simulation Results 3: Daylight and lighting consumption

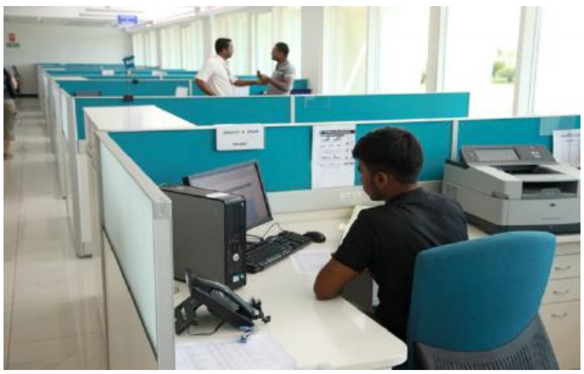


In simulation, the lighting power density reduction to 5 W/m², a level recorded in a few exemplary buildings, created a 55% whole-building savings in lighting consumption in every model, and the provision of daylighting sensors reduced the remaining consumption by half. An envelope promoting natural, glare-free daylight is a critical ECM.

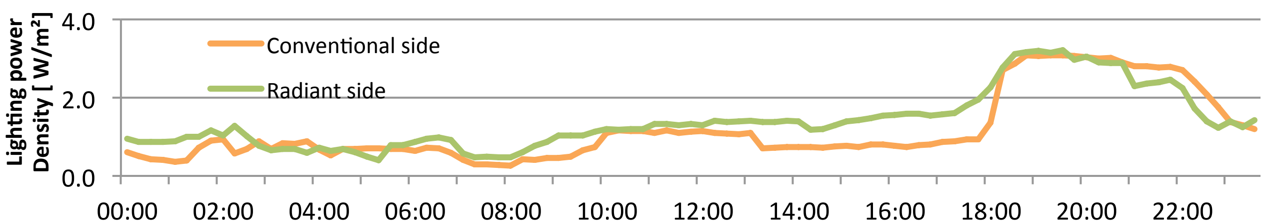
Data Point 12: SDB-1 at Infosys, Pocharam: Optimized daylight design

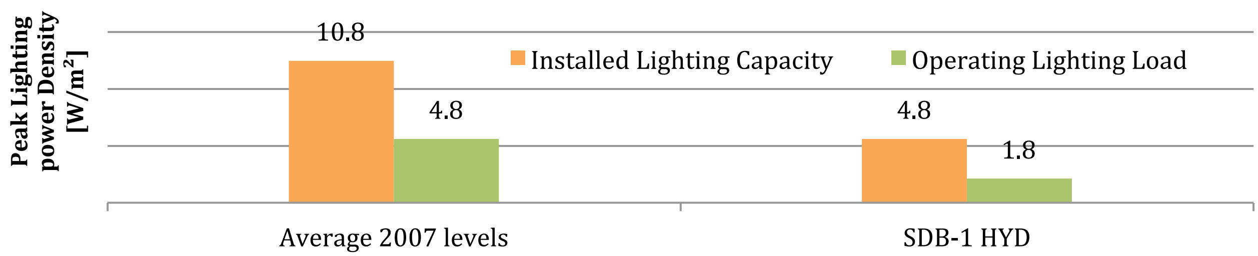
At SDB-1 Infosys, Pocharam, direct/indirect suspended fluorescent T5 lights and a few 8-W LED down lights have been used. Very few lights need to be switched on during daytime working hours due to adequate daylight. There are daylight sensors in open office areas, occupancy sensors in the restrooms, and all external lights have LED lamps with timers. A combination of lighting and daylighting ECMs have led to significant energy savings.





Figures: Infosys, Pocharam. Top left: occupancy sensors in the restrooms. Top right: T5s and LED down lights are used. Bottom left and right: The amount of daylighting in the office spaces and lobbies has minimized the requirement for artificial lighting substantially (photos: Infosys Green Initiatives Team).





Figures: (Top) Lighting demand profile. Artificial lighting is switched on only as needed after 6 p.m. (Bottom) Use of lighting and daylighting strategies have led to a two-thirds reduction in the operational lighting load (source: Infosys Green Initiatives Team).

Best Practices Optimize Lighting Design

Data Point 13: Making the case for LED retrofits

A Delhi-based energy and engineering firm conducted a payback analysis that studied the impact of the replacement of conventional T5 luminaires with LEDs. The study showed that based on a 10-hour duty cycle (of which 8 hours are on normal power and 2 hours on a diesel generator set) each LED lamp retrofit could achieve per year (1) direct power consumption savings of INR 1,670, (2) savings on lamp replacement cost (owing to longer 50,000 hour LED lamp life) of INR 240, and (3) savings due to reduction in electrical load on the AC system of INR 690. An initial investment of INR 3,800 per LED lamp retrofit leads to an INR 2,600 per year savings.

Data Point 14: Suzlon One Earth, Pune: Reduced lighting power density

At Suzlon One Earth Pune campus, the interior lighting system incorporates dimmable ballasts, electronic ballasts, occupancy sensors, motion sensors, and daylight sensors. These ensure that lights get switched on only when required. The general lighting level from the ceiling luminaires is fixed at 350 lux. The artificial lights can be dimmed up and down from 0% to 100% depending on the adequacy of available daylight to meet the 350-lux requirement. The task lights in offices have a built-in occupancy sensor in conjunction with a continuous dimmer. Combined daylight and occupancy sensors control lighting of individual offices. Enhanced energy savings is also achieved due to an LED-based outdoor lighting system, which results in approximately 65% savings (in wattage) when compared with a conventional scheme. All the outdoor lights are controlled through the integrated building management system (BMS) (source: Synefra).

Figure: The calendaring-based lighting controls system in a conference room

Data Point 15: ITC Green Center, Gurgaon: Low LPD example

At the ITC Green Center, Gurgaon building, T5s and CFLs are used in reflective mirror optic fixtures in the occupied spaces. In unoccupied spaces such as the storage and mechanical and engineering rooms, 36-W fluorescent lamps and magnetic ballasts are used. Lighting controls—switch-off daylight sensors that turn off artificial lights when daylight is sufficient—are used. Clerestory lighting in the atrium and large punched openings in the office spaces provides adequate daylight for most working hours (source: The Energy and Resources Institute, TERI).

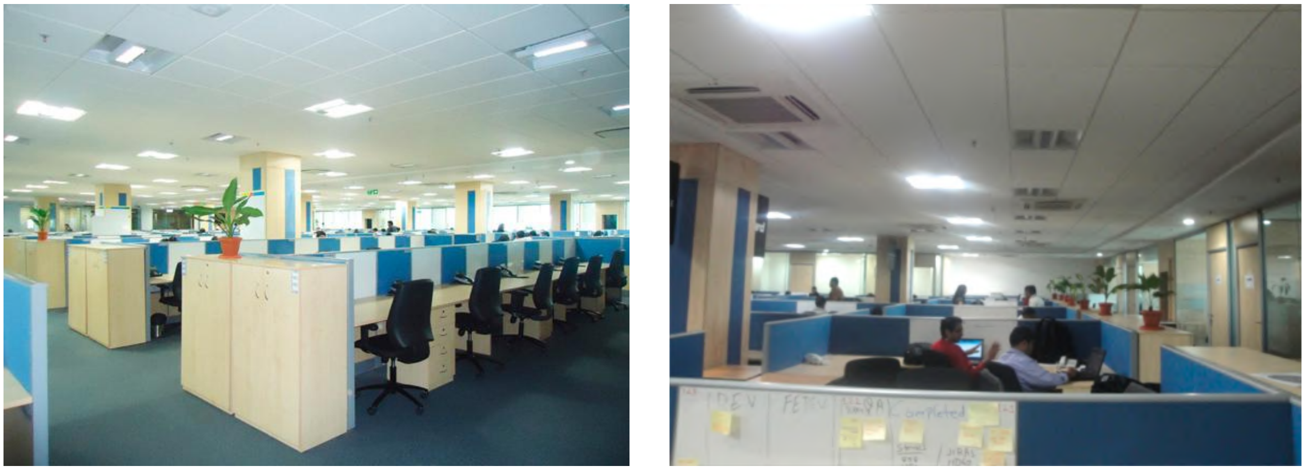
Figure: ITC Green Center building (photo: TERI).

Figure: Inside the ITC Green Center, daylight is harnessed to reduce artificial lighting needs.

Best Practices Optimize Lighting Design

Data Point 16: Sears Holdings, Pune: Alternate lighting aisles

At the Sears Holdings offices in Pune, even with standard 12-W CFL and T12, 8-W fluorescent fixtures, several operational measures keep the lighting power density (LPD) low. Alternate aisles of lights are switched off to conserve electricity while providing for adequate lighting levels at 450–500 lumens/m^2. This indicates that there is an overdesign of lighting levels. The cabins in the perimeter zones have glass partitions to maximize daylight penetration.



Figures: (Left) Sears Holdings holding office interiors, Pune (photo: Facilities Team, Sears Holdings India). (Right) Showing practice of switching on only alternate aisles of lights.

Develop Low-energy HVAC Strategies

Hearing, ventilation, and air conditioning (HVAC) systems use approximately 40%–60% of the electricity consumed in Indian high-end office buildings. The HVAC often the single most energy consuming system, with greatest opportunities for energy savings. Outlined below are best practices for HVAC loads and systems optimization.

Right-size the efficient equipment, and build in modularity at the right scale

a. Decrease the number of hours and months when active cooling is required, using envelope strategies to reduce external heat gain, thermal mass to enable heat lag, ceiling fans for air movement, and night ventilation to dissipate the internal heat (see section called Implement HVAC Sensors and Control Strategies). Use night-flush cooling for removing building heat, especially in climates with diurnal swings. Our simulation studies have shown that while other climates achieve a 2%–4% savings through night flush, largely from savings occurring in the summer's edge months (April, September, and October), Bangalore's moderate climate can provide up to a 12% opportunity for savings, with savings occurring throughout the entire summer. Refer to Appendix 5 for details.

b. Size all equipment to meet the peak building load, based on "most likely maximum loads" (Brown 2002) rather than peak cooling loads. Use a diversity of space types in the building to limit oversizing of mechanical plant and electrical services.

c. Use unequal chiller sizes, and make sure the smallest size can efficiently accommodate the loads at initial occupancy, or during base weeknight/holiday periods

d. Use a modular approach, adding capacity incrementally as loads materialize. Consider providing mechanical and electrical space (plinth area), and design in the ability to meet much larger loads, especially in any one space, and connect to those loads only as they appear. For example, provide space for additional cooling towers and pumps, "oversized" (relative to the initial load) process cooling water distribution piping, with valves and blank-off plates in the plant to allow additional cooling equipment to be added as the load materializes.

e. Use well-established strategies for equipment efficiency: right-size pumps, use inline pumps, locate air handler units (AHUs) on every floor rather than on the rooftop, install chillers with magnetic bearings, and use bigger piping and ducting to enable low-pressure drop for water and air flow.

f. For server rooms and datacenters, water-cooled chillers may be worth the additional capital cost.

g. Consider superefficient non-vapor compression air-conditioning systems such as absorption chillers, membrane heat pumps, or other equipment using low global warming potential (GWP) refrigerants to reduce operational electricity and greenhouse gas emission (GHG) impact.

h. Utilize a district cooling system for campuses with multiple buildings and dense occupancy where there is a diversity of loads, with non-coincident peaks. It avoids duplication of equipment, enabling a more efficient fully loaded condition resulting in efficiency improvements, reduced operating and maintenance costs and potential coupling with renewables. Centralizing the comfort cooling infrastructure offsets the need for mechanical rooms in each building and frees up leasable front-of-the-house real estate.

i. Perform systems commissioning to ensure that the building's HVAC systems are operating as intended.

Consider ultra-low-energy cooling options

Options like variable refrigerant flow (VRF), displacement ventilation (DV), radiant cooling (RC), and underfloor air distribution (UFAD) generally have significant longer-term benefits as compared to variable air volume (VAV) systems, as discussed below.

a. **Variable refrigerant flow (VRF)** can be considered particularly for small to mid sized facility retrofits. Instead of designing a central cooling plant, consider the use of a VRF system that is simpler and advantageous for smaller offices because it is more flexible (it can be controlled at an individual level and requires no ductwork, just electrical wiring and tubing) and has quieter operations. Simulations show a 5%–18% energy savings opportunity from a centralized VAV system, in temperate through warm and humid climate (see Table 22 in Appendix 5).

b. **Displacement ventilation systems** deliver the air at low speeds using the principle of air stratification. Air is delivered at close-to-floor level to condition primarily the occupied volume (up to the first 2 m of room height) and extracted at the ceiling height rather than conditioning the unoccupied higher volume first. Well-designed DV systems provide better indoor air quality since the air in the occupied zone is generally fresher than that for mixing ventilation. There are no perceived air drafts. Any released pollutants rise rapidly to above the occupied zone. Large cooling energy savings are possible, as it uses a higher supply air temperature of 18°C, which also increases the efficiency of mechanical cooling equipment and lowers equipment requirements with reduced chiller lift.

c. **Underfloor Air Distribution (UFAD) systems** use the underfloor plenum beneath a raised floor to provide conditioned air through floor diffusers directly to the occupied zone. A thoughtful design can overcome the usually cited challenges of uneven floor surfaces, difficulty in providing added airflow to the perimeter of the building, and perceived control difficulty. The advantages of a well-designed UFAD system are: improved thermal comfort, occupant satisfaction, ventilation efficiency and indoor air quality, reduced energy use, and the potential for reduced floor-to-floor height in new construction.

Data Points
Campus for Agilent Technologies, Manesar: Hybrid HVAC solutions for diverse space loads (Data point 17)

d. **Hydronic (water-based) cooling systems** work on the principle that water can store ~3,400 times more thermal energy per unit volume than air. Some radiant systems circulate cool water in dedicated chilled panels or radiant panels; others cool the building structure (slab, walls, ceilings, and/or beams). Radiant slabs offer the potential to dramatically reduce cooling energy consumption and peak cooling loads since it has the advantage of coupling water based thermal transfer within building thermal mass. Because radiant surfaces are often cooled only a few degrees below the desired indoor air temperature, there are opportunities for innovative cooling energy sources such as night cooling and ground-coupled hydronic loops.

Hydronic systems use dual-temperature chilled water loops. The radiant cooling system supply water temperature would typically operate at a higher setpoint, 15°C–18°C for cooling; typical supply water temperatures for a traditional forced air system are around 5.5°C–7.5°C. The central cooling equipment can operate more efficiently at these temperature setpoints. An LBNL study based on manufacturers simulated data of the same chiller shows that the efficiency of the chiller increases with the increase in the temperature of chilled water. If the chilled water supply temperature is 5.5°C (42°F), the efficiency is 0.49 kW/TR, while for 15.5°C (60°F) used in a medium temperature for radiant cooling, efficiency increases to 0.31 kW/TR, a 36 % improvement (high-tech.lbl.gov).

Thus the temperature of the chilled water supply produced directly affects the chiller efficiency—chillers operate most efficiently when the temperature lift (the difference in temperature between the evaporator and the condenser) is minimized. The rule of thumb (Weale 2011) is that:

- Every 1°C increase in chilled water temp = 2.7% more efficiency, or
- Every 1°C decrease in condenser water temp = 2.7% more efficiency.

For all hydronic systems, adequate care needs to be taken to manage indoor moisture levels such that the dew point of the indoor air is lower than the chilled water temperature, usually by using a dedicated outdoor air system (DOAS) and tight building envelope. If combined with a DOAS, a well-designed radiant slab system is adequate to provide for office-type loads, even in a hot-humid climate, with reduced risk of condensation, as long as the building is well insulated, reasonably airtight and the supply air is dehumidified. Optimally controlled radiant-DOAS combinations are more comfortable for occupants and reduce the energy demand (Feustel & Stetiu 1995). Studies have shown that the use of a tower-side economizer coupled with radiant cooling and a DOAS can reduce cooling season energy costs significantly when compared to traditional forced air VAV systems (see strategy below, Manage Loads by Decoupling Ventilation and Cooling). As a U.S. point of reference, this savings is estimated to be as high as 67% when applied in San Francisco, California (Energy Design Resources 2012).

Best Practices Develop Low-Energy HVAC Strategies

There are other advantages of a well-designed radiant system:

- No wall or floor space is required for diffusers, except small diffusers for ventilation air that can be located at one end of the space.
- There is no associated noise.
- Increased pump consumption is compensated by a large cut in fan consumption, compared to air-conditioned systems.
- It tolerates wide load fluctuations if coupled to high mass surfaces such as floor slabs.
- It tolerates a wide range of air temperatures.
- It can extend the operating range of the water-side economizer.
- It has a gentle failure mode, compared to a standard VAV system's more drastic failure mode. This means that the building can drift for a while without occupants realizing the difference or feeling uncomfortable, even after the equipment is switched off.

Simulation Results
VAV Cooling vs. Radiant Cooling (Simulation result 4)

Data Points
SDB-1 at Infosys, Pocharam: Twin building (Data point 18)
SDB-1 at Infosys, Pocharam: Radiant slabusing DOAS (Data point 19)
Infosys, Bangalore: Radiant panels (Data point 20)
Infosys, Pune: District system with hydronic cooling (Data point 21)
Indira Paryavaran Bhavan, New Delhi: Active chilled beam system (Data point 22)

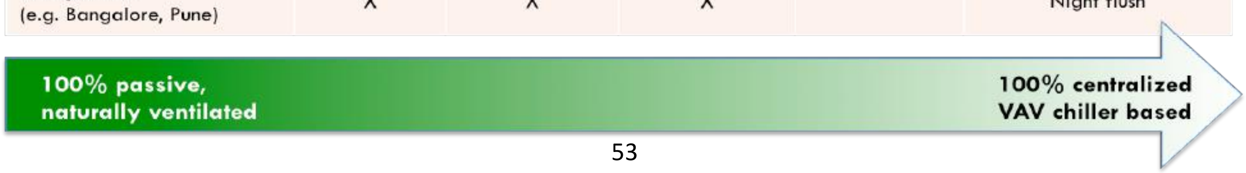
e. **Active chilled beam systems** work with chilled water and conditioned air circulated through modular units attached to ceilings. Sensible cooling using water in a finned cooling coil is combined with the integrated delivery of conditioned ventilation air designed to meet minimum indoor air requirements. Room air is induced through the coil and combined with the supply air to ensure adequate air movement. Chilled beams differ from radiant slabs in that they transfer heat through convection rather than radiation. The advantages to this system with comparatively higher upfront costs are:

- Higher efficiency, since it uses higher chilled water temperatures of 13.5°C–16.5°C, suits free cooling applications, and requires less energy for fan-blown air.
- Higher comfort level due to adjustable airflow pattern, non-drafty air flow, and low noise levels owing to lower air pressures.
- Lower overall operating costs since sensible cooling is achieved with water, elevated inlet water temperatures provide improved chiller efficiency, and it also enables improved integration with a water-sized economizer or geothermal source.
- Reduced space requirements for smaller mechanical equipment leading to higher proportion of rentable space—airflow requirements allow for smaller AHUs with lesser horsepower; smaller ductwork allows for lower floor-to-floor heights, less building skin, and smaller vertical chases.
- Easier maintenance, since this system requires no moving parts or motors to cool; maintenance is based on longer cleaning cycles.

f. **Evaporative cooling systems** use latent energy

Table 7: Potential cooling strategies per climate zone

	Mixed Mode Zoned or changeover; ceiling fans	**Hydronic** Radiant slab/ panel/active chilled beams) +DCV	**Decentralized** possibly progressive/ and seasonal	**Centralized** with high COP, innovative delivery +DCV	**Special considerations:**
Composite (e.g. Delhi, Chandigarh)	X	X		X	Progressive/and seasonal
Warm-humid (Chennai, Kolkata, Mumbai)	X			X	Desiccant cooling
Hot-dry (e.g. Jaipur, Hyderabad)	X	X			Direct/indirect evaporative cooling, Night-flush
Temperate (e.g. Bangalore, Pune)	X	X	X		Night flush



and water to cool down hot and dry air. For example, small droplets of water are sprayed in the air and evaporate. While the air humidity increases, the temperature decreases. This process can be either direct, when water evaporates in the supply air; or indirect, when a heat exchanger transfers heat from the supply conditioned air to the humidified air that is rejected into the environment. This process can reduce the need of a compression or absorption cycle for air conditioning. Direct evaporative cooling is very efficient in hot and dry climates, while indirect evaporative cooling can be used for pre-cooling in more humid climates. In that case, a conventional cooling device will help dehumidify the air supplied to the room, while the rejected air from the zone is used as an evaporative medium. Now cold and moist, the rejected air can absorb the sensible heat of the incoming outside air.

Data Points
Torrent Research Center, Ahmedabad: Passive evaporative cooling (Data point 23)

An overview of potential low-energy cooling strategies by climate zone is provided in Table 7.

Manage loads by decoupling ventilation and cooling

In a typical office space, the airflow required to cool and ventilate the space can be three to four times greater than that required to just ventilate the space. If the space cooling is decoupled from the ventilation, especially through a hydronic system, the central air handling system and associated distribution system can be downsized accordingly. A DOAS system is typically used to serve the ventilation needs and latent loads. A DOAS also allows for the effective use of energy recovery on the incoming outside air to further reduce the associated heating and cooling ventilation loads. Localized demand control ventilation (DCV) also can be implemented (in all climate zones) to turn off the ventilation air when the space is unoccupied, which further reduces the total system energy. The efficiency gain of this DCV strategy needs to be weighed against the additional system complication, cost, and fan energy necessary for the required air terminals.

Also, the traditional air distribution system has air terminal devices to modulate the cooling capacity to each individual space. These air terminals add additional pressure drop and increase the associated fan energy. The space saved by using a DOAS can be used to install a low-static air-side distribution system to further reduce the associated fan energy.

Therefore, consider decoupling the cooling and ventilation. Separate the process load (equipment load) and the sensible load (from cooling, lighting, envelope heat gains) from the latent load (from people and some equipment). Serve different types of loads with various levels of cooling relevant to the specific need, by using chiller plants that simultaneously produce chilled water at different temperatures (called dual-temperature chiller plants).

Provide thermal mass and storage

a. Provide thermal mass through additional concrete or phase-change materials in the walls and roof that can absorb and retain solar heat gain during the day, creating a time lag for entry of heat into the interior. For passive cooling, thermal mass is combined with ventilation—heat is absorbed during the day; ventilation is used to dissipate heat when it is released at night. The thermal mass must be shielded from solar gain by shading, and oriented such that cooling breezes will remove heat. This strategy works well with mixed-mode operations and night flush.

b. Chilled water or ice thermal storage can be used to achieve further reductions in the size of the chiller cooling capacity on hot days and shift cooling load to off-peak hours. The provision of such a storage tank helps to reduce the peak cooling load for hot days and provides flattened thermal and electric load profiles.
The benefits of thermal storage are that it can provide energy cost savings, provide capital cost benefit by helping shave the peak load by creating a time lag, decrease the size of the HVAC equipment, and have a dual use as fire protection (Ford 2012)

Data Points
Nirlon Knowledge Park, Mumbai: Thermal storage (Data point 24)

Consider progressive and hybrid systems

Often, commercial buildings have a variety of spaces, functions and occupancy. Loads can differ in their intensity and sensible-to-latent ratio, or by their spatial and time distribution. For example, separate systems by areas such as comfort air conditioning (occupied spaces), critical load conditioning (24/7 server, equipment rooms); ventilated areas (restrooms and electrical rooms); and pressurized areas (lobbies, staircases, lift wells). Use two or more HVAC sub-systems to compensate for progressive levels of part load. Incorporate and exploit the schedule and load diversity to achieve deeper whole-building energy savings.

Best Practices Develop Low-Energy HVAC Strategies

Implement component-level strategies

Component-level strategies can also bring significant energy reductions. Two examples are:

- Design ducting and piping with minimum bends and turns, use 45-degree bends rather than 90-degree bends, and use gravity to aid downstream flow.
- Provide variable-speed drives on all fans, pumps, and compressors.

Table 8 and Figure 15 provide HVAC metrics for standard-, better-, and best-performing buildings. NOTE: Further details on simulation and thermal comfort results are discussed in Appendix 5: Climate Specific Modeling and Analysis for High-Performance Indian Office Buildings.

Table 8: Table of metrics - HVAC.

HVAC Metrics		Measured	Simulation			
			Temperate *(Bangalore)*	**Hot Dry** *(Jaipur)*	**Warm Humid** *(Mumbai)*	**Composite** *(New Delhi)*
HVAC annual consumption [kWh/m²/year]	**Standard**	110	160	208	181	196
	Better	80	56	77	74	77
	Best	25	18	47	33	49
HVAC Peak [W/m²]	**Standard**	65	80	103	76	91
	Better	25	20	52	27	52
	Best	4	8	21	14	22
Chiller plant kW/ton	**Standard**	1.3	0.83	0.83	0.83	0.83
	Better	0.9	0.83	0.83	0.83	0.83
	Best	0.5	0.62	0.62	0.62	0.62
Cooling load (building) efficiency [m²/tons of refrigeration (TR)]	**Standard**	20	24	21	22	21
	Better	40	37	32	33	31
	Best	67	77	44	53	41

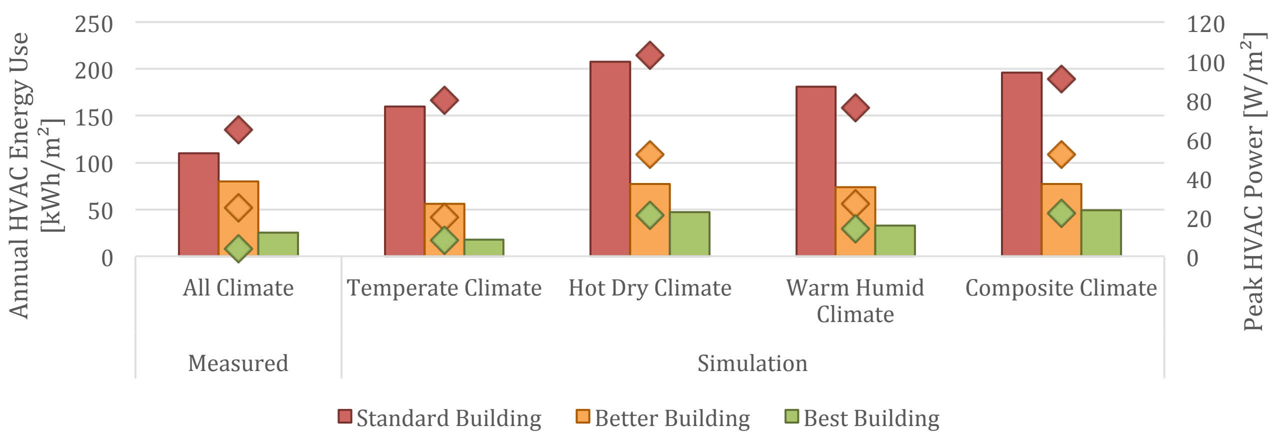
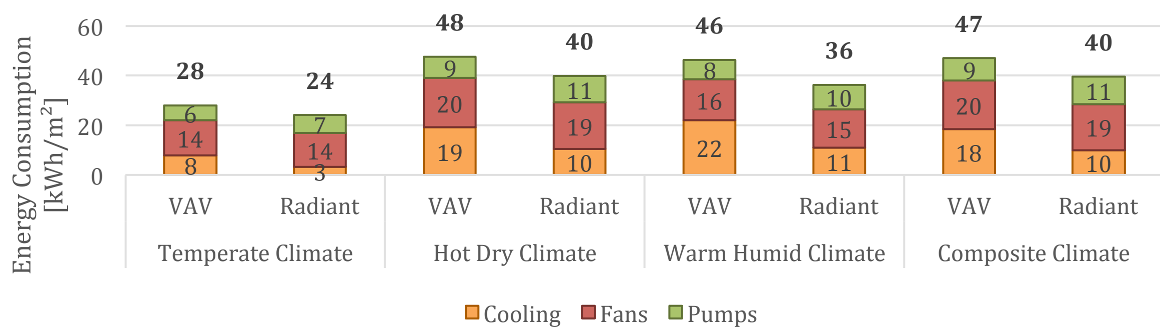


Figure 15: HVAC metrics showing annual energy use (column chart) and peak energy use (diamonds) per climate and for standard, better, and best building performance

Best Practices Develop Low-Energy HVAC Strategies

Simulation Result 4: VAV cooling vs. radiant cooling



A simulation comparison with efficient VAV cooling (model series BP2) showed that use of a radiant panel cooling system (model series BP6) helped to reduce the overall HVAC consumption in all climate zones, and that the latter offers better thermal comfort for occupants. These HVAC consumption savings translate into whole-building energy savings of 4% in the temperate and hot and dry climates, 5% in the composite climate, and 12% in the warm and humid climate. The strategy would be to first control the moisture in the air through dehumidification using a dedicated outdoor air system, and then control the surface temperature of the floor (dew point).

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Data Point 17: Campus for Agilent Technologies, Manesar: Progressive HVAC solutions for diverse spatial loads

At the campus for Agilent Technologies, Manesar, different HVAC systems are installed in this triple-shift building so it can respond optimally to diverse load types. The basic underlying system for its office spaces is underfloor air distribution. Each cubicle has one diffuser with a setpoint maintained at 23 +/- 1°C. The UFAD system uses a larger number of smaller diffusers, rather than conventional ceiling diffusers, and the airflow can be adjusted to meet the comfort requirements of a small group of offices. Return air is evacuated through ceiling outlets, which allows for better air stratification than a system that uses both inlets and outlets in the ceiling. The conference rooms use UFAD that carries the baseload, and an additional ceiling-mounted split unit system carries the load during fully occupied durations. Server rooms and laboratories are provided with an additional packaged air conditioner with its own direct compressor hookup, since they are not connected to the main chillers, to maintain a tightly controlled indoor climate during unoccupied weekend hours. The gym is served by a VAV system with an AHU that is on the gym's morning and evening time occupancy schedule. For all HVAC solutions, cooling is provided with separate water loops. Chilled water is mostly produced during night off-peak hours, and at a higher coefficient of performance (COP) to ensure optimal chiller efficiency and lower energy costs. Chilled water is stored between 6°C to 9°C in large thermal stratification tanks.

Left: picture of the underfloor air distribution outlets in the office spaces. Center: conference room with UFAD and ceiling-mounted split air system, with punched windows for diffused light. Right: the server room with a ceiling diffuser for ventilation and individual air conditioner for cooling.

Data Point 18: SDB-1 at Infosys, Pocharam: A twin building employing efficient VAV and radiant slab systems

Figure: SDB1 Building at Infosys in Pocharam

The SDB-1 building is already optimized through envelope design to have a reduced exterior heat gain of 10 W/m2, and energy-efficiency measures to have a reduced lighting load of 5 W/m2, an 8-W/m2 computer load, and 2–3 W/m2 for other equipment. If occupant load and fresh air load are considered, the combined peak cooling load is an optimized ~45 W/m2, as compared to a "rule of thumb" of 65 W/m2 for owner-occupied, and 110–120 W/m2 for leased buildings.

The building was divided into two symmetric wings. One wing is conventionally cooled with an efficient VAV system, with variable-frequency drives on the AHUs, chillers, pumps, and cooling tower. The other wing employs in-slab radiant cooling. Here, the sensible and latent (dehumidification) loads are decoupled, and two levels of cooling and chiller coil temperatures are provided. The radiant system caters to sensible cooling loads. Chilled water is delivered through a concrete floor core with embedded tubes. The slab temperatures are maintained at about 20°C by controlling the inflow of chilled water through the floor, maintained at 15.5°C. This increase in temperature of supply water has considerable energy benefits (see table below). The latent loads are served by a DOAS. Ceiling fans are used throughout the office spaces to create thermal comfort through the sensation of air movement on the skin.

Using a robust control system with specified average water temperature to control the manifolds mitigates the risk of condensation. The room dew point is the override for the manifold control, and condensation sensors are installed in the shaft override.

The radiant wing requires 75% lesser air and performs 30% better than the VAV conventional wing. The former also provides higher occupant thermal comfort due to the better mean radiant temperature, and better indoor air quality. These changes in cooling methods have also shown radical results in the building's energy consumption patterns. As long as the services are planned out during the planning stage, a radiant slab solution is at par or even more advantageous with respect to space utilization and robustness in comfort benefits as compared to a VAV system.

	VAV Side	Radiant Cooling Side
Peak design efficiency plant	0.64 kW/TR	0.57 kW/TR
Design chilled water temperature	8°C	14°C
Annual power consumption	38 kWh/m^2	25 kWh/m^2
First cost of HVAC system	~INR 3220/ m^2	~INR 3190/ m^2

Data Point 19: SDB-1 at Infosys, Pocharam: The radiant slab solution using DOAS

At the Infosys SDB-1 building in Pocharam, the DOAS (Dedicated Outdoor Air System) is employed to supply fresh air to maintain indoor air quality and to cater to latent loads, i.e. indoor humidity levels. The DOAS needs to supply higher-than-minimum ventilation to keep the office air dry. Supply air is dehumidified and supplied at 15–20 cubic feet per minute (cfm) per person and also keeps the building positively pressurized, which delivers better air quality with occupant health benefits. Ventilation loads are also managed through Demand Control Ventilation (DCV) by constantly monitoring carbon dioxide (CO2) levels in the zones. The air was originally dehumidified through a dedicated direct-expansion (DX) unit to achieve a clear separation of energy consumption for conventional and radiant sides of the building. After about six months of operation, the DX unit and coil was replaced by a chilled water coil to improve the overall system efficiency further. The DOAS uses a runaround coil to transfer heat between the entering fresh air and the air leaving the chilled water coil. A total energy recovery wheel recovers energy from the exhaust air. Additionally, ceiling fans are provided throughout the building to increase air circulation if required.

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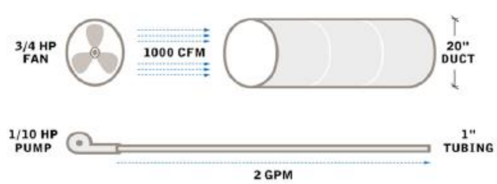


Figure: For the same amount of energy distributed, air ducts (top) take more space and 7.5X more pumping cost than hydronic pipes (bottom).

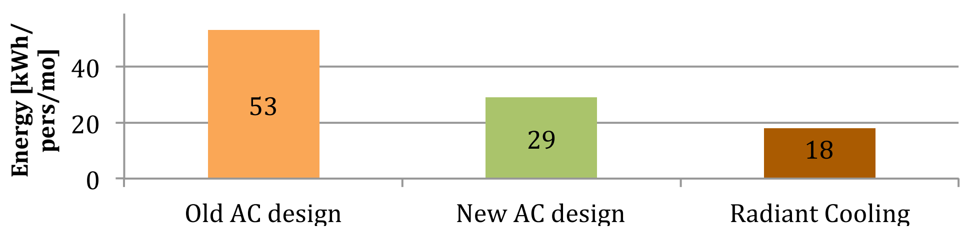


Figure: Comparison of the energy consumption of different HVAC systems between April 2011 and February 2012

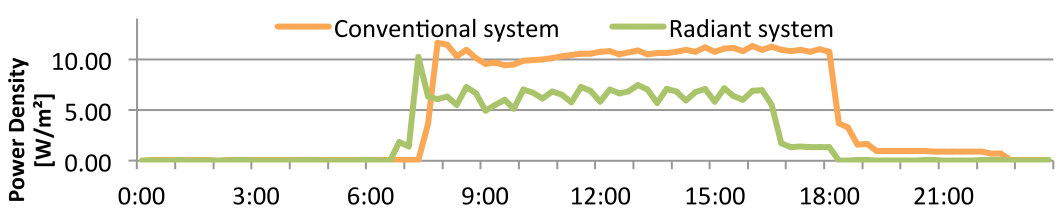


Figure: Comparison of the power density of both sides of the SDB1 building at Infosys, Pocharam

Best Practices Develop Low-Energy HVAC Strategies

Data Point 20: Infosys, Bangalore: Radiant panels

The MC-1 building at Infosys, Bangalore, uses radiant ceiling panels for cooling. Radiant panels are uncommon in Indian buildings and cost ~20% more than a conventional system. At MC-1, there are ~10,000 radiant panels. The panels consist of multiple layers, including the piping to deliver the cold water, graphite to uniformly distribute heat, metal cassette to hold the piping and graphite, and white fleece for acoustics and aesthetics. Supply water enters the panel at 15°C and exits at 18°C, which allows for energy benefits of medium-temperature chilled water.

Although more expensive than a radiant slab, radiant panels are more flexible in design. The pressure drops tend to be higher, and acoustics may be a challenge in certain office typologies. The Infosys team developed in-house panels that produce 193 W/m^2 at a temperature differential of 10 Kelvin as per EN 14240 standard. Additionally, a robust controls system is employed.

With regards to the air distribution, Therma-Fuser™ diffusers provide independent zone control that includes the thermostat, modulating damper, and diffuser in a single package. Unlike conventional building controls, these diffusers have no complicated electronics or pneumatics, and, as a result, require less maintenance. The Therma-Fuser diffusion dampers are mechanically actuated by thermostats to open and close and regulate airflow into the room in response to room temperature.

Figure: Radiant panels and ceiling fans at the MC1 building at Infosys, Bangalore. (Source: Infosys, Uponor)

Data Point 21: Infosys, Pune: District system with hydronic cooling

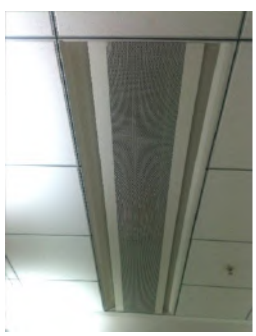
At the Infosys campus in Pune, two of the software development blocks (SDBs) utilize hydronic cooling: SDB 10 has a chilled beam installation and SDB 11 a radiant slab. Further, these are amongst four buildings that share a common central chiller plant, or district cooling system, that contains two medium-temperature chillers (1300TR) for the hydronic systems and two low-temperature chillers (1000TR) for the DOAS. Carrier chillers are used in a series counter flow arrangement; the work done (lift) by each compressor is reduced, which improves the efficiency of the chillers at full- and part-load conditions. The capacity of the district cooling is 2300TR, serving ~ 150,000 sq m and 12000 occupants.

At SDB-10 and SDB-11 Infosys, Pune, energy-efficient air conditioning is achieved by first categorizing the spaces into four types and leveraging this load diversity: (1) comfort air conditioning (workstations, conference and discussion rooms, cabins, and training class rooms), (2) critical load conditioning (server, hub, UPS, and battery rooms), (3) ventilated areas (restrooms, electrical, and transformer rooms), and (4) pressurized areas (staircases, lift wells, and lobbies).

In SDB-10, the comfort air conditioning is provided through a combination of DOAS for dehumidification and an active chilled beam (ACB) system for providing sensible cooling, with water temperature delivered at ~16°C to 20°C through the beams. Each thermal zone is conditioned independently, using a pressure independent balancing control valve (PIBCV) that controls the amount of chilled water going through the chilled beam. The chilled beam valves are controlled to maintain the zone temperature per the setpoint, while the ventilation rate is managed for CO_2 levels using DCV and the dewpoint. If the dewpoint increases above the chilled water temperature, there is a risk of condensation; therefore, dehumidified air is brought into the room to limit the dewpoint under 14°C.

In addition, the following strategies are used: BMS to control and monitor the HVAC system, reduced face velocity across DOAS filters, and coils that allow for low pressure drop. A primary variable flow chilled water pumping system facilitates sequential operations of the pumps to optimize part-load operations. An optimized cooling tower approach temperature, variable flow condenser water system, and variable-speed cooling towers all allow for sequential operations of pumps to modulate the flow during part-load and favorable ambient wet-bulb temperatures. An additional feature deployed at one of the floors in SDB-11 is radiant baffles that deliver cooling capacity in the range of 90-110 W/m2 for a temperature differential of 6 °C.

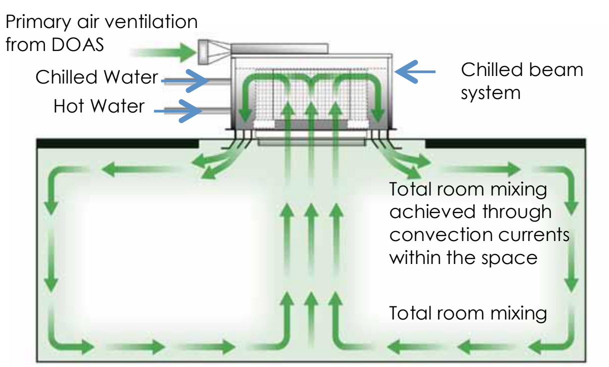
	SDB 10 **Chilled beam**	**SDB 11** **Radiant Slab Cooling**
Building EPI	75 kWh/ m^2	57 kWh/ m^2
HVAC peak load	5.2 W/ m^2	4.2 W/ m^2
First cost of HVAC system	~INR 2820/ m^2	~INR 2450/ m^2

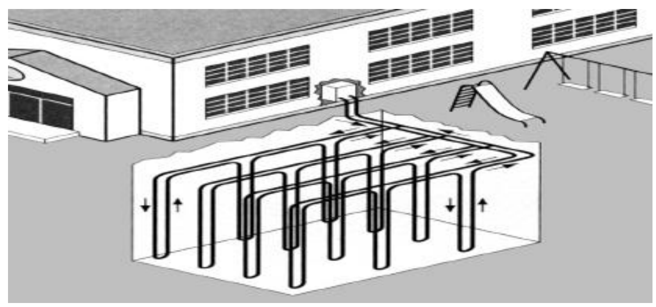




Figures: View of SDB-10 and SDB-11; Chilled beam installation in SDB-10; Office space with radiant baffles in SDB-11.

Data Point 22: Indira Paryavaran Bhavan, New Delhi: Active chilled beam system

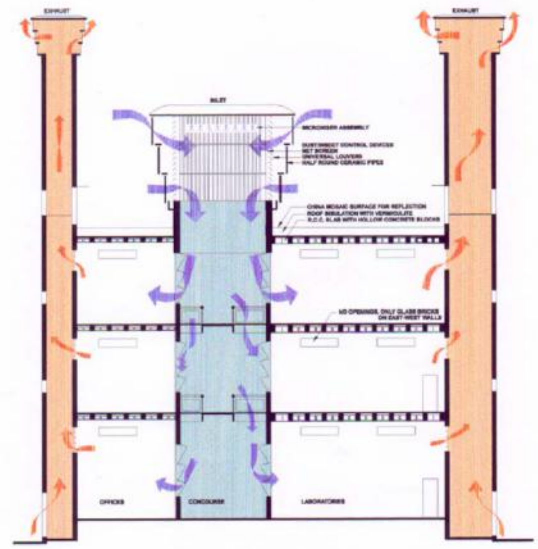
At the Indira Paryavaran Bhavan Building in New Delhi, the cooling load is addressed by first reducing the external heat gain through the provision of deep shading and recessed fenestration. Additionally, aesthetic *jaalis* (latticed screens) are provided for naturally ventilated hallways between blocks that bring the surface temperature of walls closer to the air temperature. An aggressive 40 m^2/TR is achieved through an active chilled beam system. Chilled beams are used in the office spaces for three of seven floors to meet ~169 TR of the entire building load. The inlet water temperature is 16°C, and outlet water temperature is 20°C. The room temperature is maintained at 26+/-1°C. A drain pan is used to drain out condensate, which is expected during the monsoon season. This chilled beam system is used in combination with a geothermal heat exchanger that acts as a free source of cooling. There are 180 vertical bores of 80 m depth along the site, with a minimum distance of 3 m between bores. Condenser hot water is sent at 38°C and back at 32°C. Each bore provides a heat rejection capacity of 0.9 TR; hence, a total of 160 TR of heat rejection is obtained without the use of a cooling tower. (Note: the numbers provided here reference public information, and modeling data provided by Kalpakrit Sustainable Environments.)





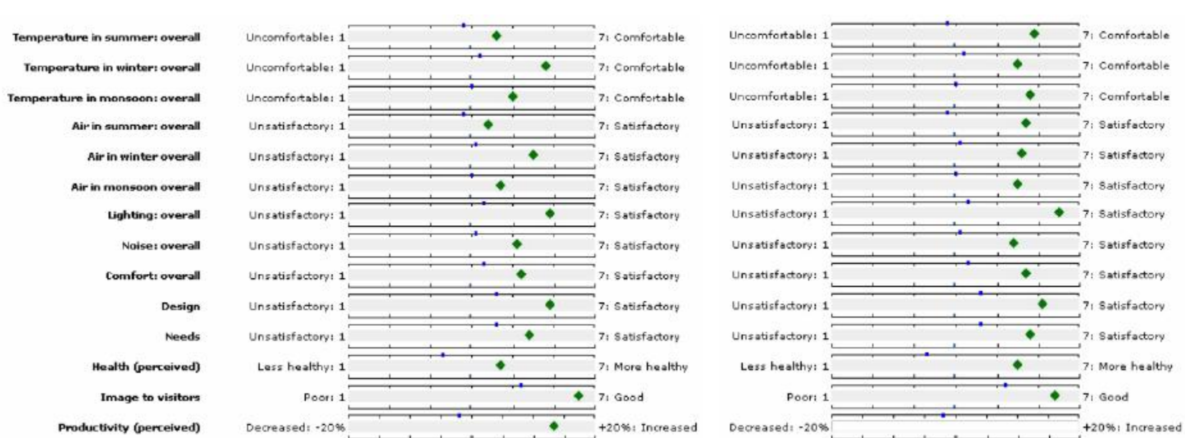
Figures: (Top left) Diagram representing the function of chilled beams in the office spaces. (Top right) Geothermal heat exchange vertical closed loops. (Source: Central Public Works Department). (Bottom) Front façade of the building. (Source: Rehau).

Data Point 23: Torrent Research Center, Ahmedabad: Passive evaporative cooling



Figures: (Left) Picture of the Torrent Research Center (Source: Environmental Health Perspectives). (Right) Schematic section of the passive downdraft evaporative cooling system (Source: Abhikram, Ahmedabad).

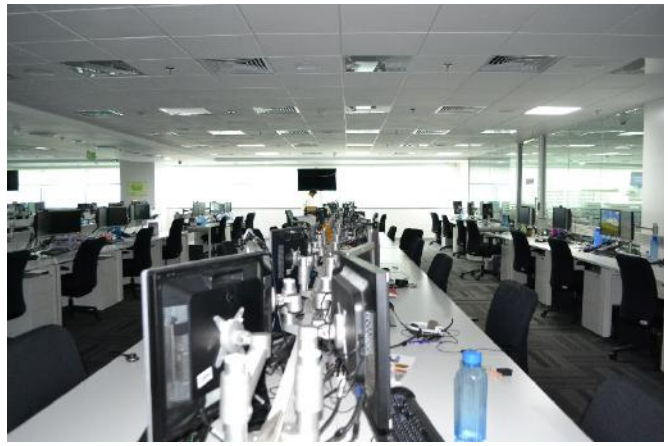
At the Torrent Research Center, four out of six laboratories and office spaces incorporate a passive down-draft evaporative cooling system (PDEC). During the hot and dry season (March–June), outside air is naturally drawn into the three central towers where it is cooled and humidified by a fine mist of water piped through nozzles at a pressure of 50 pascals (Pa). The air is naturally distributed in all spaces and can be redirected to adjacent spaces by the use of hopper windows on the central shaft. During the monsoon season (July–September), the nozzles are closed, and the air is mechanically ventilated through the central shafts. The operational energy data provided show an EPI of 54 kWh/m^2. Further, an occupant survey conducted in 2004 revealed that the buildings incorporating those systems are deemed comfortable by occupants in all seasons, and performed almost as well as their mechanically conditioned equivalent. In complement to the innovative passive down-draft cooling system, the conventional temperature deadband control was dropped to a less constraining and higher temperature threshold of 28°C—that can be exceeded for a limited number of hours per year.



Figures: (Left) Results of a survey in 200) for 100 respondents in the PDEC buildings. (Right) Results of 64 respondents in the mechanically conditioned buildings. (Source: Abhikram)

Best Practices Develop Low-Energy HVAC Strategies

Data Point 24: Nirlon Knowledge Park, Mumbai: Thermal storage



Figures: Picture of the Nirlon building exterior and office spaces (source left: Nirlon).

The Nirlon Knowledge Park is a 23-acre brownfield site built in two phases with expected tenant occupancy of ~25,000. The mechanical system integrates district cooling and thermal energy storage systems (TES) to relieve the chilled water production during the hottest hours, and reduce consumption during energy peak periods. Chillers exploit the cooler night air temperature while cooling down ethylene glycol in a 150-k-liter tank to -6°C and store it in a large tank. During the day, the stored solution is used to contribute to the air conditioning. While the electricity required to cool the ethylene glycol overnight costs Rs 7.25/kWh, the same process would cost Rs 8.00/kWh during the day due to differential tariffs, with the additional impact of higher outdoor temperatures that makes heat rejection more energy intensive. The use of TES has reduced the initial peak-load requirement by two chillers, and it provides a four-hour HVAC backup. The district cooling in the Phase-I consists of nine 350-TR air-cooled chillers with a COP of 3.1, with redundancy built in. Phase-II uses water-cooled chillers. The developer provides chilled water metered by a Btu meter at the chiller that runs at an average of 0.6kWh/Btu; the tenant has AHUs with heat-recovery units. The campus tenants receive the power savings benefits.

Figures: Pictures of the ethylene glycol storage system at Nirlon Knowledge Park, Mumbai.

Best Practices Develop Low-Energy HVAC Strategies

Data Point 25: Suzlon One Earth, Pune: Progressive HVAC systems

The Suzlon One Earth campus in Pune has 6 lakh square feet of office space plus ancillary functions serving its ~2300 occupants. Active, passive, and natural cooling techniques, based on space use, have been used to reduce power consumption. Additionally, the use of microclimatic effects helps reduce ambient air temperature by 3-4 °C. Occupied spaces such as informal meeting rooms and break areas are naturally ventilated, and some break spaces are provided as generous balconies, leveraging the temperate climate of Pune. Circulation spaces, foyers, and atrium spaces use indirect evaporative cooling to maintain comfortable temperatures that infiltrate in about 40% of the conditioned spaces. The remaining 60% of conditioned spaces employ a low-energy water-cooled variable refrigerant flow.

The HVAC system also utilizes strategies including pre-cooling of fresh air and heat recovery/exchanger mechanisms to minimize energy consumption. The indoor unit's cooling operation offers flexibility to the user to control the desired temperature in any location on the premises per individual preferences. Scheduling and on-off for controls for temperature and air flow are possible for each enclosed space. Such flexibility of operation, based on users' needs, curtails waste and enables substantially higher energy savings than conventional systems.

The basement is the main entrance for occupants. It is designed with light wells and wind risers, coupled with jet fans connected to carbon monoxide sensors, to create a stack effect that brings in fresh air through large openings that double as plumbing shafts at the basement perimeter. The entire HVAC system is designed for 30% higher ventilation rates than ASHRAE standards. The programmable logic controller (PLC)-controlled dual-speed jet fans towards the center of the basement sense CO and CO2 levels, pick up stale air from 10 locations, and exhaust it onto the terrace. The connected load is brought down to 216 kW, as opposed to 472 kW expected using conventional air-conditioning methods, thereby saving 50%of the energy that would be used to operate a ducted basement ventilation system. Overall, the BMS shows that the campus has reduced its energy consumption by about 40% below the baseline. Only after energy-efficiency optimization is the 155-kW wind-solar hybrid renewable system used for lighting and air conditioning.

Figures**:** Suzlon One Earth building, Pune. (Left) Jet fans provide ventilation to the entire basement parking area. (Right) An energy-efficient water-cooled variable refrigerant volume system is used for the main office and conference areas. Additionally, no-energy details, such as mesh chairs, improve ventilation comfort for occupants (source: Synefra).

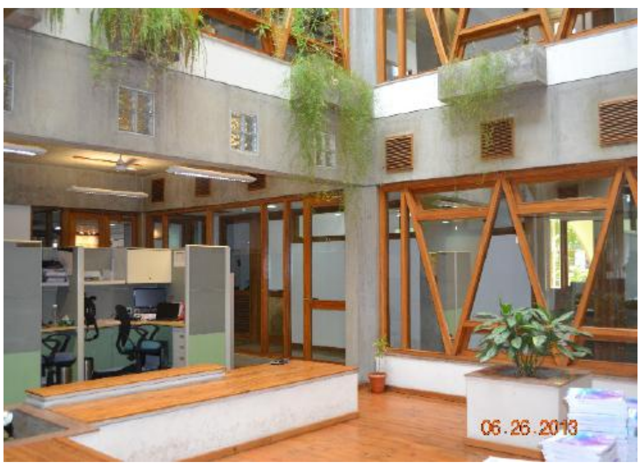
Best Practices Develop Low-Energy HVAC Strategies

Data Point 26: Campus for Agilent Technologies, Manesar: Heat from all sources

The use of free, renewable, and eco-friendly heat sources can not only reduce energy consumption for space-heating and service hot water, but it can also be applied to space cooling. At Agilent Technologies, Manesar, hot water for kitchen appliances is provided by solar panels with a gas backup. Absorption chillers that use waste heat as a power source, thus greatly reducing energy consumption, produce chilled water used for air conditioning. High-performance screw chillers generate the balance of chilled water. Finally, space-heating is provided by a co-generation gas tank, which reduces the losses from a conventional gas heater by simultaneously producing electricity.

Data Point 27: S M Sehgal Foundation (SMSF), Gurgaon: Multiple HVAC solution

The SMSF building is an innovative example of the use of a hybrid HVAC system to cater to the diversity of spaces (front vs. back of house, cubicles vs. private offices, singly vs. doubly loaded corridors, office vs. guest house, etc). In Phase-I buildings, the offices and canteen are cooled by AHUs with variable frequency drives (VFDs) in each wing. The auditorium is ventilated and cooled with UFAD using a raised floor, but catered through AHUs with VFD. The guest house uses a variable refrigerant flow unit for each room, to account for the variable occupancy. In Phase-II buildings, the office spaces use radiant cooling, achieved through a chilled water loop embedded in the floor. Fresh air is supplied using displacement ventilation. The overall cost of the radiant-slab cooling is comparable to that of a conventional system since labor is relatively inexpensive, making first costs comparable and operating costs considerably lower. Water at 16°C is run through the radiant slab, and ceiling fans are run in reverse such that it sets up an upwards convection current to pull air up and away from the slab.



Figures: (Left) Picture of the office spaces in SMSF Phase-I, where traditional chilled air terminals are installed above the occupant's cubicle and ceiling fans are used to create air movement and gentle breeze for comfort. (Right) In the auditorium, the cooling air is provided through UFAD, using small air diffusers.

Implement Climate Control Strategies

Sensors and control strategies are key to an optimal load utilization and distribution.

Integrate naturally ventilated and mixed-mode cooling fully or partially

This approach helps to decrease air-conditioning load. Two different solutions have different attributes (Brager 2007):

a. **Zoned mixed-mode:** Spatially separate the zones that could be naturally ventilated. A variety of spaces can be designed without air conditioning, such as semi-outdoor or naturally ventilated lounges, lobby spaces, corridors, active stairwells, cafeterias, common areas, mechanical and engineering rooms, and others. In this case, fully naturally ventilated spaces are contiguous to mechanically conditioned areas.

b. **Changeover mixed-mode:** It is also possible to design spaces with an air-conditioned mode, but with manually or automatically operable windows or mechanical systems to benefit from natural ventilation daily or seasonally when the outdoor environment is conducive. This type of operation allows temporal shifts between air conditioning and natural ventilation.

Naturally ventilated and mixed mode spaces are deemed more comfortable for a wider range of temperature than conditioned spaces. ASHRAE Standard 55 and Indian model for adaptive comfort, IMAC (CARBSE, 2014) suggest that people adapt their comfort range with the outdoor air temperature so that, in a hot environment, naturally ventilated and mixed mode spaces are perceived as being comfortable at a higher temperature than mechanically conditioned ones. The National Building Code 2017 validates the use of IMAC for mixed-mode spaces.

Simulation Results
Changeover mixed mode (Simulation result 5)

Data Points
SDB-1 at Infosys, Pocharam & Suzlon One Earth, Pune: Mixed-mode operations (Data point 28)
SM Sehgal Foundation (SMSF), Gurgaon: Reduced conditioned zones (Data point 29)
Development Alternatives, New Delhi: Adaptive comfort: (Data point 30)

Use ceiling fans to deliver occupant comfort

Several high-performance and business-as-usual office buildings in India use ceiling fans in conjunction with operable windows. However ceiling fans have somehow fallen out of favor, being regarded as being too low-tech for the image of contemporary buildings. CBERD surveys in Indian offices show that the lack of air movement is a primary reason for thermal discomfort, and occupants cite dissatisfaction about the inability to control air movement. Occupants are more comfortable with the sensation of air movement on their skin. They perceive fans as fast acting and rely on it for achieving comfort in a short span of time (Honnikeri 2014). These studies show that occupants prefer to have air movement; a combination of operable windows and fans worked well in providing comfort. Please see Appendix 5: Simulation for more details.

Data Points
SDB-1 at Infosys, Pocharam (Data point 28) and Sehgal Foundation (SMSF), Gurgaon (Data point 29): Use of ceiling fans

Demand control ventilation

Most conventional buildings use a constant or scheduled ventilation rate, resulting in unnecessary ventilation—and air conditioning when cooling and ventilation are coupled—when rooms are partially occupied or even vacant. Installing CO2 sensors in occupied rooms and controlling the ventilation rate to maintain a CO2 setpoint can reduce fan consumption by up to 20%.

Data Points
Paharpur Business Center, New Delhi: Fresh air and pollutant control (Data point 31)

Best Practices Implement Climate Control Strategies

Monitor and control operable shadings and windows

Having control over the position of shading and window openings can enable optimal daylighting, temperature, and ventilation conditions. An optimal shading position reduces glare and unwanted solar radiation while maximizing outdoor light; when controlled correctly, operable windows potentially can create a more comfortable environment for occupants and reduce the need for mechanical air conditioning.

Educated choice of sensor type and location

The objective of air conditioning is to maintain a comfortable indoor environment for occupants. However this is often an unmet need despite sophisticated air conditioning, with office occupants being too hot or too cold, or the indoor air quality at questionable levels.

Sensors should be used to monitor and provide feedback loops for control of temperature, humidity, and indoor environmental quality. Ideally, they should be placed away from appliances, openings, or ventilation and cooling devices, to represent the zone average conditions more faithfully. For instance, thermal comfort derives from multiple values, and an ideal temperature sensor should measure temperature as a human would. A small (3 to 5 cm), half-spherical grey sensor can report air and radiant temperatures similar to the way a human body does.

Simple rule-based control

Simple rule-based HVAC control strategies are considered no-cost improvements, since they use elements that already exist in most—if not all—building design.

a. **Night setback:** Increase cooling temperature setpoint when the building is unoccupied (nights, weekends, and holidays). Gradually reverse back to a chosen comfort setpoint in early morning to reduce a sudden strain on HVAC equipment. This is most effective almost year-round in a moderate climate zone.

b. **Night ventilation:** Over-ventilating the building when nights are cool will pre-condition the building and help reduce cooling demand during the day. When possible, opening windows can even reduce the cost of this solution by reducing fan consumption, but that decision must consider the use of effective, well-maintained filters for outdoor pollutants, as well as safety risks. Night ventilation works best in buildings with high thermal mass, such as concrete buildings, since the building structure can absorb more heat during the day and maintain a comfortable environment longer. Night ventilation can be controlled with a simple outside air temperature sensor, or with an enthalpy sensor in climates with high humidity, to prevent the unnecessary introduction of water vapor.

Data Points
Infosys, Pune: Enthalpy-based night flush (Data point 32)

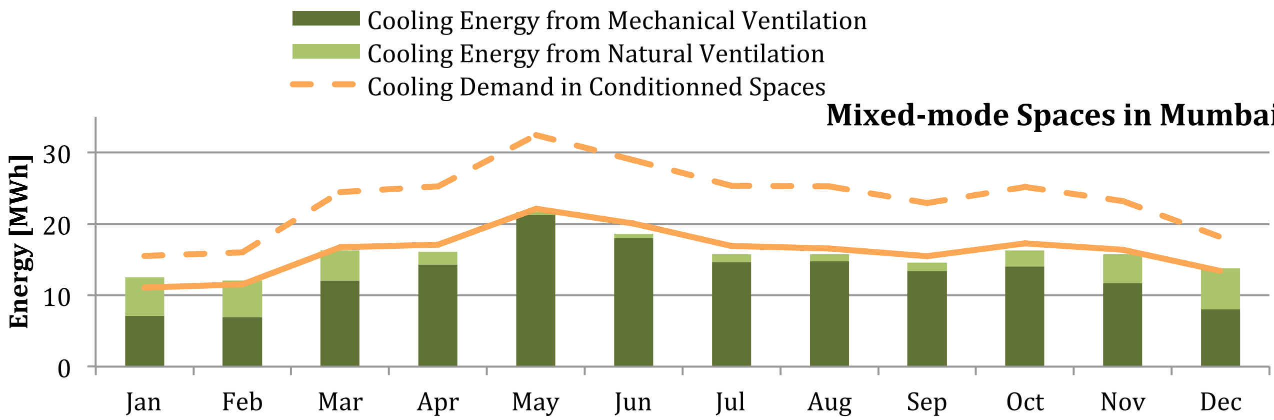
c. **Adopt a flexible setpoint and lifestyle changes:** As controls in buildings are becoming more prevalent, it is technologically simple to adopt a flexible setpoint based on external environmental factors and occupant adaptations. According to a modeling study (Manu, et al 2011), a savings of 5%–6% in EPI can be realized per 1°C increase in thermostat setpoint temperature, and this savings is greatest for an internal load-dominant building. Separate setpoints could be adopted for summer and winter seasons. The critical temperature for comfort is generally assumed to be 26°C, but research conducted in hot and humid climates suggest that an acceptable temperature for occupants acclimated to such environments is up to 28°C in air-conditioned buildings and 31°C in naturally ventilated buildings (Thomas, et al. 2010) (Nicol 2004). Further preliminary findings from chamber studies conducted by the CBERD project reveal at least 90% thermal acceptability for up to 32°C (89.6°F), 60% relative humidity (RH). With moving air, people stayed thermally neutral up to this threshold.

Data Points
Sears Holdings, Pune: Flexible setpoint (Data point 33)
Torrent Research Center, Ahmedabad: Comfort threshold (Data point 34)

d. **Add use of economizer:** An economizer is a combination of sensors, actuators, and dampers that reduce air conditioning by introducing more outside air into the supply loop. In cooling mode, if the outside temperature (or enthalpy) is lower than the return air from the building, then return air is driven out of the building while more outside air is brought into the mix—reducing the load on the cooling equipment. The opposite control can be used in heating mode. Economizers are the most effective in temperate climates and for building (or zones) with high internal gains, such as server rooms. High quality filtration should be maintained in polluted environments to assure good indoor air quality.

Data points and Simulation Results

Simulation Results 5: Changeover mixed mode



In Mumbai, due to the high temperature in summer, spaces that can be naturally ventilated still require mechanical cooling to address high thermal load during the daytime when there is no sea breeze. Naturally ventilated spaces are perceived as more comfortable by an occupant, which enables a higher temperature setpoint and thus creates a significant opportunity for reducing cooling demand. While all climate zones benefit from natural ventilation, simulation shows that climate zones with low diurnal temperature variability (e.g., coastal climate of Mumbai) are the best candidates for a good integration of mixed-mode spaces, since occupants are more likely to adapt to warmer spaces. The energy-savings opportunity ranges from 8%–12% in composite, warm and humid, and hot and dry climates to 17% in temperate climates. However, the number of hours of mixed-mode opportunity ranges from 38% of the occupied time in hot and dry and composite climates to 52% and 64% of occupied time in warm and humid and temperate climates.

Best Practices Implement Climate Control Strategies

Data Point 28: SDB-1 at Infosys, Pocharam & Suzlon One Earth, Pune: Mixed-mode operations

Figures: Naturally ventilated spaces at SDB-1 on Infosys Pocharam campus, and at Suzlon One Earth campus. (Left) The cafeteria at Infosys, Pocharam, utilizes natural ventilation enhanced with breezeway and ceiling fans) in dining and interaction spaces despite high occupancy density. (Right) Small terraces interspersed between office blocks serve as attractive break room spaces at Suzlon One Earth in Pune (photo: Synefra).

Data Point 29: S M Sehgal Foundation (SMSF), Gurgaon: Reduced conditioned zones and zoned mixed-mode

At the SMSF building, only 45% of the built environment is conditioned, while the rest is open to the outdoor and uses passive design to maintain a comfortable, naturally ventilated environment (zoned mixed mode). The central atrium uses a lattice screen that allows air to permeate through while losing some of its heat to the stone. The water body in the courtyard further cools air through evaporative cooling, while the stones surrounding it collect rainwater. The microclimate is cooler than the ambient temperature by 3°C–4°C without the need for active cooling. This also allows cheaper, single-pane windows to be used for spaces adjacent to the courtyard since the heat gain is reduced. All habitable workspaces are conditioned, while the basement, courtyard, restrooms, lobby, and passages are not.

Figure: Pictures of the atrium and view from the adjacent spaces into the courtyard

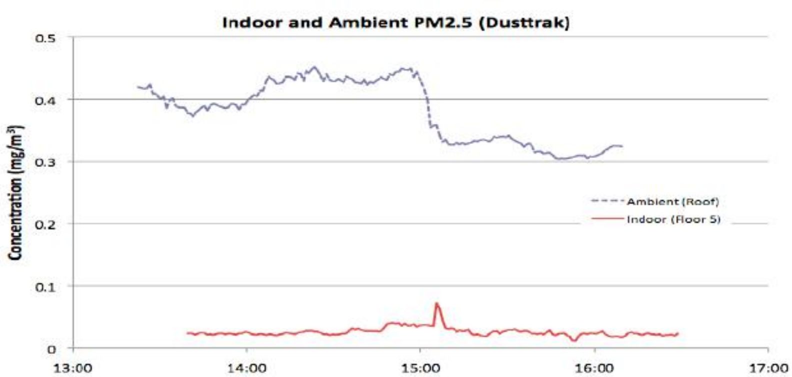
Additionally, the workspaces have been designed for changeover mixed-mode operation. For the cool seasons, all spaces have operable windows. All spaces have ceiling fans. There is a possibility of night flushing when nights are cool but days are warm. It is anticipated that those who find this temperature warm would switch on their ceiling fans. However, for reasons of security, dust, and insects, windows are rarely opened apart from the ones facing the internal courtyard, even in the best seasons. The operation of the air-conditioning chiller is managed by the building maintenance staff to minimize the time when the chiller is on in the summer. Occupants use ceiling fans during the in-between seasons while the building floats at a higher adaptive temperature comfort setpoint of 26.5°C.

Data Point 30: Development Alternatives, New Delhi: Adaptive comfort

At the Development Headquarters building, there is a strong behavioral component of comfort and sustainability. There is user acceptance of an indoor temperature range (using air movement) from 18°C (in winter) to 28°C (in summer), and 30°C on exceptional days instead of the industry norm of a 24°C setpoint. The idea is that if the ambient air temperature is, for example, at 37°C ambient, non-compressor cooling can bring temperature down to 31-32°C, while air movement using ceiling fans can yield comfort at that temperature. Hence comfort is manageable at 31°C– 32°C, rather than needing to expend unnecessary cooling energy to bring the indoor temperature all the way down to 24°C. With a little extra energy to dehumidify, the space can become comfortable, given the ASHRAE adaptive comfort model's strong applicability to India (CARBSE 2014). Second, the concurrent mixed-mode strategy has been employed such that circulation areas, stairways, and services are naturally ventilated. Third, the mechanical system is a "hybrid" air-conditioning system, given the composite climate of Delhi that has extremely hot and dry summers and warm and humid monsoons, as well as cold winters. Evaporative cooling is used during hot and dry months (April–June). This is supplemented by refrigerant cooling during hot and humid months (July–September). These strategies have reduced the peak cooling load significantly and allowed for a cooling system downsizing that decreased first costs and reduced operational energy use by 30% compared to the design baseline (source: AB Lall and Associates).

Data Point 31: Paharpur Business Center, New Delhi: Fresh air and pollutants control

At the Paharpur Business Center (PBC) in New Delhi, lifestyle changes such as implementing a climate-suitable dress code and mesh-back chairs that aid ventilation have also been adopted. The setpoint for offices is maintained at 24 +/- 1°C (75 +/- 2°F), with relative humidity not exceeding 60%. For this building, each 1°C-increase in temperature provides a 5% savings in air-conditioning costs. Additionally, volumes of fresh air are treated with the help of selected varieties of plants, then filtered and supplied through the mechanical system to the building. The treated fresh air is constantly monitored for volatile organic compounds and other contaminants, and has proven to be of high enough quality to enable adequate ventilation delivery at 11.8 cfm/person. This optimization between quality and quantity has provided a 10%–15% energy benefit.



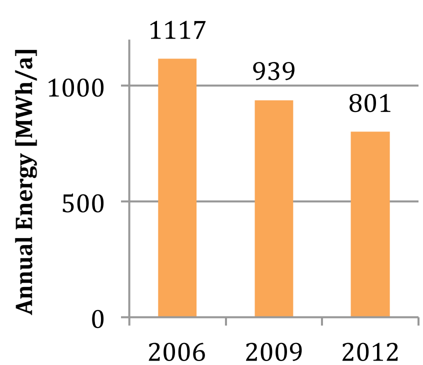


Figure: Data from PBC, Delhi. Left: typical day real-time study of $PM_{2.5}$ (2.5 micrometer particulate matter). The red line shows highly reduced indoor levels, while the blue line shows ambient (roof) levels. (Right) A graph showing a 30% reduction of energy consumption from the pre-retrofit level in 2006 at PBC, owing to cross-cutting retrofits (source: PBC team).

Data Point 32: Infosys, Pune: Enthalpy-based night flush

At Infosys, Pune, the building ventilation is switched on for a few hours at night if the outside air enthalpy is less than 48 kilojoules per kilogram (kJ/kg). This allows for free cooling, where cool outside air reduces the heat stored in the building structure while consuming very low energy (for ventilation fans only). This helps in reduced cooling load in the daytime when the cooling system is switched on.

Data Point 33: Sears Holdings, Pune: Flexible setpoint

The air conditioning controls at Sears Holdings, Pune, offices. If occupants leave their office for a few hours, they reset their individual thermostats from 24°C to 28°C to save energy.

Figure: Flexible Setpoint Management
(Photo: Facilities Team, Sears Holdings India)

Data Point 34: Torrent Research Center, Ahmedabad: Comfort threshold

At Torrent Research Center, in addition to the innovative passive evaporative cooling system, the conventional temperature deadband control was dropped to a less constraining and higher temperature threshold of 28°C that can be exceeded for a limited number of hours per year.

Despite a warmer temperature, an occupant survey revealed that the level of satisfaction for overall comfort was high. The results of the survey can be found in the section “Optimize HVAC Systems”, in the data points for the evaporative cooling system at the Torrent Research Center.

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Section 3: Building Information Systems

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Install an Energy Management and Information System

Buildings waste 10%–30% of their energy due to operational inefficiencies (Mills 2009). Energy management and information systems (EMIS) consist of data acquisition hardware, communication systems, and performance monitoring software used to store, analyze, and display building energy data. EMIS can enable significant energy savings by tracking energy cost and consumption patterns, identifying system- and component-level energy use and waste, and benchmarking performance against the building's past performance or similar buildings. EMIS offer facility managers the capability to track and report hourly, daily, and weekly energy use, to take data-driven actions and reports for tighter schedules and controls, repairs, audits, and upgrades, as well as to offer building owners insights into their quarterly and annual operational costs—enabling better investment decision making for efficiency retrofits.

Using an EMIS

In Indian government buildings, 20%–25% of energy is wasted (Ministry of Power 2004), with even greater waste likely in private-sector buildings (Jones, Lang, and Lasalle 2008). The first step to understanding energy use and potential waste is to install an EMIS. EMIS collect, analyze, and display building energy data and enable site operational efficiency (Granderson 2012) (Figure 16). An EMIS measures the energy consumption of given equipment, zones, end uses, and spaces. It offers building energy data for building operations. Whereas a BMS controls mechanical equipment and connects the HVAC, lighting, security, and protection systems, an EMIS focuses primarily on the energy information, gathering electricity and gas consumption data from meters and sub-meters to monitor various loads (i.e., end uses and specific spaces). If used well, an EIS enables a building to become "self-aware" and operators to continuously correct and optimize operations towards persistent energy savings.
Specific strategies concerning EMIS are outlined below.

Data Points
Paharpur Business Center, New Delhi: Accurate measurements (Data point 35)

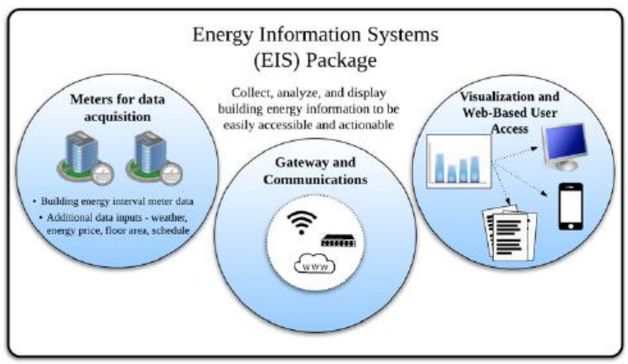


Figure 16: EMIS components including interval sub-metering hardware, communication gateway, and software with user interface.

Design for meterability

Design the mechanical, electrical, and lighting system circuits so that these distinct end uses are separated at the panel level (New Buildings Institute 2011). This will enable sub-metering to be disaggregated cleanly at the system level to enable operators to better understand and manage system-wide energy consumption.

Promote data-driven decision-making

Energy data must be "actionable." If energy data can provide insight leading to specific actions, operations and maintenance staff can focus on proactively managing energy performance rather than retroactively responding to occupant complaints or waste-related energy bills. Understanding close-to-real-time energy consumption from an EMIS enables building managers to identify and correct inefficient systems and components quickly, and facilitates better servicing and extended life of equipment and assets.

Organizational business drivers should provide the rationale for EMIS design and use on various timescales.

Facilities operators need answers to explicit questions, on an hourly, daily, or weekly basis, pertinent to specific business drivers (provided in bold). Each question has corresponding metrics (provided in italics) (Singh et al 2017):

Business Driver: Monitor energy use

i. What is the daily/weekly absolute energy use? *(kWh/day or week)*
ii. What is the daily/weekly normalized EPI? *(kWh/m^2/ day or week); (kWh/ FTE/ day or week)*
iii. What is the daily/weekly end-use breakdown? *(% portion of the total energy use)*

Business Driver: Track demand

iv. What is the load demand per end use of my building, and are the end uses operating efficiently? What are the average loads, and the peak: base ratio between occupied and unoccupied period loads. These data provide insight into the extent to which unnecessary loads are shut off during nighttime or weekend hours. *(kW, or kW/Ton)*

Business Driver: Track cost

v. What is the daily/weekly fuel consumption and cost? *(INR/day or week)*

Business Driver: Benchmark compared to past

vi. How is my building performing compared to a past time period? What are trends for continuity and breaks in energy usage? What is the electricity waste that should inform energy-efficiency actions? Charts include simple tracking of energy consumption (KWh) and load profiling of critical loads (KW).

On the other hand, for executives, sustainability managers, owners, and other investment decision makers, visibility regarding energy cost, consumption, and waste should be provided quarterly or annually. These data can answer some important questions pertinent to the business drivers (provided in bold), each with corresponding metrics (provided in italics) (Singh et al 2017):

Business Driver: Monitor energy use

i. What is the quarterly or annual snapshot of the building's energy use? *(kWh/year or quarter (qtr), kWh/m^2/year or qtr, INR/year or qtr)*

Business Driver: Track cost

ii. What are the absolute energy costs for fuels and cost trends? This helps in reconciling energy billing costs and identifying variances in cost vs. actual consumption vs. budget. The answer indicates surplus or deficit, and calculates return on investment (ROI) and the cost of various projects. (*INR/fuel increases or decreases across quarters or years*)

Business Driver: Benchmark performance compared to others

iii. How is my building performing compared to its peers, or within the portfolio (i.e., cross-sectional benchmarking)? *(kWh/m^2/year)*

Business Driver: Report emissions

iv. What are the carbon emissions (especially if required for disclosures)(*metric tons of carbon dioxide [$MTCO_2$]/year*)

From the EMIS data, a facility operator should glean the answers and determine energy patterns, loads, and costs at various time scales. Next, they can drill deeper to identify sources of any energy waste, and inefficient equipment and system operation. Then, based on data insights, the operator can take actions (Figure 17) such as:

i. Updating schedules and tighter setbacks
ii. Implementing closer controls
iii. Performing the required repairs.

Finally, as needed, they can make the case to higher management to invest in following actions:

iv. Conducting energy audits
v. Making capital investments for implementing energy-efficiency retrofits.

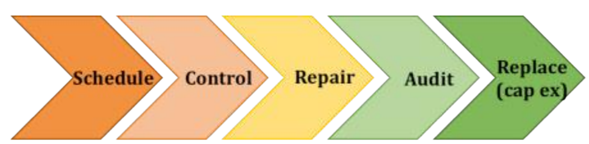


Figure 17: Key energy management actions that may be derived from EMIS data insights

Data Points
Suzlon One Earth, Pune: Controlled loads (Data point 36)
Sears Holdings Offices, Pune: Sectored building management system (Data point 37)

Select functionality based on your organizational needs

A best practice recommendation is to install an EMIS that offers all or some of the above-mentioned functionality, based on what is most appropriate for business drivers. These may include monitoring energy use, tracking cost and demand, benchmarking performance, identifying and tracking energy-efficiency project performance, and reporting emissions. Figure 18 shows the process for selection and mapping the EMIS functionality to the business drivers.

An EMIS provides a user interface with charts, notifications (such as alerts and recommendations to the facility manager), and quarterly reports to executives. More sophisticated systems can provide regular or fault-based e-mail or texts and generate work orders.

Train vigilant building managers and empower facility engineers

Train managers with a keen eye to walk around the building and/or manage BMS and EMIS regularly—and to decipher building symptoms and maintain hardware.

Train engineers and operators to conduct EMIS analyses and first-order responses such as energy-based troubleshooting in-house, with vendor support limited for actions such as recalibration of meters and software upgrades. Capable in-house staff helps to keep the EMIS cost effective. The use of EMIS dashboards with built-in charts, notifications, alerts, reports, and the use of best practice recommendations such as tracking of energy consumption energy fuel cost and hourly load profiling of critical loads enables operators to gain insights into energy consumption patterns. These insights enable data-driven actions as detailed above.

Data Points
Infosys: Energy data-driven decision-making (Data point 38)

Implement performance-based design and contracting

A *performance-based contract* is a results-oriented contracting method that focuses on the outputs, quality, or outcomes that may tie at least a portion of the contractor payment, contract extensions or renewals to the achievement of specific, measurable performance standards and requirements. (GAO, 2002). A performance based contract can hold the design-build team accountable to a certain energy design goal that has been agreed upon, such as, say, 30% better than the baseline model, or a specific target effective EPI. A certain percentage of the overall contract award be can retained until the first year of performance is verified through a measurement and verification (M&V) process. This keeps the contractors accountable, and involved, and takes integrated design process into operations.

Recommend a green lease

A *green lease* is an environmental and energy-savings agreement between the building owner and the tenants, in the case of tenanted operations. It encourages tenants to segregate their loads at the panel level, meter the loads, and enable better energy management for the entire building including the tenanted spaces. A recent report estimated that green leases have the potential to reduce energy consumption in U.S. office buildings by as much as 22%, yielding reductions in utility expenditures in commercial buildings up to $0.51 per square foot. It shows that, when executed, green leases have the potential to provide the leased U.S. office market $3.3 billion in annual cost savings (Institute of Market Transformation 2015).

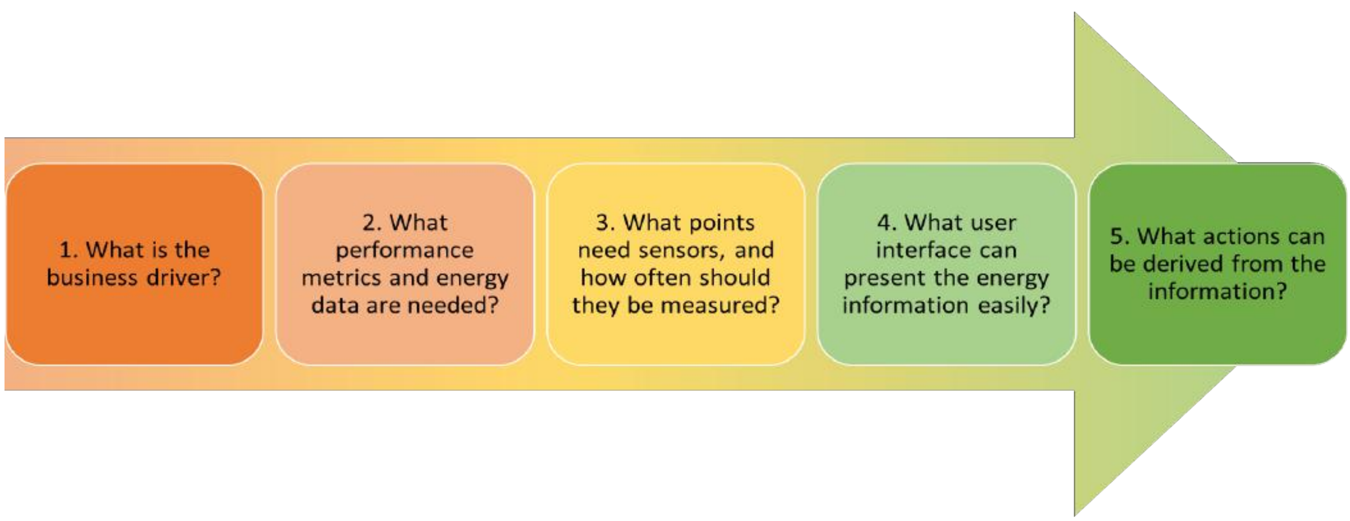


Figure 18: Process for mapping of EMIS functionality to organizational business drivers

Figure 19: Suggested dashboards for an energy management and information system (EMIS). Relevant for different timescales as indicated, the daily dashboard is pertinent to facility operators, whereas the monthly/annual dashboard provides higher-level visibility to decision-making executives (source: Singh, et al 2017)

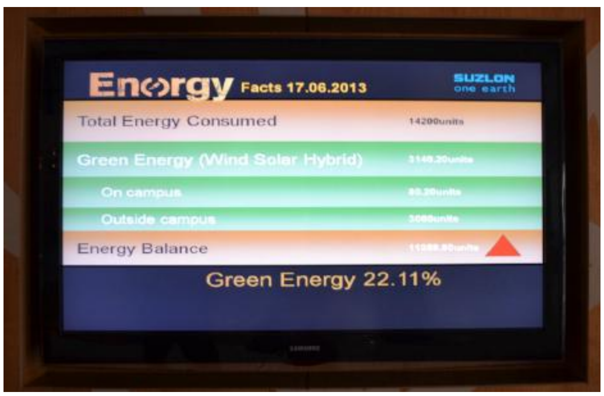
Best Practices Install an EMIS

Data Point 35: Paharpur Business Center, New Delhi: Accurate measurements

At the Paharpur Business Center, the executive management team understands that accurate measurement is at the core of any monitoring and reporting system. Therefore more than 50 calibrated meters have been installed during the retrofit. The BMS system logs and stores hourly energy consumption from these meters. The Engineering Department analyzes the energy consumption data from these meters and identifies areas for improvement. The Quality Assurance Department reviews measurement and calibration methodology; it is checked and verified during internal audits, surveillance, and third-party audits under ISO-9001 and ISO-14001. The daily report of energy- and water-consumption is shared with the highly engaged CEO for input and major improvement decisions. Quarterly internal audits are conducted to analyze the efficiency of the energy management system and for continual improvements.

Data Point 36: Suzlon One Earth, Pune: Energy data display and management

At Suzlon One Earth, dashboards that provide energy metrics from whole-building energy meters are prominently displayed in the building as part of the LEED requirement. Whole-building energy measurement and tracking is a first step toward energy management.



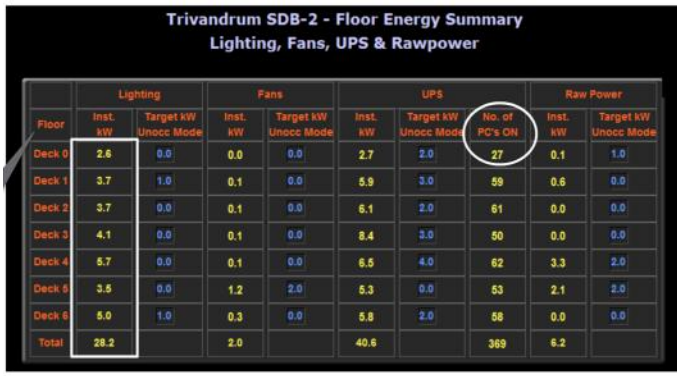
Figures: The energy dashboards for visitors (left) and operations staff (right) at Suzlon One Earth.

Data Point 37: Sears Holdings Offices, Pune: Sectored building management system

At the Sears Holdings offices in Pune, controls for HVAC and lighting are provided for each pod of four workstations. Also, each individual DX unit is controlled at the pod level; these are less efficient units, but the higher level of control offsets the inefficiency. Building guards have been empowered to check in every hour to make sure that lights and laptops are turned off when not being used and air conditioners are not unnecessarily functioning. These actions have resulted in substantial energy benefits.

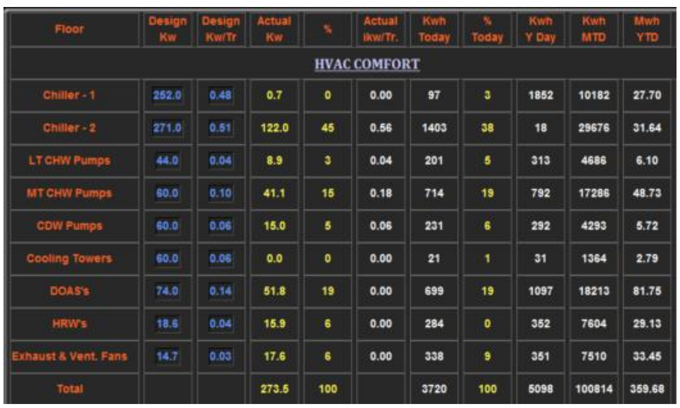
Data Point 38: Infosys: Energy data driven decision-making

At their buildings, Infosys has installed meters and sub-meters at different levels to measure various building loads. These loads are segregated by floor and by equipment. The energy data acquired by the system are analyzed by at least two dedicated personnel, to compare to historical averages, understand trends and identity anomalies. These data are further tied into a building management system (BMS), to drill down further and identify potential areas of improvement, such as better scheduling and tighter controls. The cost of the BMS was ~Rs 515/m2, or ~Rs. 60 lakhs for a 12,000m2 wing. Infosys uses the following factors to make data actionable: setting baselines and targets, installation of field sensors, data-driven engineering, performance-based contracts with design and product professionals, and continuous measurement and verification. Building performance has been maintained consistently by studying real-time data and taking remedial action immediately wherever necessary.



Trivandrum SDB-2 - Floor Energy Summary
Lighting, Fans, UPS & Rawpower

	Lighting		Fans		UPS			Raw Power	
Floor	Inst. kW	Target kW Unocc Mode	Inst. kW	Target kW Unocc Mode	Inst. kW	Target kW Unocc Mode	No. of PC's ON	Inst. kW	Target kW Unocc Mode
Deck 0	2.6	0.0	0.0	0.0	2.7	2.0	27	0.1	1.0
Deck 1	3.7	1.0	0.1	0.0	5.9	3.0	59	0.6	0.0
Deck 2	3.7	0.0	0.1	0.0	6.1	2.0	61	0.0	0.0
Deck 3	4.1	0.0	0.1	0.0	8.4	3.0	50	0.0	0.0
Deck 4	5.7	0.0	0.1	0.0	6.5	4.0	62	3.3	2.0
Deck 5	3.5	0.0	1.2	2.0	5.3	0.0	53	2.1	2.0
Deck 6	5.0	1.0	0.3	0.0	5.8	2.0	58	0.0	0.0
Total	28.2		2.0		40.6		369	6.2	



Floor	Design Kw	Design Kw/Tr	Actual Kw	%	Actual ikw/Tr.	Kwh Today	% Today	Kwh Y Day	Kwh MTD	Mwh YTD
HVAC COMFORT										
Chiller - 1	252.0	0.48	0.7	0	0.00	97	3	1852	10182	27.70
Chiller - 2	271.0	0.51	122.0	45	0.56	1403	38	18	29676	31.64
LT CHW Pumps	44.0	0.04	8.9	3	0.04	201	5	313	4686	6.10
MT CHW Pumps	60.0	0.10	41.1	15	0.18	714	19	792	17286	48.73
CDW Pumps	60.0	0.06	15.0	5	0.06	231	6	292	4293	5.72
Cooling Towers	60.0	0.06	0.0	0	0.00	21	1	31	1364	2.79
DOAS's	74.0	0.14	51.8	19	0.00	699	19	1097	18213	81.75
HRW's	18.6	0.04	15.9	6	0.00	284	0	352	7604	29.13
Exhaust & Vent. Fans	14.7	0.03	17.6	6	0.00	338	9	351	7510	33.45
Total			273.5	100		3720	100	5098	100814	359.68

Figures: Left: screenshots from the energy information system showing floor-wise and equipment –wise sub metered data. Right, top: picture of the command and control center at Infosys, Pocharam. Constant monitoring and verification is conducted of designed vs. actual energy in order to obtain persistent energy savings. Right bottom: Demand control ventilation being conducted through Carrier Automated Logic Corporation BMS system installed at Infosys, Pocharam

Conclusions

Conclusions

The best practices described in this guide offer opportunities and non-prescriptive recommendations to the design-build-operate team. Architects, engineers, developers, and occupants should best work in order to improve energy efficiency within a larger triple-bottom-line framework. Although the practices are presented individually, they should not be thought of as an "a la carte" menu of options. Such integrations are critical to capitalize on the synergies between systems, as well as between the traditional and novel, in order to drive innovation, and optimum environmental, social and economic cost benefits.

Owners, developers, and facility operators seek strategies to make their buildings comfortable, attractive, and profitable. Given the highly price-sensitive nature of Indian commercial real estate, and a globally competitive context for enterprises, office buildings need to be especially responsive to the market needs. The design should maximize the usable built footprint, and the construction must meet schedule and resource goals. Moreover, during operations, a building must perform at the highest possible level in terms of energy (reduced waste, operating, and maintenance expenses), environmental quality, and occupant comfort (high client retention).

Shared framework and metrics

In order to respond to multiple such drivers (Figure 20), it is important for building owners and operators first to have the relevant data to enable better decision-making. This *Building Innovation Guide* provides **best performance guidelines**, based on modeled and monitored data for Class A office buildings in India. While several typologies of Indian buildings still have low energy use intensity, Class A offices are a high-growth sector where the intensity of use is increasing exponentially due to high service levels.

This *Building Innovation Guide* provides extensive **Tables of Metrics** for building energy use at the granularity of whole-building and end-use metrics. These are based on analyses of simulation and operational data from business-as-usual and exemplary buildings, both new construction and retrofits, derived from four out of five different climate zones in India. Visibility into these proof-of-concept strategies, as **Data Points** can help mitigate some of the perceived misconceptions that energy conservation strategies are difficult to implement. (See Appendix 2: *Exemplary Buildings in this Guide*). The selected data points in the Guide are intended to be illustrative, to provide proof of concept, and do not comprehensively represent all the exemplary buildings that are operating at a high performance level in India.

Another salient feature is the provision of a set of **core, common metrics and a shared vocabulary** across stakeholder groups across the building life cycle –i.e., designers, architects, and engineers during the design phase; developers during the construction phase; and facility/IT operators, tenants and owners during the operations phase of the building.

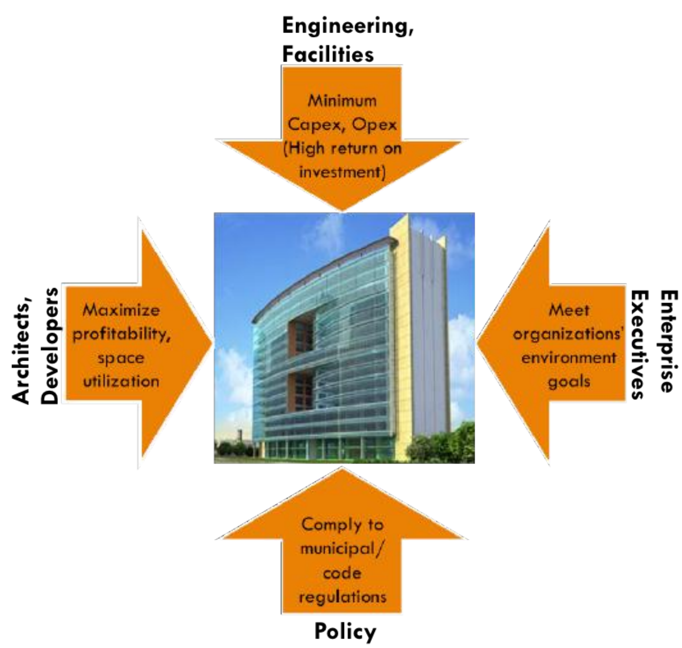


Figure 20: Primary drivers and stakeholders in the design, construction, and operations of an office building

Conclusions

These metrics include:

- Whole-building and system-level annual energy use [kWh/m²/year]
- Whole-building and system peak energy use [W/m²]
- Annual energy use per occupant [kWh/ year /person]
- HVAC plant efficiency [kW/TR]
- Cooling load efficiency [m²/TR]
- Envelope thermal performance [kWh/m²/ year]

Further, comfort and cost metrics are explored, including:

- Ratio of uncomfortable hours (as a ratio of total occupied time)
- Cost (INR/sf) and simple payback (years).

Cost metrics such as cost (INR) and return on investment (ROI, usually through payback in years) are important for owners, developers, and tenants. Any strategies need to be cost effective when taken in their entirety and when amortized over the life of the structure. While first costs and operational energy cost savings have been briefly referenced in the data points in this guide, cost benefits will need deeper exploration in the context of market data. A key occupant thermal comfort metric is uncomfortable hours. It it relates to predicted mean vote (PMV) metric in the Fanger and adaptive comfort models (the latter takes human behavior into account), that are both discussed in depth in Appendix 5 *Climate Specific Modeling and Analysis for High-Performance Indian Office Buildings*.

These energy, comfort and cost metrics are critical in advancing triple-bottom-line decision-making, which encompasses the following expanded sets of metrics (CBERD 2018):

- **Financial impact:** including first asset cost or mortgage, energy cost, facilities management cost, churn cost, waste cost, real estate value, and vacancy cost (in INR, INR/occupant)
- **Environmental impact:** including carbon emissions (in metric tons of carbon dioxide, $MTCO_2$), SOx, NOx, PM2.5, methane, and water impacts of energy use
- **Social impact:** including task performance, absenteeism, and health symptoms that may impact annual productivity savings (INR/occupant).

Stakeholders with a shared vocabulary and common set of metrics can impel localized and customized solutions for high performance throughout the building's life cycle. They can implement energy-saving strategies early in the building delivery process that has the advantage of being more cost effective – incremental first cost within 5% to 10% – with less risk of being value-engineered out of the project. Setting energy targets early in the design process and carrying them through the measured building operations can translate to first-cost and life cycle cost efficiencies, enhanced operations and management, and improved occupant comfort and well-being—leading to positive environmental and societal benefits.

Prioritization of best practices

Through the analyses of simulations and available data, the guide presents energy investment strategies for the office building typology. An important approach is integrating the best in traditional wisdom– such as controlled mixed mode operations, high thermal mass, cool materials, sensible fenestration and shading– with relevant new technologies– such as low-e glazing, lighting controls, and high-efficiency mechanical systems– to achieve the full benefit of the best practice solutions.

In order to navigate through the spectrum of strategies and customize the approach for a particular organization and building, it may be advantageous to characterize and

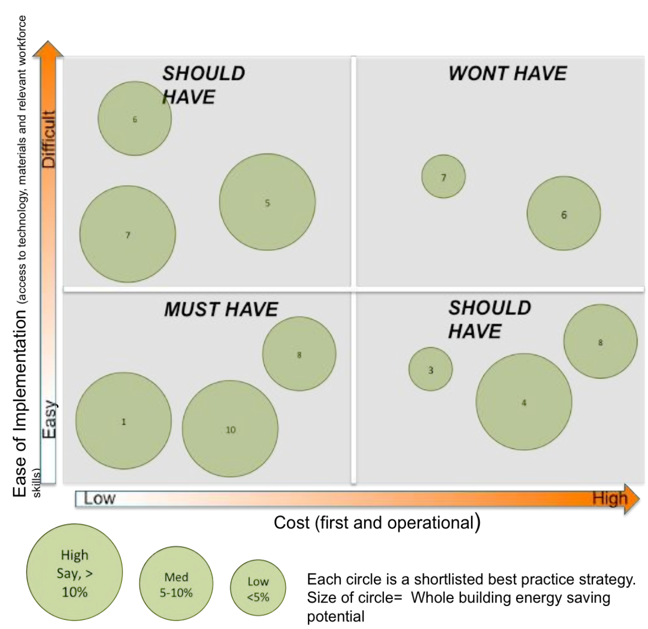


Figure 21: Illustrative prioritization matrix for energy efficiency strategies. This matrix must be customized for local/regional implementation ease and cost

Conclusions

prioritize the energy strategies. We suggest a modified "**M**o**S**co**W**" framework (Figure 21) with the following categories:

1. **M**ust have: strategies that are relatively easy to implement with significant energy savings potential
2. **S**hould have: strategies that are relatively easy to implement with modest energy savings potential, or somewhat difficult to implement with significant energy savings; OR critical strategies even though they are costlier or tougher
3. **W**on't have: strategies that are difficult to implement and have only modest energy savings potential

Figure 21 is a representation of this **prioritization framework –** as a 2X2 matrix considering two important characteristics: *ease of implementation* (market readiness for the strategy) and *cost* (compared to energy savings and other environmental and human benefits including operational energy savings for first-cost and eventually triple-bottom-line savings). The matrix also offers a window into whether a strategy already enjoys broad applicability, or if it should be a candidate for policy advocacy. This prioritization framework can be adapted for specific Indian regions and markets and be constructed at a more granular building-by-building level. This is beyond the document's scope, and would be require an analysis of the local market factors, and triple-bottom-line costs.

Next steps to consider for the customization of the energy investment prioritization framework is normalization based on climate, organization, and building type, as follows:

- **Regional/climate attributes:** Evaluating the geographical availability of materials and technologies and cultural variations in construction (e.g., north and south regions of India). For instance, a capital expense of INR 1 lakh/m^2 for a high-quality envelope may provide a better energy savings benefit in Delhi with its composite climate; whereas a similar investment of INR 1 lakh per ton of air conditioning delivered may be a better investment in Mumbai with its warm, humid climate. A similar investment in a relatively more expensive but more efficient water-cooled chiller would provide a better benefit in Jaipur with its hot, dry climate.

- **Organizational attributes:** Considering the significant differences between owner-occupied and built-to-suit tenanted speculative buildings while selecting strategies. Asset selection and even rule-of-thumb for HVAC electrical loads vary from approximately 65 W/m^2 for owner-occupied buildings and 110–120 W/m^2 for leased buildings.

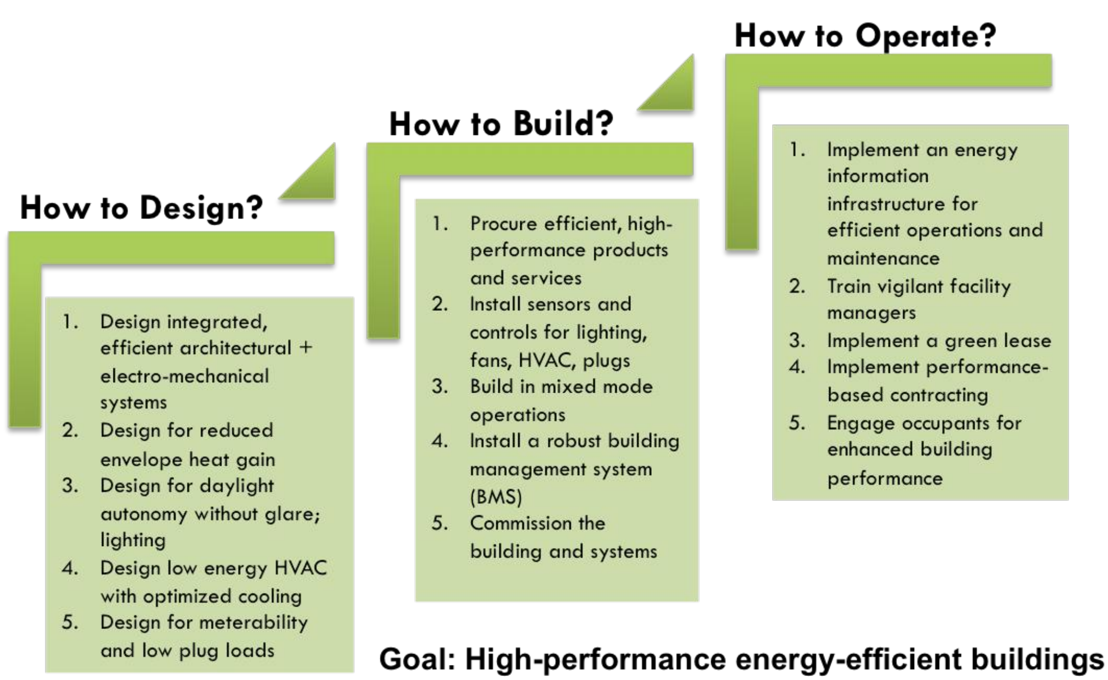


Figure 22: A brief synopsis of the best practice solutions provided in the *Building Innovation Guide*

Conclusions

There are also differences between multi-national and national corporations, private and public sector entities, and energy and environmental standards and demands.

- **Building facility attributes:** Analyzing the building type, occupant density, and overall size since this impacts perimeter versus core loads, as well as single, double, or triple shifts.

As mentioned, while selecting strategies, building systems must be integrated to realize maximum energy and cost benefits. Designers, engineers, developers, and tenants need to work together to capitalize on the synergies between building systems for cost-effective energy savings.

Macro-level implications

India's urbanization is a key driver of energy trends: an additional 315 million people—almost the entire population of the United States today—are expected to live in India's cities by 2040. Hence, India's power system needs to almost quadruple in size by 2040 to catch up and keep pace with electricity demand that increases at almost 5% per year, boosted by rising incomes and new connections to the grid (IEA 2015). Increasing from the current level of 153 GW to about 690 GW by 2035-36 requires an infrastructure investment of INR 2,60,000 crore in the current five year plan (2017-2022)(Central Electricity Authority, 2016).

Commercial buildings are responsible for 8% of national electricity use and this is growing at 8% annually. The total energy savings from space cooling efficiency improvement alone in using the best available technology has the potential reach over 118 TWh in 2030. The potential peak demand saving is found to be 60 GW by 2030, equivalent to avoiding 120 new coal fired power plants of 500 MW each. (Phadke, et al, 2014). In order to cost-effectively meet the growing load, it becomes imperative to aggressively manage building energy efficiency in each building being designed and operated in India. A CBERD study (2018) has identified commercial building technical electricity savings potential of 200 TWh/year in India by 2030 over a business-as-usual baseline. This assumes that 66% of the building footprint that would be extant in 2030 still needed to be built, and there is a ~38% potential for energy savings in the new construction. Linking this to India's intended nationally determined contribution (INDC) goal of reducing emissions intensity by 28%–33% in 2030 over 2005 levels (UNFCC 2015), the building energy-efficiency potential is aspirational and a target that is worthy of achieving.

Building codes are crucial for managing and delaying the requirement for overall buildings energy. Passive cooling, adaptive thermal comfort and appliance efficiency improvement strategies are also important. Also, given the increasing penetration of renewable energy, smart buildings could provide several valuable services to the grid including demand response and ancillary services. Smart building energy management and control systems can enable these services.

Building stakeholders can help advocate for favorable **regulations and policy, and shift markets towards a high-performance building stock.** For instance, a relatively simple, low-cost, traditional strategy in Indian business-as-usual buildings is the use of overhangs or recessed window shading. However, overhangs are counted as part of the floor space index (FSI), even though it is not rentable space, which provides a dis-incentive for their use. Hence, it would require advocacy to modify regulations to encourage such strategies.

As India embarks on designing, building, and operating its next generation of buildings, this is a unique, opportune time for energy experts to start a broad dialogue about shared metrics and common solutions to enhance building energy efficiency. The strategic frameworks and solutions in this guide (Figure 22) foster the delivery of a high level of building performance with integrated decision-making based on data and knowledge. An ideal outcome of this Guide is to help support the transfer of building science, and the state-of-the-art, to transform the state-of-practice. This would provide an impetus to accelerate energy-efficient processes, resources, products, and policies, and to scale up to improve life-cycle efficiency throughout the country's building stock.

India is at a point of inflection in its history. High performance buildings are a prime opportunity to propel India into a digitized, decarbonized future.

And time is of the essence.

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Appendix

Appendix 1: Glossary of Terms and Abbreviations

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Appendix 1: Glossary of Terms and Abbreviations

AC: Alternating current is the form in which electric power is delivered to businesses and residences.

Adaptive comfort: A thermal comfort model that add a little more human behavior to the mix than PMV and PPD (see these items further down in the Glossary). The assumption is that, if changes occur in the thermal environment to produce discomfort, then people will generally change their behavior and act in a way that will restore their comfort. Such actions could include taking off or adding layers of clothing, reducing activity levels or even opening a window. The main effect of such models is to increase the range of conditions that designers can consider as comfortable, especially in naturally ventilated buildings where the occupants have a greater degree of control over their thermal environment.

AHU: Air handler units

Albedo: The dimensionless reflection coefficient. The root is from albus ("white") and indicates the reflecting power of a surface. It is defined as the ratio of reflected radiation from the surface to incident radiation upon it.

ASE: Annual sun exposure describes how much of space receives too much direct sunlight, which can cause visual discomfort (glare) or increase cooling loads. Specifically, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year.

BAU: Business as usual is the normal execution of operations within an organization

BEE: Bureau of Energy Efficiency

BMS: A building management system is a computer-based control system installed in buildings that controls and monitors the building's mechanical and electrical equipment such as ventilation, lighting, power systems, fire systems, and security systems.

BPO: Business process outsourcing services in India, catering mainly to Western operations of multinational corporations (MNCs).

CFL: Compact fluorescent lamp

CO_2: Carbon dioxide

Changeover mixed-mode: *(Same space, different times)*: The building "changes-over" between natural ventilation and air-conditioning on a seasonal or even daily basis. The building automation system may determine the mode of operating based on outdoor temperature, an occupancy sensor, a window (open or closed) sensor, or based on operator commands. Typical examples include individual offices with operable windows and personal air conditioning units that shut down for a given office anytime a sensor indicates that a window has been opened; or a building envelope where automatic louvers open to provide natural ventilation when the HVAC system is in economizer mode, and then close when the system is in cooling or heating mode.

Daylight Autonomy: The amount of time that you can expect to reach a certain light level through the use of just daylight.

DC: Direct current, unidirectional flow of electric charge. Direct current is produced by sources such as batteries and solar cells.

District cooling: District cooling systems produce chilled water, steam, or hot water at a central plant and then pipe that energy out (either underground or over rooftops) to buildings for air conditioning, space heating, and water heating. As a result, these buildings don't require their own chillers, air conditioners, boilers, or furnaces. It is the distribution of cooling energy from a centralized plant to several buildings in a district. Centralizing the comfort cooling infrastructure offsets the need for mechanical rooms in each building within the district. The result is up to 40% improvement in efficiency and up to 20% life-cycle cost savings.

DCV: Demand controlled ventilation is a combination of two technologies: CO2 sensors that monitor CO2 levels in the air inside a building, and an air-handling system that uses data from the sensors to regulate the amount of ventilation air admitted.

DOAS: A dedicated outdoor air system is a type of HVAC system that consists of two parallel systems: a dedicated outdoor air ventilation system that handles latent (dehumidification) loads and a parallel system to handle sensible (cooling) loads.

DV: Displacement ventilation is a room air distribution strategy where conditioned outdoor air is supplied near the floor level and extracted above the occupied zone, usually at ceiling height.

Appendix 1: Glossary of Terms and Abbreviations

DX: A direct-expansion unitary system located the evaporator in direct contact with the air stream so that the cooling coil of the airside loop is also the evaporator of the refrigeration loop. The term “direct” refers to the position of the evaporator with respect to the airside loop.

ECBC: The Energy Conservation Building Code, which was launched in India in May 2007 under the Energy Conservation Act, 2001. ECBC takes into account the five climatic zones present in India. This document specifies the energy performance requirements for all commercial buildings to be constructed in India. Buildings with an electrical connected load of 500 kW or more are covered by the ECBC. BEE, with the support of the USAID ECO-III Project, is promoting ECBC awareness and voluntary adoption through training and capacity-building programs and pilot demonstration projects, and identifying steps for compliance checks and monitoring.

ECM: An energy conservation measure is any type of project conducted or technology implemented to reduce the consumption of energy in a building.

ECO-III: The third phase of the Energy Conservation and Commercialization (ECO) Bilateral Project Agreement ECO-III, which started October 2006, is helping BEE implement the ECBC in Gujarat and Punjab, with an overall focus on improving energy efficiency in the building sector, developing capacity of states to implement energy-efficiency programs, and establishing energy-efficiency centers and institutions. As part of the ECO-III project, building-level energy use data has been collected from more than 860 buildings (office, hotel, hospital, retail) along with a detailed analysis.

Embodied energy: The energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery.

EPI: The energy performance index indicates the specific energy use of a building. It is the ratio of total energy used to the total built-up area. This total energy used includes both purchased electricity as well as that generated on site, but excludes renewable sources like solar photovoltaics and others. The total built-up area excludes basement and parking area. EPI is calculated after completion of one year of operation with full occupancy of the building and is measured in units of kilowatt-hours per square meter per year (kWh/m²/year).

Floor plan: Floor plan is the size of the floor space on a story of a building. Smaller floor plans with smaller core areas have a higher ratio of window walls to interior space. Large floor plans have a more limited ratio of window walls to interior space and are more suitable to open space plans with workstations.

Floor plate: The concrete slab on the floor of a building, this can also refer to amount of rentable area on one whole floor

Fritted glass: This type of glass is produced by permanently fusing ceramic frits to the glass surface at high temperatures. Fritted glass used in windows helps reduce glare, cut cooling costs, and lower the danger to birds. It can also give the building facade a distinctive look with patterns ranging from simple shapes and gradients to intricate designs

FTE: Full-time equivalent is a unit that indicates the workload of an employed person (or student) in a way that makes workloads comparable across various contexts. FTE is often used to measure a worker’s involvement in a project, or to track cost reductions in an organization. An FTE of 1.0 means that the person is equivalent to a full-time worker (8 hours, 1 shift), while an FTE of 0.5 signals that the worker is only half-time (4 hours, ½ shift).

GBCI: Green Building Council of India

GHG: Greenhouse gas are gasses in the earth’s atmosphere that absorb and emit radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect.

Green lease: A green lease is a lease of space in a green building that incorporates principles to ensure that the ongoing operation and maintenance of the building minimizes environmental impacts.

GREHA: Green Rating for Integrated Habitat Assessment

Humidity ratio (W): The quantity of water vapor in air, expressed as “grams of water vapor per kilogram of air. Units are grams of water/kilogram of dry air, gw/kgda, sometimes abbreviated as g/kg

HVAC: Heating, ventilation, and air conditioning refers to technologies the condition air and provide comfort in indoor and automotive environments.

Appendix 1: Glossary of Terms and Abbreviations

INR or Rs: Rupees, the currency of India.

IGBC: Indian Green Building Congress

IT: Information technology. Also used in conjunction with ITES

ITC: Indian Tobacco Company is one of India's foremost private sector companies with a diversified portfolio.

LEED: Leadership in Energy and Environmental Design

ITES: Information technology enabled services

LCD: A liquid crystal display is a flat-panel display, electronic visual display, or video display that uses the light modulating properties of liquid crystals. LCDs are more energy efficient and offer safer disposal than CRTs. The low electrical power consumption of LCDs enables it to be used in battery-powered electronic equipment.

LED: A light-emitting diode is a semiconductor light source. LEDs present many advantages over incandescent light sources, including lower energy consumption, longer lifetime, improved robustness, smaller size, and faster switching. LEDs powerful enough for room lighting are relatively expensive and require more precise current and heat management than compact fluorescent lamp sources of comparable output.

Low-e: Low emissivity, or low-e coatings, are microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window or skylight glazing surface primarily to reduce the U-factor by suppressing radiative heat flow. Windows with spectrally selective, low-e glass have the ability to reduce solar heat gain while retaining high visible transmittance.

M&E room: Mechanical and electrical room.

Met: Metabolic rate is the rate of transformation of chemical energy into heat and mechanical work by metabolic activities of an individual, per unit of skin surface (expressed in units of met), equal to 58.2 W/m^2 (18.4 $Btu/h \cdot ft^2$), which is the energy produced per unit skin surface area of an average person seated at rest.

Mixed-mode: Mixed-mode buildings employ a hybrid approach to space conditioning that combines operable windows and mechanical cooling. In mixed mode buildings natural ventilation is used as the primary means of providing cooling and, when this is inadequate to provide comfort conditions, active cooling is introduced By taking advantage of the strengths of both systems, well designed mixed-mode buildings can be more comfortable and use less energy. Also see *changeover mixed-mode* and *zoned mixed-mode.*

NBC: National Building Code

PBC: Paharpur Business Center, Delhi.

PM2.5: Particulate matter 2.5 is the group of air pollutants with a diameter of 2.5 micrometers or less, small enough to invade even the smallest airways. It is a standard measure of environmental air quality. Adverse health effects from breathing air with a high PM2.5 concentration include premature death, increased respiratory symptoms, and disease, chronic bronchitis, and decreased lung function, particularly for individuals with asthma.

Predicted Mean Vote (PMV): Refers to a arguably the most widely used thermal comfort index today that runs from Cold (-3) to Hot (+3), originally developed by Ole Fanger and later adopted as an ISO standard. The recommended acceptable PMV range for thermal comfort from ASHRAE 55 is between **-0.5 and +0.5** for an interior space.

Predicted Percentage of Dissatisfied (PPD): Predicts the percentage of occupants that will be dissatisfied with the thermal conditions. It is a function of PMV, given that as PMV moves further from 0, or neutral, PPD increases. The maximum number of people dissatisfied with their comfort conditions is 100% and, as you can never please all of the people all of the time, the recommended acceptable PPD range for thermal comfort from ASHRAE 55 is less than 10% persons dissatisfied for an interior space.

QA: Quality assurance refers to the planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled.

Appendix 1: Glossary of Terms and Abbreviations

RH: Relative humidity.

RC: Radiant cooling systems are temperature-controlled surfaces that cool indoor temperatures by removing sensible heat and where more than half of heat transfer occurs through thermal radiation. Radiant cooling systems are usually hydronic, cooling using circulating water running in pipes in thermal contact with the surface. Typically the circulating water only needs to be 2°C–4°C below the desired indoor air temperature. Once having been absorbed by the actively cooled surface, heat is removed using water flowing through a hydronic circuit, replacing the warmed water with cooler water.

SDB-1: Software Development Block, the generic name given to buildings at Infosys campuses across India.

SEZ: The Special Economic Zone is a geographical region that has economic and other laws that are more free-market-oriented than a country's typical or national laws. Usually the goal of a structure is to increase foreign direct investment by foreign investors. India's SEZ was set up in 2005; currently there are 143 SEZs operating throughout India and more than 500 more have been approved.

SHGC: Solar heat gain coefficient is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward. SHGC is expressed as a number between 0 and 1. The lower a window's solar heat gain coefficient, the less solar heat it transmits.

Site energy: The amount of heat and electricity consumed by a building, as reflected in utility bills.

Spatial Daylight Autonomy (sDA): This term describes how much of a space receives sufficient daylight. Specifically, it describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours.

Thermal mass: Thermal mass is the capacity of a material to store heat energy. In building terms, it reduces temperature fluctuations by absorbing heat when the ambient temperature is hotter than the mass, and then releasing the heat when the ambient temperature falls below the temperature of the mass. When used effectively, this results in improving indoor comfort.

TR: Tons of refrigeration is a unit of measure used to rate commercial and industrial refrigeration systems. Historically, one TR was defined as the energy removal rate that will freeze one short ton of water at 0°C (32°F) in one day.

T-vis, or VT: Visible transmittance is the amount of visible light that penetrates a material. This is influenced by glass selection, as well as the amount of opening taken up by non-transparent components such as the frame and sash. The greater the VT, the better the potential for daylighting. Normally, a reduction in SHGC comes with a reduction in VT.

U value: U-factor gives the rate of heat transfer through the window or wall (from inside to outside when it is cold, and from outside to inside when it is hot) per unit area and per unit temperature difference. The lower the U-factor, the more heat enters a space in the summer.

UFAD: Under floor air distribution is an air distribution strategy for providing ventilation and space conditioning in buildings as part of the design of an HVAC system. UFAD systems use the underfloor plenum beneath a raised floor to provide conditioned air through floor diffusers directly to the occupied zone. UFAD is frequently used in office buildings—particularly highly reconfigurable and open plan offices where raised floors are desirable for cable management. UFAD is also common in command centers, IT data centers, and server rooms that have large cooling loads from electronic equipment and requirements for routing power and data cables. The ASHRAE Underfloor Air Distribution Design Guide suggests that any building considering a raised floor for cable distribution should consider UFAD.

UNEP: United Nations Environment Programme.

UPS: Uninterruptible or universal power supply is an electrical apparatus that provides emergency power to a load when the input power source, typically mains power, fails. While not limited to protecting any particular type of equipment, a UPS is typically used to protect computers, data centers, telecommunication equipment, or other electrical equipment where an unexpected power disruption could cause injuries, fatalities, serious business disruption, or data loss. UPS units range in size from units designed to protect a single computer to large units powering entire data centers, buildings, or even cities.

VAV: Variable air volume is a type of HVAC system. The simplest VAV system incorporates one supply duct that, when in cooling mode, distributes approximately 55°F (13°C) supply air. Because the supply air temperature, in this simplest of VAV systems, is constant, the air flow rate must vary to meet the rising and falling heat gains or losses within the thermal zone served. There are two primary advantages to VAV systems. The fan capacity control, especially with modern electronic variable-speed drives, reduces the energy consumed by fans, which can be a substantial part of the total cooling energy requirements of a building. The other advantage is that dehumidification is greater with VAV systems than it is with constant-volume systems, which modulate the discharge air temperature to attain part load cooling capacity.

VFD: A variable-frequency drive is a system for controlling the rotational speed of an AC electric motor by controlling the frequency of the electrical power supplied to the motor. VFDs are used in a wide number of applications to control pumps and fans in HVAC systems.

VRF: A variable refrigerant volume system (VRV/VRF) is basically a large multiple split system. The system can comprise several indoor fan coil units matched to one or more outdoor condensing units.

WWR: A window-to wall-ratio is the measure of the percentage area of a building's exterior envelope that is made up of glazing, such as windows.

Zoned mixed mode: *(Different spaces, same time)***:** Different zones within the building have different conditioning strategies. Typical examples include naturally ventilated office buildings with operable windows and a ducted heating/ventilation system, or supplemental mechanical cooling provided only to conference rooms. For many mixed-mode buildings, operating conditions sometimes deviate somewhat from their original design intent (e.g., a building originally designed for seasonal changeover between air-conditioning and natural ventilation may, in practice, operate both systems concurrently).

Zero net energy building: A building with zero net energy consumption, meaning the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site

UNITS

Cfm: Cubic feet per minute, a unit of volumetric capacity

kVA/VA: kilovolt amperes / volt amperes is the unit used for the apparent power in an electrical circuit.

kW/TR: kilowatt per ton refrigerated, a measure of chiller efficiency

kWh/m^2/year: kilowatt-hours per square meter per annum, a measure of energy performance

W/m^2: watts per square meter, a unit for peak energy uses

W/m^{2}K: watts per square meter per degree kelvin, a unit for measuring U-value

Appendix 1: Glossary of Terms and Abbreviations

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Appendix 2: List of Exemplary Buildings in the Guide

Appendix 2: List of Exemplary Buildings in the Guide

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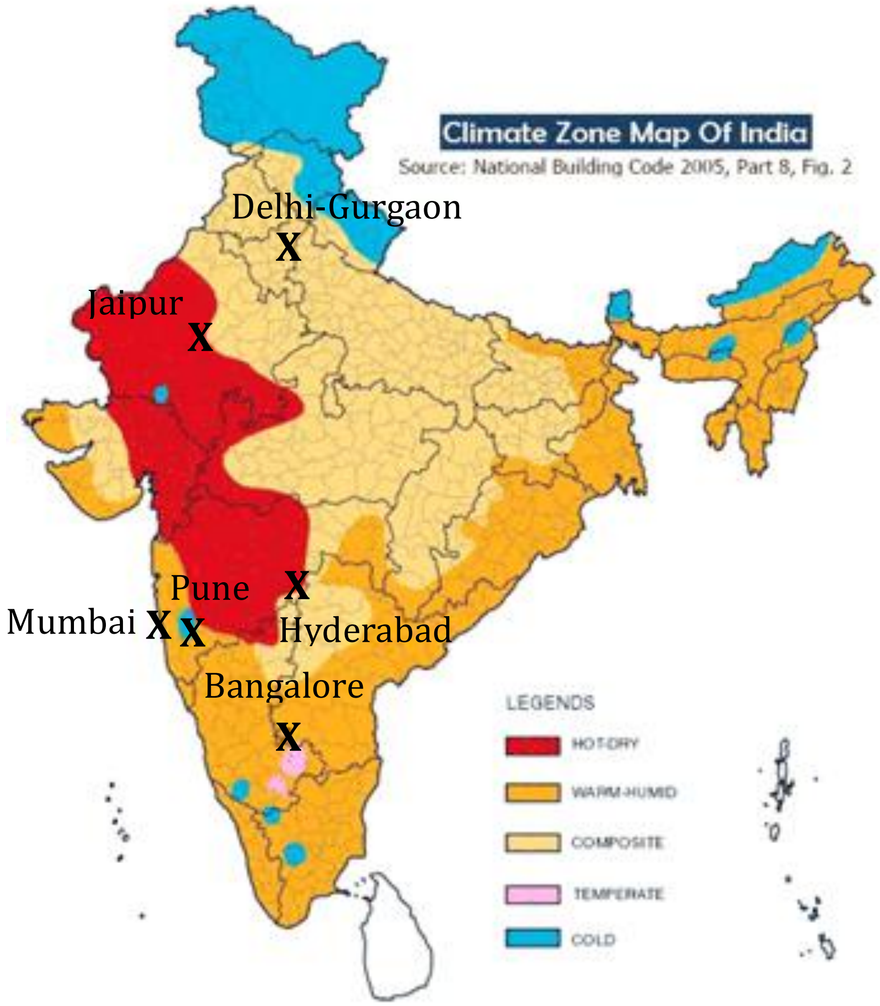
Appendix 2: List of Exemplary Buildings in the Guide

Climate	Building and Location	Stage	Building area	Occupancy /# of shifts
Composite	**Campus for Agilent Technologies** Manesar	New Construction In Operation	46,400 m^2	3 shifts 1,200 people
	Development Alternatives New Delhi	New Construction In Operation	4,500 m^2	1 shift
	Indira Paryavaran Bhawan New Delhi	New Construction In Operation	3,100 m^2	1 shift 300 people
	SMSF Gurgaon	New Construction In Operation	5,100 m^2	1 shift
	ITC Green Center Gurgaon	New Construction In Operation	17,000 m^2	1 shift
	Paharpur Business Center New Delhi	Retrofit	4,800 m^2	2 shifts
Hot and Dry	**SDB-1 at Infosys** Pocharam (Hyderabad)	New Construction In Operation	24,700 m^2	1 shift 2600 people
	Torrent Research Center Ahmedabad	New Construction In Operation	19,700 m^2	1 shift 600 people
Moderate*	**MC-1 at Infosys** Bangalore	New Construction In Operation		1 shift
	SDB-10 at Infosys Pune		41,800 m^2	
	Sears Holdings Pune	Retrofit	9,100 m^2	2 shifts
	Suzlon One Earth Pune	New Construction In Operation	86,500 m^2	1 shift
	Godrej Bhavan Mumbai	Retrofit	4,100 m^2	1 shift
Warm and Humid	**Nirlon Knowledge Park** Mumbai	New Construction In Operation	20,100 m^2	3 shifts, tenanted ~22,000 people

* Moderate and Temperate are used interchangeably in the guide for climate of Bangalore and Pune

Appendix 2: List of Exemplary Buildings in the Guide



India map that shows the five climatic zones and geographical location of cities where the exemplary buildings are located. (Source: ECBC)

Appendix 3: List of Technologies

Appendix 3: List of Technologies

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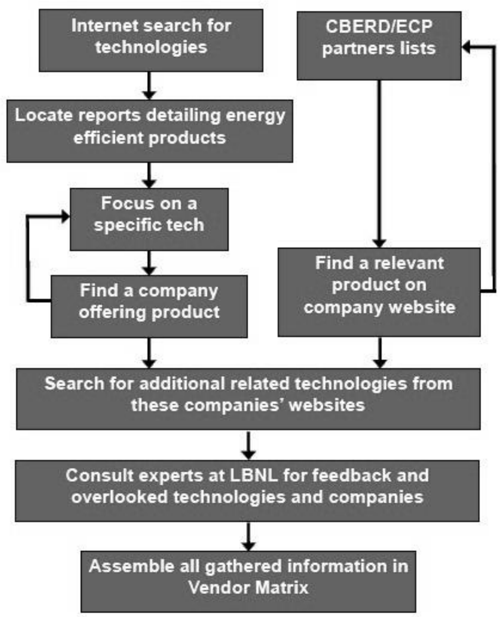
Appendix 3: List of Technologies

A list of relevant energy efficiency building technologies

Energy efficient building systems have been shown to significantly decrease the energy usage of commercial buildings. Technologies were investigated to determine those that could have a substantial impact on Indian buildings and a list of available technologies and related services was assembled. The goal is also to promote growth of the energy efficient building sector in India by illustrating what technologies and services are available and which companies are providing those products. The objective of this list is to help find manufacturers and services for those interested in constructing a high-performance, smart, green building. The methodology used to assemble this list is shown in the flowchart below:



Methodology flowchart

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KEY:

Building Physical Systems | Services providers

Climate zones: H Hot-Dry; W Warm-Humid; X Composite; T Temperate; C Cold; A All

Appendix 3: List of Technologies

I. Building Physical Systems: Products and Services Providers

Category / Technologies	Technology	Illustrative Companies	Brief Description	Potential relevance to Best Practices (BP #) as provided in the Guide	Climate Zones
HVAC	Variable refrigerant flow	1. Trane 2. Carrier	Outdoor compressor cools liquid which is piped and used to cool air with separate AHUs in each room/zone for extra control.	BP 2.42 Consider ultra-low energy cooling options. Allows individual rooms or zones to be controlled separately so that total conditioning and electrical use may be reduced.	A
	Radiant cooling	1. Carrier 2. Trox 3. Price 4. Titus	Pumps water through tubes to cool a floor, ceiling panel, beam, etc. which then radiates that cold to the air.	BP 2.42 Consider ultra-low energy cooling options. Water can be cooled to a lesser extent than in air distribution systems, and water as a medium is a much more efficient distribution medium than air causing far greater energy efficiency; additinally, geothermal/night cooling could be used. Must be careful about condensation formation.	H,X,T
	Dedicated outdoor air system	1. Reliant 2. Carrier	Handles cooling of outdoor and indoor air separately. Latent loads handled in outdoor air, sensible loads handled in indoor air.	BP 2.43.Decoupling ventilation and cooling systems allows for more right sized equipment to reduce energy wastage	A
	Thermal storage (Phase change)	1. Ice Energy 2. Trox	Freezes or chills phase change material (water or other, such as ethylene glycol) overnight to store thermal energy which is used to cool buildings during the day.	BP 2.44.Peak demand reduction technology	H,X,T
	Displacement ventilation	1. Carrier 2. Trox 3. Price 4. Titus	Conditions only the occupied space using air vents near the floor and uses natural air stratification to move air with only low speed fans.	BP 2.42 Consider ultra-low energy cooling options. Energy is not wasted cooling the unoccupied area near the ceiling; lower air temperatures can be used than traditional cooling methods; provide "gentler" cooling	H,W,X,T
	Direct evaporative cooling	1. Trane 2. Aztec 3.Mammoth 4. SPX	Adds humidity to the air to cool the air using mechanical fans, with lower energy input requirement.	BP 2.42 Consider ultra-low energy cooling options. Low energy method of cooling by using natural process of evaporation. Cannot be used in a high humidity environment.	H,T
	Indirect evaporative cooling	1. Aztec 2. Mammoth 3. SPX	Adds humidity to cool air that is not cycled into the room. This air cools the room air through a heat exchanger, keeping air streams separate, as to not add humidity to the room.	BP 2.42 Consider ultra-low energy cooling options. Low energy method of cooling by using natural process of evaporation.	H,W,X,T
	Energy recovery ventilators	1. Trane 2. Carrier 3. Xetex 4. York	Uses waste exhaust air to precool incoming fresh air through a heat exchanger before regular cooling method.	BP 2.42 Consider ultra-low energy cooling options. Lowers the amount of cooling that needs be done through electrical means.	A
	Air duct sealing	1. Aeroseal	Seals HVAC ducts to keep air from leaking out.	BP 2.46 Implement component level strategies. Keeping air in ducting reduces the amount of wasted cool air and the amount of electricity used for HVAC.	A
Lighting	Light emitting plasma	1. Ceravision 2. Luxim	Energizes plasma using radio frequency to acheive a white light with very high light output for relatively low energy input.	BP 2.32 Implement highly efficient lighting equiment and optimized lighting layout. Reduced energy as compared tp a T12 luminaire, and is dimmable to save energy when some natural light is available.	A
	T8 fluorescent	1. GE 2. Philips 3. Sylvania	High efficiency fluorescent lighting by using a smaller tube and more effective phosphor than T12.	BP 2.32 Implement highly efficient lighting equiment and optimized lighting layout. considerably less energy than T12 luminaire, but same length and pin arragement so retrofit is easy.	A
	T5 fluorescent	1. GE 2. Philips 3. Sylvania	High efficiency fluorescent lighting by using a smaller tube than T8 or T12 and the same phosphors as T8.	BP 2.32 Implement highly efficient lighting equiment and optimized lighting layout. Uses lesser energy than T12 or T8 luminaires for cases where extremely high efficiency is paramount.	A
	LED	1. GE 2. Philips 3. Sylvania	Small and highly efficient light source. Lower light output per point source, but an array of many can be made to generate more light.	BP 2.32 Implement highly efficient lighting equiment and optimized lighting layout. LED's use little energy and are directional (good for personal use) as well as adding little heat gain to room. Higher first cost (especially if used for ambient, instead of task, lighting, but provides high return on investment	A
	Electronic ballasts	1. GE 2. Philips 3. Sylvania	Converts 60Hz AC to ~20-40kHz AC to allow fluorescent lights to use power more efficiently than when magnetic ballasts are used.	BP 2.33 Provide lighting sensors and controls. Significantly reduces electricity use and light flicker with no tradeoffs required in building design	A

Appendix 3: List of Technologies

Envelope	Whole envelope design	1. Allana Buick & Bers 2. dtr Consulting Services	Include walls, roofing, daylighting, and architectural design to bring variousaspects of envelope together.	BP 2.12 Decrease envelope heat gain. Lowers energy losses through lower heat gain and smarter use of natural lighting	A
	Walls	1. BASF 2. Kawneer	Advanced insulation and sealing to keep air from escaping out of the building and heat from coming into the building.	BP 2.12 Decrease envelope heat gain. Lower heat gain through the walls will result in less HVAC cooling costs. Escparcially beneficial for smaller floor pates	A
	Cool Roofing	1. Sika 2.Duro-Last 3. Arkema	Uses materials that absorb less heat than conventional roofing materials to lower the heat gain through a roof.	BP 2.12 Decrease envelope heat gain. Lower heat gain through the roof will result in less HVAC cooling costs.	H,W,X,T
	Daylighting	1. LightLouver 2. Kawneer	Light shelves and fenestration orientation can be used to increase natural daylighting.	BP 2.14 Maximize daylight autonomy without glare. Increasing natural daylighting helps reduce electrical load for artificial lighting.	A
Fenestration	Solar control low-E glass	1. Saint Gobain 2. PPG 3. Cardinal 4. Viracon	Blocks short wave IR to disallow the sun's energy from entering the building. Also provides additional insulation to keep the cold inside from radiating out.	BP 2.13 Optimize fenestration and BP 2.14 Maximize daylight autonomy without solar glare. Serves hot climate zones (most of India) to help reduce cooling loads.	H,W,X,T
	Low-E film	1. EnerLogic 2. 3M	Provides similar function to low-E glass, onlyit is applied as a film on any window (including already installed windows).	BP 2.13 Optimize fenestration and BP 2.14 Maximize daylight autonomy without solar glare. Helps reduce heating or cooling load. Can also be a retrofit solution	A
	Light redirecting films	1. 3M	Film with small lenses that takes in light and uniformly distributes it around the room (rather than window being a glaring point source).	BP 2.13 Optimize fenestration and BP 2.14 Maximize daylight autonomy without solar glare. Cuts down on lighting costs through deeper room penetration while reducing glare from windows.	A
	Electrochromic windows	1. Sage	Glass with electrochromic switching that can be adjusted in steps from clear to tinted in response to daylighting and heat gain needs.	BP 2.13 Optimize fenestration and BP 2.14 Maximize daylight autonomy without solar glare. heat gain from direct sunlight, thereby reducing cooling load. Indirect sunlightis allowed to pentrate through, for daylighting.	H,W,X,T
	Automated shades	1. Mechosystems 2. Hunter Douglas	Tracks the sun and closes blinds to prevent glare and excess heat gain during direct sunlight times and orientations (opens when no direct sunlight).	BP 2.14 Maximize daylight autonomy without solar glare and BP 2.54 Monitor and control operable shades and windows Blocks heat gain from direct sunlight, thereby reducing cooling load. Indirect sunlightis allowed to pentrate through, for daylighting.	H,W,X,T
	Heat blocking shades	1. Dickson 2. Hunter Douglas	Blocks heat from sun through specifically designed fabric. Some visible light is allowed to pass depending on brand and type.	BP 2.14 Maximize daylight autonomy without solar glare, and BP 2.54 Monitor and control operable shades and windows. Blocks heat in direct sunlight taking load off HVAC while still allowing some light to pass through the fabric.	H,W,X,T
Architecture and Engineering Consultants	**Service**	**Companies**	**Brief Description**	**Potential relevance to Best Practices (BP #) as provided in the Guide**	**Climate Zones**
Architecture and Engineering	Architecture and engineering green/sustainable design	1. AECOM 2. ARUP 3. Gensler 4. HOK 5. Integral Group 6. McCarthy 7. Mazzetti	A&E firms bring together all of the systems and techniques to make buildings energy efficient. These companies are necessary to turn the parts into the whole.	Such firms integrate architectural and engineering systems to achieve high performance buildings as outlined in the best practices guide.	A
Commissioning Agencies	Commercial building commissioning	1. McKinstry 2. Heery 3. Merrick & Company	Monitoring and inspecting building systems soon after construction to make sure they are functioning and performing as intended.	Real buildings often aren't as efficient as in simulations, and commissioning can identify what needs fine tuning.	A
Auditing	Commercial building energy audits	1. ProEnergy Consultants 2. Merrick & Company 3. EnerNOC 4. Ameresco	Existing buildings often practice wasteful habits and use inefficient equipment which are identified in audits so they can be fixed.	Buildings waste 10-30% of their energy due to inefficiencies which can be identified through audits.	A
Simulations	Building simulations	1. The Weidt Group 2. CDH Energy	Helps in the design process to predict how systems will work together and how efficient they should be.	Designing a building to be efficient from the start works better than retrofitting later.	A

Appendix 3: List of Technologies

II. Building information technologies products

Technology	Description	Company	Product	Specific Product Notes
Whole Building Automation System (BAS)	Controls and monitors multiple building systems from one interface. With considerable effort, most systems have the capability to integrate and interoperate different building systems to work together for maximum efficiency. Uses standard languages such as BACnet, Modbus, or Lontalk to make communication between many different buildings systems and the use of a vast array of sensors and controllers possible. All include an online interface that allows for remote control from a PC or mobile device. Includes IoT and cloud computing.	75F	Facilisight, Central Control Unit (CCU), Smart Node, Smart Stat, Sensors	Vertically integrated solution for building intelligence and automation covering HVAC/ indoor air quality, lighting, portfolio energy management, space management . The solution encompasses sensors/controllers/predictive algorithms and apps covering the gamut from occupant experience to operational expense. Applications include dynamic airflow balancing, outside air optimization,indoor air quality, smart VAV with reheat, hydronic controls, dynamic chilled water balancing,advanced lighting.
		Emerson Climate Technologies	E2 BX	Aimed at smaller offices and retail store applications that need fewer zones for lighting/HVAC than the other systems profiled.
		GE	HabiTEQ	Many available "pre-wired" modules for easy installation and expandability of many different systems controllers.
		Honeywell	Enterprise Buildings Integrator	Also integrates security, access, safety, and other services on top of energy management.
		Johnson Controls	Metasys	Also includes fire, security, and more. Ties legacy devices together, even from other manufacturers.
		Schneider Electric	Controls	Also provides maintenance planning, personnel records, schedules, fault detection etc. Legacy system compatible.
		Siemens Building Controls	APOGEE	Building Automation system: Allows for room scheduling to adjust energy. Unlimited users can be given access with custom privileges.
		Trane	Tracer Summit	Tracer Summit: A building's climate, lighting, energy consumption, scheduling, and other controllable features can all be programmed and managed by Tracer Summit building control units (BCUs)Includes graphical programming interface

Appendix 3: List of Technologies

Technology	Description	Company	Product	Specific Product Notes
Building Energy Information and Management Systems (EMIS)	Monitors and logs data about building energy use in all connected systems. Does not act upon data for control, but provides valuable information to building managers. All systems have multi-facility view features to manage multiple buildings from a single location.	Agilis Energy	Analytics and Solutions	SAAS: Process inyerval and utility data, and weather to symptomize poor performance using Mathematica, and communicte with the facilities manager, and provide measurement and verification
		Building IQ	Energy Worksite	SAAS: Energy software toolkit designed to provide knowledge and insight into how you are using energy from the initial energy audit through verification of energy savings
		Climatec (Bosch)	Climatec	Building comfort, safety and energy
		EnerNoc	Energy Intelligence Software	SAAS: software helps you and your teams identify the highest impact cost reduction opportunities and manage energy with operational rigor, lowering operating costs and driving profitability.
		Ecova	Ecova Platform	SAAS: Ecova provides fully segmented data, paired with actionable insight from our team of experts, to create a roadmap to shape business strategy that increases savings and efficiency
		Enovity	Commissioning and Energy consulting Services	Operates, Maintains, and Optimizes Facilities to Assure Higher Performance Places: Energy efficinecy, Commissioning, facilties engineering
		Engineering Economics Inc	Commissioning and Energy consulting Services	Engineering Consulting : Full-service building systems consulting firm
		First Fuel	Commissioning and Energy consulting Services	M&V and Energy Audits; cloud based customer engagement platform delivers accurate, insightful, and scalable customer intelligence to over 30 energy providers in North America
		Gridium	Smart Meter Data Analytics	SAAS: Gridium provides smart meter data analytics to building operators and owners and customer engagement and analysis tools to utilities.
		Honeywell	Attune Energy Dashboard	SAAS: For optimization of building performance
		IBM	TRIRIGA	Whole business solution with space, personnel, project, maintenance, etc. planning as well as monitoring energy use.
		Johnson Controls	Panoptix	Features apps that can be user developed or purchased to track a wide array of energy and environmental impact data.(Fremont, Hayward, Pleasanton)
		Lucid	Building OS	Software solutions for building energy efficiency, facilities finance, tenant & portfolio management, and occupant engagement.
		Senseware	SmartBuilding Solutions	Wirelessly monitors performance across all Mechanical, Electrical, Environmental and Plumbing systems. This helps building managers and energy consultants run their facilities more easily and cost-effectively
		Schneider Electric	StruxureWare	StruxureWare Building Operation software, facilitates the exchange and analysis of data from energy, lighting, fire safety, and HVAC.
		Trane	Trane Intelligent Services	Trane intelligent services: energy management systems and services that facilitate monitoring, analysis, alerts, reporting, tracking and data visualization of your building and system information
		Tridium	Niagara	IoT software platform, connects and translates data from nearly any device or system—managing and optimizing performance from buildings managment and control to factories to cities and beyond. Value proposition includes integration for smart city: energy, water, transportation, bldg management, govt services

Appendix 3: List of Technologies

Technology	Description	Company	Product	Specific Product Notes
HVAC Control, and Fault Detection and Diagnostics	Controls HVAC systems using feedback from sensors to operate as efficiently as possible. Works as a standalone system and information can also be exported in at least one standard protocol to a whole building system. Also features a web platform.	Honeywell	Comfort Point	Interfaces with Enterprise Building Integrator. Includes graphical programming.
		Cypress Envirosystems		Monitoring hardware especially for retrofts for energy efficiency, demand response
		Trane	Tracer	Airside and chiller controls that work within the Tracer environment, interfacing with a Tracer BAS.
		Carrier	i-Vu	Scheduling, graphical views, historical trends included. Some monitoring from other building systems included in interface.
		Emerson Climate Technologies	CX	Meant to control HVAC in smaller buildings such as convience stores that have only a few zones.
		Skyfoundry	Skyspark	SAAS: Analytical platform, for buildings for operational improvements; issues identification, MBCx.
		Building Robotics	Comfy	Building automation software that helps save energy on office air conditioning while gathering employee-contributed data about the use and occupancy of a workspace
		Schneider Electric	Building Analytics	Cloud based automated diagnostics
		Johnson Controls	Commercial Comfort System	Meant to operate on own and sold preconfigured with a rooftop HVAC unit from York
Lighting Control	Computer program which can monitor and control lighting. All connect with photosensors and occupancy sensors. All export data in a standard protocol for integration with whole building management or monitoring and feature online access.	GE	LightSweep	Modular system that esaes right sizing. Can take commands from a building management system over BACnet.
		Schneider Electric	Powerlink	Control capabilities depend on system "level" chosen. Contrtol system mounted in box with metering built in.
		Wattstopper-Legrand	Lighting controls and plug load controls	Energy efficient lighting controls technology and applications for the commercial space, designed to meet code, ensure ease of installation, and enable the control of natural and artificial light in indoor spaces
		Siemens	GAMMA	Includes weather sensors and shade automation as well as lighting.
		Enlighted	Energy Manager	Sensors communicate wirelessly, can make local decisions, and are deployed at every light fixture for added control.
		Lutron	Quantum	Controls shades as well as lighting with adaptive sensing and includes wired or wireless sensors.
Plug Load Control	Software and hardware to monitor and control plug loads in real time and generate reports on usage to identify where savings can be realized.	Enmetric	Enterprise Plug Load Management	Uses scalable wireless hardware for any size application. Uses limits, schedules, and demand response for automation.
		Tripp Lite	Includes power strips controlled by occupancy sensor, timer, master outlet, individual outlet breakers, and remote strip breaker.	
		GE		
		Synapsense-Panduit	Power Suite	System with individual outlet monitoring, meant primarily for data centers.
		Autani	PLUS	Uses schedules, occupancy, demand response, and local input for automation. Niagara and Modbus output.
HVAC Sensors	Temperature, humidity, pressure, carbon dioxide, etc. sensors to give feedback to HVAC control systems.	Carrier	All brands carry a suite of multiple sensors for nearly any HVAC related task. These sensors can often interface with the automation systems from other companies.	
		GE		
		Trane		
		Johnson Controls		
		Emerson Climate Technologies		
Lighting Sensors	Photosensors and occupancy sensors to measure light levels and room use for lighting control.	GE	Aware	Many mounting configurations including ceiling, corner, wall switch, and high bay. Ultrasonic, infrared, or dual tech available.
		Lutron	Lutron Sensors	Wall and ceiling mounted sensors with manual switches and dimmers.
		Schneider Electric	Square D	Wall and ceiling mounted sensors with manual switches.
		Enlighted	Smart Sensor	Microprocessor on board for local sensor decision making and built in power metering. Dual sensing technology.
		Siemens	GAMMA	Includes all types of sensors with a remote for scene control and a weather station for sensing sun location.

SAAS: Software as a Service

Appendix 4: List of Simulation Tools

Appendix 4: List of Simulation Tools

A list of illustrative building energy simulation software tools that can be used for various aspects of commercial building design pertaining to energy. Also see the U.S. Department of Energy repository of tools (http://www.buildingenergysoftwaretools.com/).

Type of usage	Tool	Freeware/Licensed	Developer
Whole-Building Simulation	**EnergyPlus**	Freeware	National Renewable Energy Laboratory Lawrence Berkeley National Laboratory
	OpenStudio	Freeware	National Renewable Energy Laboratory
	Simergy	Licensed	Digital Alchemy
	DesignBuilder	Licensed	DesignBuilderUSA
	eQuest	Freeware	U.S. Department of Energy and James Hirsch
	Pleiades-Comfie	Licensed	IZUBA
	IES Virtual Environment	Licensed	IES, Inc.
	TNSYS	Licensed	University of Wisconsin at Madison
Retrofit Calculation	**Commercial Building Energy Saver**	Freeware (online tool)	Lawrence Berkeley National Laboratory
Air Flow Modeling	**Contam**	Freeware	National Institute of Standards and Technology
Environmental Parameters energy modeling	**Revit (previously Ecotect®)**	Licensed	Autodesk
	Climate Consultant	Freeware	University of California, Los Angeles
Windows/Envelope energy modeling	**COMFEN**	Freeware	Lawrence Berkeley National Laboratory
	Sefaira Architecture	Licensed	Sefaira
	WINDOW	Freeware	Lawrence Berkeley National Laboratory
Lighting energy modeling	**AGi32**	Licensed	Lighting Analysts
	DIALux	Freeware	DIAL
Daylighting energy modeling	**Radiance**	Freeware	Lawrence Berkeley National Laboratory
Mixed mode spaces modeling	**India model for Adaptive Comfort (IMAC)**	Freeware	Centre for Advanced Research in Building Science and Energy (CARBSE), CEPT University
Multitask Simulation Tools	**Modelica Building Library**	Free Library (requires a Modelica environment)	Lawrence Berkeley National Laboratory
	TRNSys	Licensed	University of Wisconsin

Also see the U.S. Department of Energy repository of tools (http://www.buildingenergysoftwaretools.com/).

Appendix 5: Climate-Specific Modeling and Analysis for High-Performance Indian Office Buildings

Appendix 5: Building Simulation Report

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CLIMATE-SPECIFIC MODELING AND ANALYSIS FOR HIGH-PERFORMANCE INDIAN OFFICE BUILDINGS

Baptiste Ravache, Reshma Singh, and Spencer Dutton

SUMMARY

ILLUSTRATIONS

INTRODUCTION

In 2015, the International Energy Agency (IEA) (International Energy Agency Statistics 2015) reported that the total primary energy supply in India represented 5% of the world's energy supply, i.e., 851 million tons of oil equivalent (Mtoe). The IEA also predicted that by 2035, India's energy demand will rise to 8.6% of the world's energy demand, to a predicted 1,464 Mtoe (International Energy Agency 2012). India is the world's third-largest energy consumer and source of greenhouse gas (GHG) emissions.

While its energy demand is growing exponentially, India faces several challenges in meeting even current energy requirements, including the following:

- Lack of power availability, quality, and reliability: there are still 300 million people in India (a quarter of the total population) who live without electricity (Pargal and Banerjee 2014). Where there are electricity grids, load shedding and power intermittency is a common problem. Load shedding is a frequent event, especially in summer months; consequently, polluting, expensive diesel generators are ubiquitous in both residential and commercial buildings. There are also extreme events such as the July 2012 blackouts that paralyzed Northern to Eastern India, with half of the Indian population being affected.
- Energy dependence: India imports 35% of its total energy from neighboring countries, and this ratio is anticipated to increase with increased energy demand (Yadav 2014).
- Continued reliance on non-renewable fossil fuels: In 2013, 68% of India's generated electricity came from plants that burn fossil fuel, while nuclear plants represented 2% and hydroelectricity and other renewable energy sources 30% (Ministry of Power - Government of India 2013). While the capacity ratio of renewable energy sources is high, the ratio in total energy consumption is greatly lowered by India's high dependency on imported energy, mostly as fossil fuel. Consequently, a future transition to low-carbon energy generation is challenging.

As represented in Figure 1, the largest energy consumer in India (as a ratio to total primary energy supply) is the power sector, with 32% of the total energy supply, followed by the building sector with 25%, industry with 23%, and transport and others representing 10% each (International Energy Agency Statistics 2015).

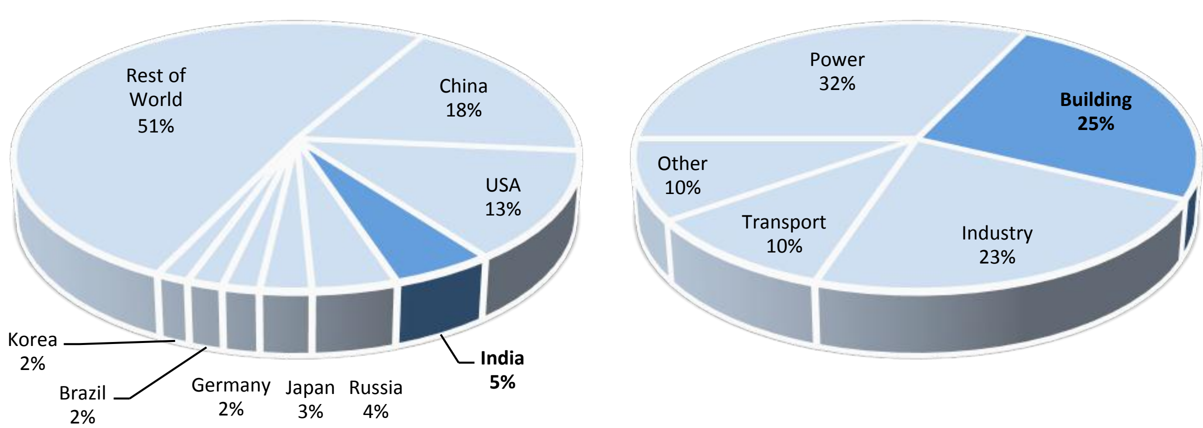


Figure 1: Primary energy demand by country (left) and end-use energy demand in India (right)

India's building energy use accounts for almost a third of the nation's energy use, and this is growing by 8% annually (Rao, Sant and Rajan 2009). The building sectors where growth in new stock floor area is most significant are the commercial (office, hospitality, retail, hospitals) and residential sectors. Given the explosive growth in floor space and increased energy use intensity in the commercial sector, India must address energy efficiency in this sector.

While the building sector represents less than a third of the total energy consumed in India, the potential savings are significant. The Energy Conservation Building Code (ECBC) (Ministry of Power - Government of India 2007), launched by the Indian Ministry of Power in 2007 to provide guidance and norms to buildings owners, reported that, through the application of climate-specific efficiency measures, designers and engineers can potentially save 40% to 60% of total building energy use, compared to conventional buildings (USAID India 2009). ECBC offers non-compulsory guidance that has shown positive simulation results as referenced above, but further simple and cost-efficient improvements in design and systems can lead to further improvements in energy efficiency. These improvements would represent an important step forward in addressing India's energy challenge.

PURPOSE AND SCOPE

This work has been realized as part as the Best Practice Guide for High-Performance Indian Office Buildings project, developed by the Energy Technologies Area at Lawrence Berkeley National Laboratory (LBNL). This project's purpose is to provide guidance for building owners and designers to help achieve enhanced working environments, economic construction / faster payback, reduced operating costs, and reduced greenhouse gas emissions. The document proposes a set of solutions in terms of design, envelope, and energy equipment, selected to maintain occupant comfort and well-being, as well as to efficiently reduce the total primary energy demand.

A first version of the *Best Practices Guide for High-Performance Indian Office Buildings* (Singh, Sartor and Ghatikar 2013) was developed based on surveyed building descriptions and energy use data from existing high-performance Indian buildings. Successful examples of the application of pragmatic energy-efficiency measures were used as the basis for the best practices. In this new version of the guide, primary data were developed by using building energy simulation (BES) to calculate potential savings of those solutions for various Indian climate zones. BES is the numerical study of the energy behavior of a building subject to different external and internal loads. For this work, we used EnergyPlus V8.5, a BES program developed for the U.S. Department of Energy (DOE) by a consortium of research groups including the Simulation Research Group at LBNL. A wide range of modeling tools can be used for building simulation, and some are referenced and compared in Crawley, et al. (2005) or in the DOE repository of tools at http://apps1.eere.energy.gov/buildings/tools_directory/. Please also see Appendix 3: List of Simulation Tools.

This research was conducted in two phases. The first phase included the creation of two baseline models: a business-as-usual (BAU) baseline and an Energy Conservation Building Code (ECBC)-compliant baseline, based on a voluntary building energy efficiency code in India. These baseline models were developed using reference data from current standard and ECBC-compliant office buildings in India. In the second phase, the two reference baseline models were used to incrementally implement selected energy-efficiency strategies and analyze their effect on building comfort and energy consumption. The energy-efficiency strategies selected were cost-effective design improvements that have been tested and validated in existing energy-efficient office buildings in India. For each section of the second phase, a specific meta-analysis was first conducted to understand the effect of a strategy on consumption and/or comfort. The strategy was then modeled to predict the potential energy savings and comfort implications.

According to the ECBC, India has been divided into five climate zones: Hot-Dry, Warm-Humid, Temperate, Composite, and Cold. This work analyzes simulation research conducted in four cities in India, located in four different climate zones: Bangalore (Temperate), Jaipur (Hot and Dry), Mumbai (Warm and Humid), and New Delhi (Composite). The goal was to determine the effect that each energy-efficiency strategy had on the different building loads and, therefore, identify the most effective strategies for each climate.

FIRST PHASE: BASELINE MODELS

The baseline models were the starting point of this study. They define a baseline for use, area, and load, and provide a reference for benchmarking and energy-savings calculations. The two baseline models used were the BAU model and an ECBC model.

BUSINESS-AS-USUAL

The elements comprising the BAU baseline model were selected to represent standard construction materials and practices in India. For ease of comparison and standardization, the geometry from an ASHRAE reference model for office buildings was adapted. Inputs from Indian buildings experts regarding India-specific construction assemblies and materials (such as the wall composition) were collected to contextualize the model.

THE DIFFERENCE BETWEEN OFFICE BUILDINGS IN THE UNITED STATES AND INDIA

Several differences can be found between common practice office buildings in India and in the United States. While there might be some variance from one location to another in both of those countries, some practices are commonly attributed nationwide. Table 1 references the main differences between a typical medium-sized office building in the United States, as described in a study by the National Renewable Energy Laboratory (Deru, et al. 2011), and construction trends in India, as gleaned from site visits and expert opinions.

Medium-sized Office Building	United States of America	India
Type of Construction	Steel-frame Structure Insulated Walls and Roof	Reinforced Concrete Foundation Brick Wall or Autoclaved Aerated Concrete (AAC) Concrete Blocks No Insulation
Windows	~33% Window-To-Wall (WWR) Ratio Double Glazing Solar Heat Gain Coefficient (SHGC) from 20% to 30%, depending on the climate zone	Glass ~80% WWR Single Glazing SHGC = 48%
HVAC	Heating: Furnace Cooling: Packaged Air-Conditioning Unit Distribution: Multi-Zone Variable Air Volume (VAV)	Heating: None Cooling: Packaged Air-Conditioning Unit Distribution: Multi-Zone VAV
Occupancy	~18 m^2/person	~10 m^2/person

Table 1: Difference between common building practices in India and USA office buildings

GEOMETRY

The physical geometry of the building model is based on the medium-sized office building model developed by the U.S. DOE (Griffith, et al. 2008) to represent a typical office layout, with a central core zone and four perimeter zones, as shown in Figure 2. An additional fourth story was added based on feedback from Indian buildings experts. Note that the results in terms of energy consumption per area unit can be extended to buildings with three stories or more. Also note that, despite the geometry of the building being changed in the Phase 2 best practice models, the floor area and the height (and therefore the volume) are kept constant across all the models in this work.

Dimensions	Occupied Area	Ceiling Height	Floor-to-floor	Perimeter Zone Depth
50 x 33 m	6400 m²	2.74 m	3.95 m	6 m

Table 2: Baseline model dimensions

The building is oriented so that the longest sides are exposed to the north and south. Based on feedback from Indian buildings experts, it became clear that a substantial proportion of office buildings in India have a glass-curtain wall design (Manu, et al. 2011) despite the presence of significant solar loads. This construction design remains an aspiration for new buildings. Hence, for this model, an 80% wall-to-wall ratio was used on each façade. This was confirmed as being a realistic ratio for existing BAU buildings by buildings stakeholders.

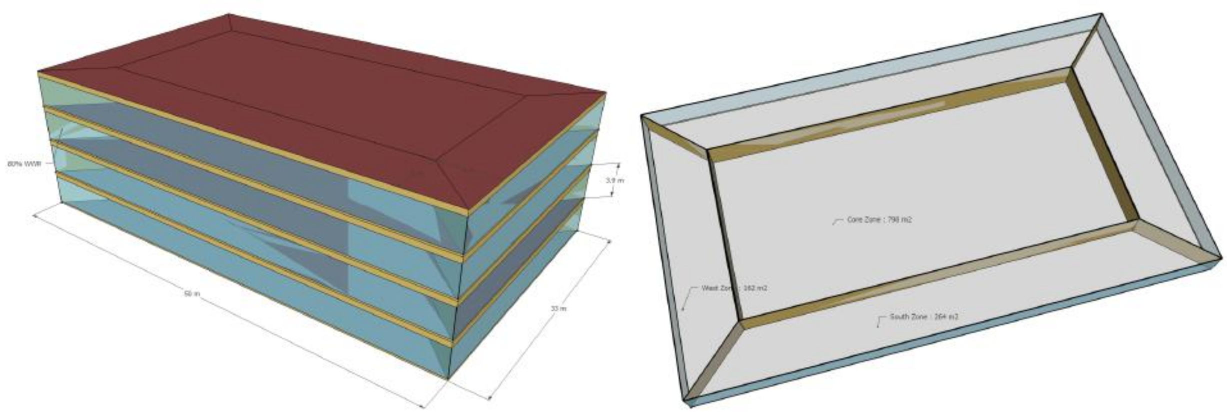


Figure 2 : Representation and cross-section view of the baseline model

ENVELOPE

The envelope composition of the BAU model is independent of climate zone. The construction set used common materials and types of architecture found in Indian buildings, as shown in Table 2. The overall thermal properties of the building models are consistent with the values used in previous studies. Glazing for the glass-curtain wall was selected from a published source of existing office windows (Efficient Windows Collaborative 2014).

For other building construction elements (including the floor and roof) and design parameters (such as the separation between spaces), default values were used from the DOE's typical medium-sized office building. Outdoor air infiltration was set through the envelope at 2.05 cubic meters per hour (m^3/h) per square meter of exterior wall (Griffith, et al. 2008).

Wall	Materials	Brick – 210 mm
	U-Value	2.177 watts per square meter kelvin (W/m^2K)
Roof	Materials	Concrete – 360 mm
	U-Value	2.177 W/m^2K
Fenestration	Type	Single Glazing
	U-Value	5.62 W/m^2K
	SHGC	48%
	Visible Light Transmission (VLT)	48%

Table 3: BAU model – envelope materials properties

HVAC SYSTEM

The choice of the HVAC system design—an important consideration in active energy use—was intended to represent a "typical" system in current Indian office buildings. At the same time, a focus of this project was to quantify relative differences in primary energy consumption that are attributed to the ventilation, cooling, and heating spaces for various building scenarios.

In the reference baseline model, the HVAC system is composed of one air-handling unit (AHU) per floor, which provides conditioned air to all five zones. The AHU comprises an economizer, a supply and a return fan, and a water-based cooling coil associated with a chiller and cooling tower. In each zone, a terminal air unit with an electric reheat coil was installed. It has been noted that most Indian buildings are not equipped with heating equipment, but analysis of simulation results showed that a small heater was required to maintain optimal comfort on certain days. The energy consumed by those heaters was found to be negligible, and it could in principle be removed assuming that occupants would adapt their clothing to maintain their own comfort during cooler periods. The EnergyPlus simulation engine automatically sized the equipment in each model to meet the cooling, heating, and ventilation load occurring on summer and winter design days specific to each climate. These summer and winter design days represent the extremes of outdoor environmental conditions that the building will likely encounter in each climate.

The model input parameters used to describe the HVAC equipment were based on DOE's medium-sized office building model (Figure 3) and are summarized in Table 3.

The chiller performance was approximated assuming a constant coefficient of performance (COP) of 5.1, which was taken to represent a centrifugal chiller. Market assessments show that, for high cooling capacity (525 kilowatts [kW]–8750 kW), the Indian market is dominated by a centrifugal chiller with a typical COP of 5.1 (PACE-D Technical Assistance Program 2014). The cooling capacity of BAU models ranges from 885 kW in the temperate climate (Bangalore) to 1,038 kW in the composite climate (New Delhi).

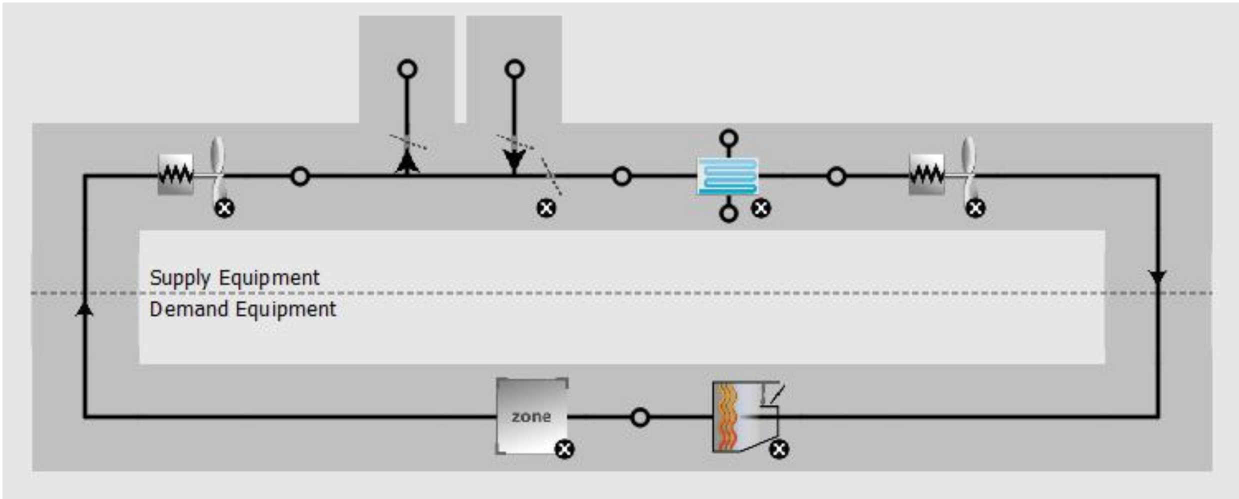


Figure 3: Representation of the air loop and associated equipment

Supply and Return Fan Variable Volume Fan VSF-1 and VRF-1	Fan Efficiency	70%
	Maximum Pressure Rise	Supply: 900 Pa Return: 350 Pa
	Maximum Flow Rate	Auto-sized
	Motor Efficiency / Ratio of Thermal Loss to Air Stream	90% / 100%
Cooling System CC2T-1	Cooling Coil Configuration	Cross-Flow
	Chiller COP	5.1
	Chiller Flow Mode	Variable Flow
	Cooling Tower	Variable Speed
	Chilled Water Temperature	Inlet 11°C – Outlet 6°C
	Condenser Water Temperature	Inlet 32°C – Outlet 38°C
Air Terminal Variable Air Volume with Electrical Reheat	Nominal Capacity	Auto-sized
	Heating Efficiency, allowing for duct losses via the plenum to the outside	99%

Table 4 : BAU model – HVAC equipment parameters

CONTROL SEQUENCE

The control sequence is a set of rules that defines how the installed HVAC is ideally operated. Optimally, a real control sequence should maintain thermal comfort when the building is occupied, turn off the active cooling during unoccupied hours, and minimize energy consumption during both occupied and unoccupied times.

The cooling and heating distributed by the air system varies with the airflow rate provided by the central air system, while the outlet temperature remains constant. Through a series of iterations, the simulation can determine the airflow rate needed to maintain comfort within a certain range. Occupant comfort is a consequence of the values of four zone environmental variables: air temperature, mean radiant temperature, relative humidity, and air speed, and two occupant-related variables: activity and clothing level. Zone temperature control is based on operative temperature, which is a weighted average of the air temperature and the mean radiant temperature, and serves as a proxy for thermal comfort.

Controlling the operative temperature was identified as a more effective method of meeting comfort requirements than using controls based on a conventional thermostat, which responds mainly to air temperature. Control using a thermostat maintains the indoor air temperature but does not consider the radiant temperature of the surrounding surfaces. Real occupants, by contrast, do feel these radiant effects. Analysis confirmed this assertion, and annual simulations predicted a significant number of hours of thermal discomfort when control of zone conditioning was based on air temperature alone. This effect is significant in thermally massive concrete buildings that experience high solar loads.

Building management systems are not able to determine the thermal comfort of occupants; however, our assumption is that occupants would have some degree of influence over setpoints—either directly by manually controlling a thermostat on the wall or indirectly by alerting the building manager. Moreover, this control sequence allowed us to focus the comparison between modeling solely on the energy consumption versus considering the ability of a design to meet a certain comfort criterion. A following section is a meta-analysis on "Comfort Model" and delves into this in detail.

The zone temperature is controlled by varying the air-flow rate to the zone using a VAV terminal unit. The supply air temperature is reset as necessary to provide just enough cooling to the hottest zone with the maximum air flow rate (as determined by the size of the air terminal), subject to a minimum value of 12°C. The ventilation is sized and controlled to provide a minimum outdoor air flow rate based on occupancy and space area, as per ASHRAE-62 recommendations: 8.5 (m^3/h)/person and 1 (m^3/h)/m².

INTERNAL LOADS

The building models use schedules based on an assumed 8-hour work day. Figure 4 shows the hourly scheduled values of the internal loads (people, lights, and plug loads).

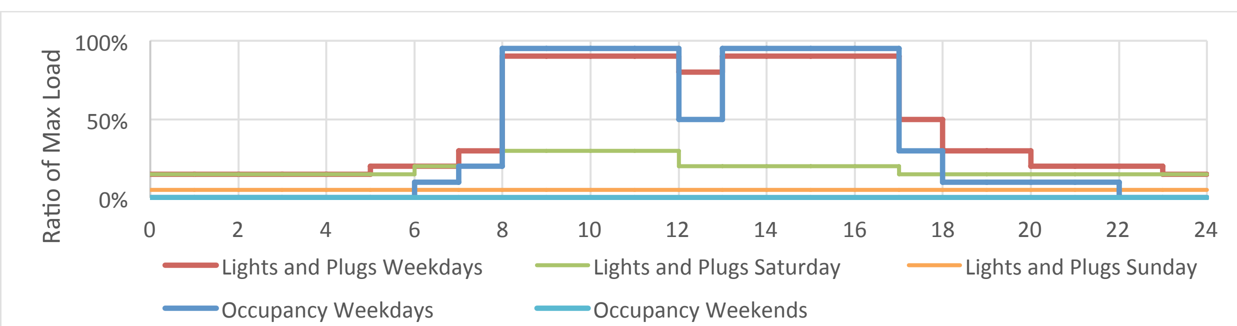


Figure 4: BAU model – internal loads schedule

The peak value for each load was taken from the standard ASHRAE value for offices (Griffith, et al. 2008). Occupancy was increased to 10 m²/person to represent the high density of occupancy in Indian offices. The clothing value was taken as constant 0.5 clo (unit for clothing) all year round to account for India's climate. The values are presented in Table 5.

Lights	Plug Loads	Occupancy		
Power Density	Power Density	Area/Person	Metabolic Rate	Clo Value
10 W/m²	10.8 W/m²	10 m²/person	120 W/person	0.5

Table 5: BAU model – internal loads parameters

META-ANALYSIS 1: COMFORT MODEL

According to ASHRAE Standard 55-2013 (ASHRAE 2013), thermal comfort in mechanically ventilated spaces can be evaluated by using Fanger's predicted mean vote (PMV) model (Fanger 1967). This model is based on the heat balance of the human body and has been developed with measurements made under steady-state laboratory conditions. The model includes a correlation between the energy balance at the surface of the skin and thermal sensation on a scale from -3 (cold) to 3 (hot), with 0 being thermal neutrality and corresponding to the optimal temperature for comfort. PMV is then used to determine the predicted percent dissatisfied (PPD) by using an inverted normal distribution centered around PMV = 0, where discomfort is minimal and only 5% of occupants are predicted to feel uncomfortable. The PMV model, as presented in ASHRAE Standard 55, can be applied in every occupied space regardless of use and geography, if the indoor climate is within the following limits (see Appendix 1: Glossary of Terms):

- Metabolic rate (met) of occupants: from 0.8 met to 4 met (46 W/m^2 to 232 W/m^2)
- Clothing insulation: from 0 clo to 2 clo (0 m^2K/W to 0.310 m^2K/W)
- Air temperature: between 10°C and 30°C
- Mean radiant temperature: from 10°C to 40°C
- Relative air velocity: from 0 meters per second (m/s) to 1 m/s
- Humidity ratio: from 0 g_w/kg_{da} to 12 g_w/kg_{da}

In our model, the previous values were set to:

- Metabolic rate: 1 met
- Clothing insulation: 0.5 clo
- Air temperature and radiant temperature: between 15°C and 30°C – determined dynamically by EnergyPlus
- Air speed: 0.137 m/s
- Humidity ratio: determined by the moisture balance on the zone performed by EnergyPlus

While some studies have showed discrepancies between the PMV (calculated with the model) to the AMV (average mean value, obtained through field surveys), and others have tried to improve the model developed by Fanger, it has been found to be accurate for a wide variety of buildings and climates, as long as the inputs are accurately determined (Hoof 2008). The model is particularly applicable for air-conditioned spaces with an optimum steady-state temperature, and therefore is a good fit to the types of buildings modeled in this study.

ECBC MODEL

This study utilizes the Energy Conservation Building Code (Ministry of Power - Government of India 2007), established in 2007. This is a code that provides design norms to buildings experts for conceiving energy-efficient buildings. The main idea behind this code is to raise awareness about solutions to help reduce the primary energy consumption in buildings. It also offers guidelines to validate building performance during the design and operation phases by providing reference baseline buildings for comparison. To be code-compliant, a building must implement all the design norms in the ECBC document (Prescriptive Method), or, alternatively, achieve the same or better performance than an equivalent building that had implemented them (Whole-Building Performance Method). It is important to note that, as of early 2017, compliance with the energy code remains voluntary in 19 states, and there are no compulsory standards that restrict building energy consumption in India. The energy code provides reference baseline end-use consumptions for building envelope, lighting systems, HVAC equipment, and plug loads. A new version of ECBC was released in 2017 after this energy modeling study was completed.

In this project, the 2007 ECBC guidelines were used to develop a second baseline model to assess the results obtained by best practice models. The ECBC baseline was used as a basis for further improvements, leading to best practice models in phase two, that are, therefore, by default, code-compliant. The ECBC models use all the structural building elements present in the BAU models but improve on systems and sub-systems to be code-compliant.

The chiller performance was modeled using a fixed COP of 5, which is slightly above the requirements for a rotary screw or scroll compressor chiller. Considering a total cooling capacity between 500 kW and 700 kW for all climates, choices for chillers are a scroll or a centrifugal chiller, which has a required rating point COP of 5.8. The use of a simplified chiller model with a constant COP of 5 is approximately equivalent to assuming a seasonal average COP of 5.

Envelope	Composition	Brick and Glass Wool
	Thermal conductivity of Walls/Roof	0.44 W/m²K / 0.41 W/m²K
Glazing	Window-to-Wall Ratio	50%
	Thermal Conductivity Value	3.30 W/m²K
	SHGC / VLT	25% / 50%
	Overhang Depth	0.6 m
Occupancy	Area/Person	10 m²/person
Lighting	Lighting Power Density (LPD)	10 W/m²K
Plug Loads	Power Density	10 W/m²
Fan	Efficiency	0.9
	Pressure Rise	Supply: 900 Pa. Return: 350 Pa
Chiller	COP	5

Table 6: ECBC model parameters

Regarding lighting control, the ECBC imposes the use of manual or automatic dimming devices that can reduce the light output of luminaires by at least 50%. This is not modeled in this study since manual dimming devices are mostly neglected by office workers (Maniccia, et al. 1999) and the potential of a more stringent and automatic daylighting control is highlighted in a following section.

METHOD

The models were simulated for an entire year, using ISHRAE weather data from four weather stations in four different climate zones: Bangalore, Jaipur, Mumbai, and New Delhi. The results from the BAU and ECBC models allow comparisons of design performance in each climate, leading to the identification of the proposed energy-efficiency strategies.

Modeling results in this work are presented using three different metrics:

- **Total energy consumption per unit area**, or energy performance index (EPI), is the metric used to assess the energy performance of a model at the whole-building level. Additionally, energy consumption by end use is used to determine if an end use needs to be improved or if its potential savings are negligible.
- **Total heat gains and losses of the building** are sorted by sources, used to indicate that potential passive measures can help reduce the cooling and ventilation loads. More specifically, in hot climate zones, energy-efficient envelopes promote heat loss from the interior and avoid excessive heat gains.
- **Occupant thermal discomfort** is assessed based on the number of hours where PPD exceeds 20%. In ASHRAE Standard-55, a design is considered comfortable when the fraction of discomfort hours does not exceed 4% of the total occupied time. The discomfort value is used to validate whether the HVAC system is providing adequate thermal comfort.

Table 7 shows the total energy consumption and the total ratio of uncomfortable hours by orientation for the BAU and ECBC models in the four climate zones. Figure 5 shows the energy consumption per end use of the building. Figure 6 shows the total heat gains and losses accumulated over the year. The actual energy consumption is lowered by the fact that sometimes losses are simultaneous with gains (for instance losses through the envelope simultaneous to heat gain from plug loads).

City Climate	Bangalore Temperate		Jaipur Hot and Dry		Mumbai Warm and Humid		New Delhi Composite	
Model Name	BAU	ECBC	BAU	ECBC	BAU	ECBC	BAU	ECBC
EPI [kWh/m²]	232	125	280	146	253	144	268	146
Savings	46%		48%		43%		46%	
Uncomfortable hours (Ratio of Total Occupied Time) (%)								
West	0	0	1	1	1	1	1	1
North	0	0	1	1	1	1	1	1
East	0	0	1	1	1	1	1	1
South	1	0	2	1	4	1	2	1
Core	4	0	5	1	7	1	5	1

Table 7: EPI and comfort values for BAU and ECBC

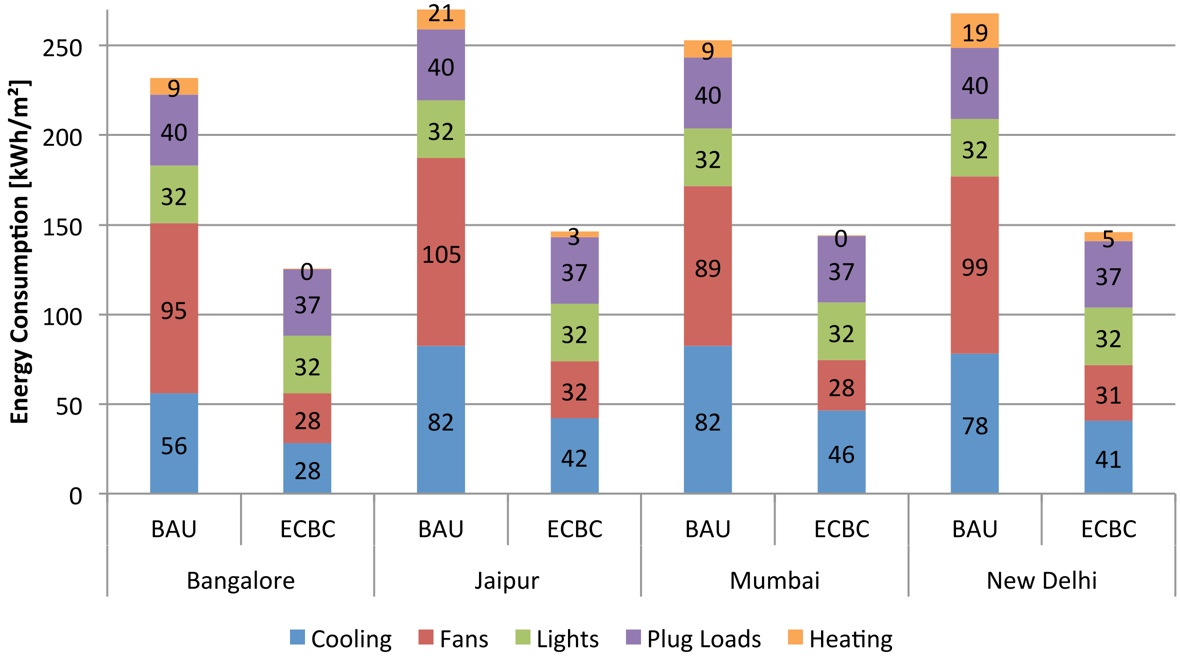


Figure 5: End-use energy consumption for BAU and ECBC models

The results show significant similarities between climate zones. Figure 5 and Figure 6 indicate that even though there are significant variations between climate zones, the same building model provided similar results in each zone. This can be explained by the fact that climate zones with more extreme summer conditions, such as Jaipur and New Delhi, also show a higher seasonal variation than the other climate zones, which have lower annual maximum and variation. While the cooling demand peaks in the summer for New Delhi and Jaipur, it remains more or less constant all year in Bangalore and Mumbai. A more extensive study of each climate can be found in the section Best Practice 3: Night Flush.

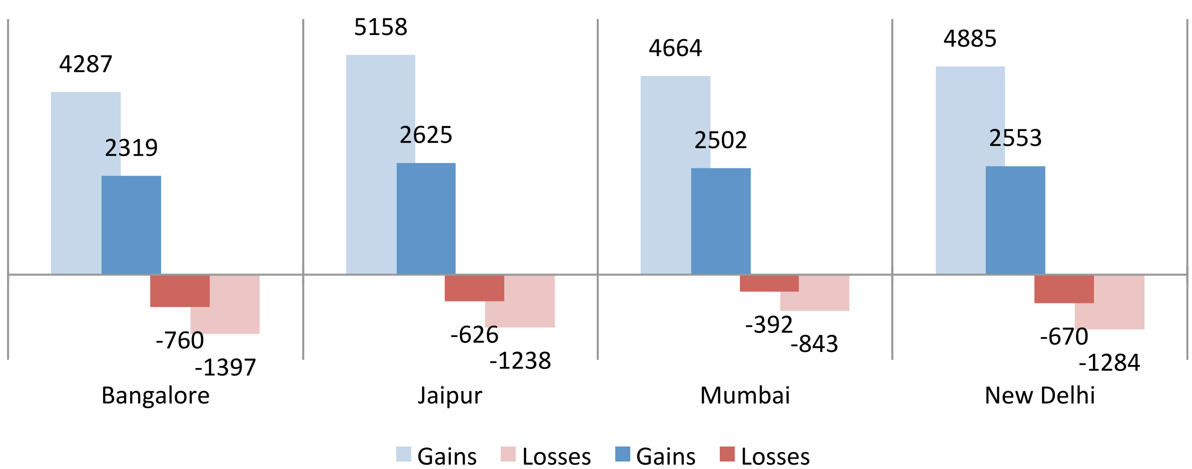


Figure 6: Annual heat gains and losses [GJ] for BAU (lighter hue) and ECBC models (deeper hue)

An analysis of the two models reveals that savings in the ECBC models is primarily from a reduction in the energy consumption of equipment used for air conditioning (labeled Cooling, Fans, and Heating). The savings in the cooling demand energy are the result of a reduction of heat gains from the windows by 75%, due to a reduction of both the window-to-wall ratio and the solar heat gain coefficient, and from the wall by almost 100%, due not only to a reduced U-value but also by a reduction of the solar absorptivity of the opaque surfaces. This also reveals that attention must be given to the fenestration and to radiant absorption by opaque surfaces: bright and reflective materials or paints are preferable, especially when the overall insulation is low.

EPI results shown in Figure 6 are congruent with the first version of the *Best Practice Guide for High-Performance Indian Office Buildings*(Singh, Sartor and Ghatikar 2013), realized through data collection from real buildings given in Table 8. The difference in EPI between the BAU models and the ECBC models represents a 40% to 50% reduction, which aligns with the results of the *ECBC User Guide*.

	Standard Building	**ECBC Compliant Building**
Data collection	250 kWh/m²	150 kWh/m²
Simulation	258 kWh/m² (BAU)	140 kWh/m² (ECBC)

Table 8: Comparison of measured data and simulation results of standard (BAU) and ECBC-compliant building

The predicted occupant thermal comfort generally complies with our ASHRAE-based comfort requirement, except for the core zones in hot climates in the BAU model. This can be attributed to the high thermal load difference between the perimeter zones and the core zone, which is more difficult to address with a single loop. By incorporating better windows and overhangs in the ECBC-compliant building, the maximum discomfort was reduced from 7% to 1%, implying that the system was sized to meet the load at any time. As expected, the energy demand for heating was very low: less than 7% in the BAU model and less than 4% in the ECBC models.

PHASE 2 GUIDELINE

After completing Phase 1, which focused on the BAU and ECBC models, we proceeded to Phase 2. In Phase 2 we selected specific energy-efficiency strategies based on theoretical prediction and empirical data from case study high-performance buildings. The selected strategies that provide energy savings without adversely affecting occupant comfort can be grouped into two types:

1. Passive design strategies, or demand-side optimization:
    a. Reducing the heat energy transfer into the building during building design by improving the massing, orientation, window configuration, or insulation of walls and roofs.
    b. Reducing the internal loads (lights and plug loads) that directly affect EPI and have a secondary affect since cooling is used to mitigate their internal heat gains.
2. Active design strategies, i.e., reducing the HVAC consumption through the following:
    a. Natural ventilation, using night flush and mixed-mode operation, to increase heat losses through a better control sequence that flushes out the stored heat when the outdoor conditions are conducive.
    b. Efficient HVAC equipment and design for producing and/or distributing the cooling. This measure directly affects the HVAC energy consumption that represents more than half of the total energy use in the code-compliant buildings.

During Phase 2, these alternative strategies were assessed individually, and then in combination, with the objective of identifying simple packages of efficiency measures. The design idea of combinations of measures originates from existing high-performance Indian buildings.

SECOND PHASE: BEST PRACTICE SOLUTIONS

In Phase 2 we assessed the energy-saving potential of various solutions. The following sections correspond to a different approach to address the energy consumption. Some of those solutions are incremental and will be added to each other to see a progressive performance improvement. The HVAC system solutions are alternatives.

BEST PRACTICE 1: ENVELOPE AND BUILDING DESIGN

When designing an energy-efficient building, it is important to adapt its design and operations to its environment. Whether the building is in a cold or hot climate, attention must be given to the solar azimuth and altitude over the course of the year. In cold climates where the building heating load is dominant, the building orientation and the glazing should be designed to increase the solar gains in the winter and minimize the glazing on façades that receive less radiation, to reduce thermal losses. In the case of the four climate zones in this study, the cooling load is dominant, and therefore energy-efficient design will need to focus on reducing the glazing on the façades that receive significant solar radiation throughout the year.

Careful consideration should therefore be given to window type. In cooling-dominated climates, which contain the major population centers in India, windows with a low solar heat gain coefficient (SHGC) and a high VLT are favored. To better understand this, a meta-analysis was conducted on solar loads as detailed in the following section.

META-ANALYSIS 2: SOLAR LOADS THROUGH WINDOWS ANALYSIS

Solar distribution (incident radiation by orientation) was evaluated in the four climate zones with the objective of informing model efficiency measures. Building models were used to estimate the total amount of solar energy transmitted through a vertical window for each orientation.

The results obtained for Jaipur (hot and dry climate zone) are provided in Figure 6, and similar results were derived for the other climate zones. Results for the four climate zones can be found in Appendix A.

As Figure 7 shows, the south façade, as expected, receives the most solar energy per square meter. This is closely followed by the west façade. The combination of east and west is largely dominant in comparison with the combination of north and south. When annual energy is broken down into monthly solar energy (Figure 8), it appears that the radiation received by the west and east façades is dominant in the summer (from April to August).

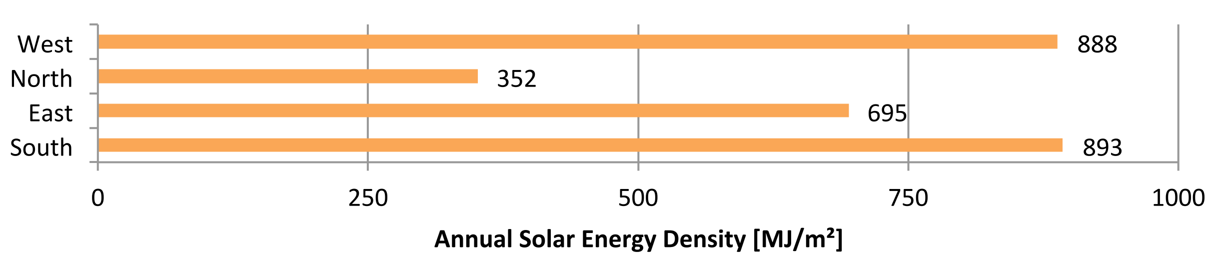


Figure 7: Annual solar energy transmitted to a vertical surface, for ECBC model, by orientation (Jaipur)

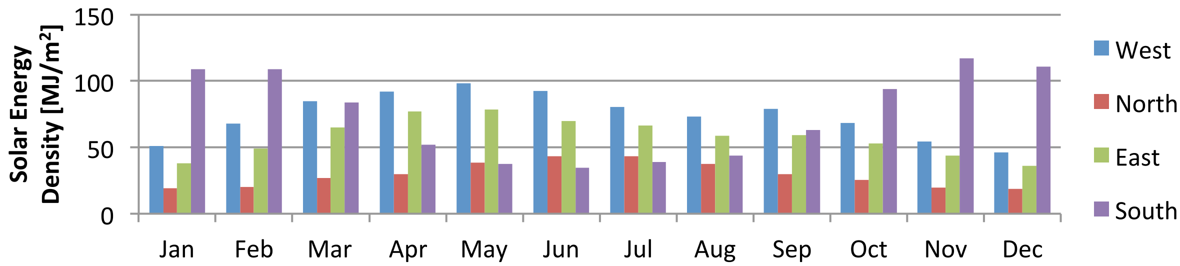


Figure 8: Total transmitted solar energy by month and orientation, for ECBC model (Jaipur)

Moreover, the radiation received by the east and west façades is mostly from low morning and evening sun that is difficult to block with shading devices. The radiation on the south façade is from a higher solar elevation and can easily be avoided with overhangs, while the radiation on the north façade is from early morning and late evening sun with an azimuth close to east and west that can be shaded with fins.

Carnegie Mellon University (Parekh and Dadia 2014) conducted a more detailed study of energy-efficient building façades that investigates the sun's position and angle and proposes effective shadings solutions for each climate zone. That study has been used to determine the optimal overhangs and fins depth for this model.

BEST PRACTICE 1 (BP1) MODELS

Based on the above meta-analysis, a Best Practice 1 (BP1) model was developed using enhanced building and envelope design features. This first best practice model, BP1, had the main purpose of reducing the heat energy transferred to the building, and, more specifically, the solar radiation. The building was oriented with the major façades facing north and south, which proved to be the optimal solution when the correct shading devices were used. It also enabled the building to receive optimal daylighting and helped reduce lighting consumption in the next model (BP2). In comparison to the previous BAU and ECBC models, the building aspect ratio was modified to a longer and thinner floorplate, while keeping the same total internal area and volume. The windows on the east and west walls were removed. Shading devices were optimally sized to cut down the most radiation while maintain adequate daylight. The size of shades is given in terms of shading depth to window height/length ratio.

Building Dimension		80 x 33 m			
Window-to-Wall Ratio		West	North	East	South
		0%	40%	0%	30%
Shading Devices	City	Bangalore	Jaipur	Mumbai	New Delhi
	Façade orientation / Fin depth to window length	North: 0.36	North: 0.36	North: 0.36 South: 0.36	North: 0.17
	Façade orientation / Overhang depth to window height	South: 0.17	South: 0.40	South: 0.40	South: 0.55

Table 9: Building- and envelope-based BP1 model parameters

RESULTS AND DISCUSSION

The results are presented in comparison with the ECBC model that was the baseline upon which the BP1 model was layered.

City Climate	Bangalore Temperate		Jaipur Hot and Dry		Mumbai Warm and Humid		New Delhi Composite	
Model Name	ECBC	BP1	ECBC	BP1	ECBC	BP1	ECBC	BP1
EPI [kWh/m²]	125	114	146	136	144	134	146	137
Savings	9%		7%		6%		6%	
Uncomfortable hours (Ratio of Total Occupied Time) (%)								
West	0	0	1	1	1	1	1	1
North	0	0	1	1	1	1	1	1
East	0	0	1	1	1	1	1	1
South	0	0	1	1	1	1	1	1
Core	0	0	1	1	1	1	1	1

Table 10: EPI and comfort value comparisons for ECBC and BP1

The results in Figure 9 show that the impact of the new design on the energy consumption varied between 6% and 10%, which is not negligible for a medium-sized office: this corresponds to an annual energy savings ranging from 59 megawatt-hours (MWh) to 63 MWh. This savings of 6%–10% came solely from the HVAC end use, with a reduction of the cooling coil load and the fan consumption driven by a 31%–44% reduction of the total solar energy transmitted into the building. It is important to note that the two models used the same type of windows—but, by eliminating all windows on east and west façade, the overall window area was reduced by 40%. This orientation-based approach to windows-to-wall ratio provided a 20% energy reduction, and the overhangs and side-fins added another 20% reduction in heat gain.

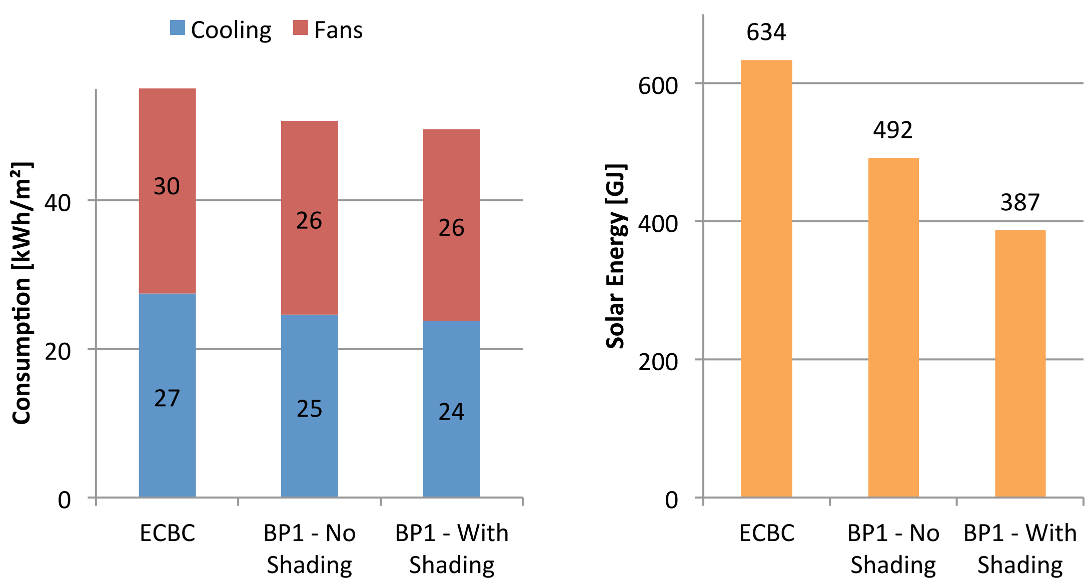


Figure 9: End-use HVAC energy consumption (left) and total solar gains (right) for ECBC and BP1 models on average for all climate

LESSONS LEARNED

- ***The main source of heat gain in Indian buildings is from solar radiation—this is referred to as an external heat dominant building. Energy-efficient designs should focus on reducing window area where those heat gains are difficult to avoid. A low window-to-wall ratio is recommended if daylighting is not compromised.***
- ***Even though solar gains are annually higher on a south façade, a north-south orientation is recommended, as it is more difficult to shade direct sunlight on west and east façades, and it reduces solar gains in the summer when higher cooling loads occur.***
- ***Optimal shading allows shading of direct sunlight, and therefore heat gains, while maintaining visual comfort (glare-reduction) with diffused daylight.***
- ***Shading designs must be climate specific and consider the evolution of solar azimuth and altitude during the year.***
- ***This energy-efficiency strategy shows a similar positive result in all four climate zones, with an average reduction of solar heat gain by ~60%, bringing down the total EPI by ~10%.***

BEST PRACTICE 2: INTERNAL LOADS (PLUGS AND LIGHTING)

The next energy-efficiency strategy is to directly reduce the energy consumed by lights and electric equipment. A meta-analysis of internal loads was conducted to begin this process.

META-ANALYSIS 3: INTERNAL LOADS ANALYSIS

To prepare this model, the BP1 model presented in the previous chapter was used. As stated earlier, the electric equipment in the building has a dual effect on energy consumption: it directly consumes electricity, and then transforms this energy into heat that increases the cooling load and, therefore, HVAC system energy consumption. As shown in Figure 10 in the BP1 model, the electric equipment (lights and plug loads) consumes 49% of the total energy used and additionally accounts for 67% of the total heat gain.

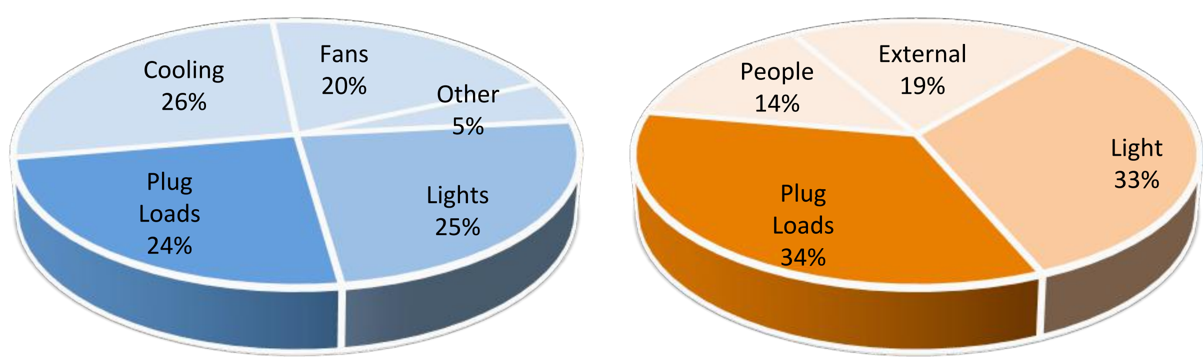


Figure 10: Part of plug loads and lighting in energy demand (left) and heat gains (right) for BP1

There is, therefore, significant energy-saving potential from reducing the amount of energy consumed by the interior lights and equipment. This can be achieved by having more efficient lights and electrical equipment installed, as well as by turning off lights and unnecessary equipment during adequately daylit or unoccupied hours. By installing photosensors, it is possible to reduce artificial lighting proportionally to the daylight in the space while maintaining an optimal visual comfort for occupant.

BEST PRACTICE 2 (BP2) MODELS

For the BP2 model, plug loads and maximum lighting power were reduced based on peak power values found in existing best practice buildings. The schedule used for modeling the operation remains the same. Additionally, daylighting controls were implemented (to reduce artificial lighting when it is superfluous) in the south and north zones. The other zones had no windows and were, therefore, considered entirely dependent on artificial lights. The daylighting controls consist of two light sensors positioned in the middle of the spaces, at 3 m and 6 m away from the window. When the illuminance detected by one of those sensors exceeds 300 lux, artificial lights dim off. Each sensor controls 50% of the total light power in each zone. These inputs are shown in Table 11.

Plug Loads	Lights	Daylighting Control		
Power Density	Power Density	Zones	Sensors Position	Illuminance Setpoint
7.5 W/m²	5 W/m²	South and North	3 m and 6 m away from window	300 lux

Table 11: BP2 (internal plug and light load) model parameters

RESULTS AND DISCUSSION

The new model, BP2, was layered on top of the BP1 model. Table 12 presents a comparison of the results generated by those two models.

City Climate	Bangalore Temperate		Jaipur Hot and Dry		Mumbai Warm and Humid		New Delhi Composite	
Model Name	BP1	BP2	BP1	BP2	BP1	BP2	BP1	BP2
EPI [kWh/m²]	114	64	136	90	134	82	137	93
Savings	44%		34%		39%		32%	
Uncomfortable hours (Ratio of Total Occupied Time) (%)								
West	0	0	1	1	1	0	1	1
North	0	0	1	1	1	0	1	1
East	0	0	1	1	1	0	1	1
South	0	0	1	1	1	0	1	1
Core	0	0	1	2	1	0	1	3

Table 12: EPI and comfort value for BP1 and BP2

Results in Table 12 show that reducing electric lighting and plug loads had a significant impact on the EPI without creating discomfort.

Figure 11 shows that these savings are based on two drivers: reduction of the power density that provides 25% reduction of the lighting energy consumption; and the daylight controls that provide an additional 60% savings.

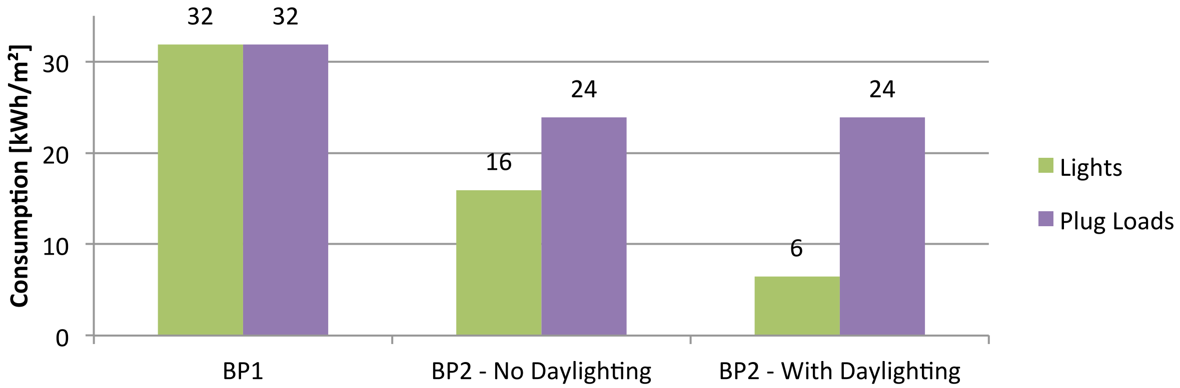


Figure 11: Total energy consumption for plug loads and light in BP1 and BP2, average for all climates

Annual heat gains are reduced by 36%, thus creating a 35% reduction in HVAC energy use. Plug loads remain the main source of energy consumption and cooling load (Figure 12).

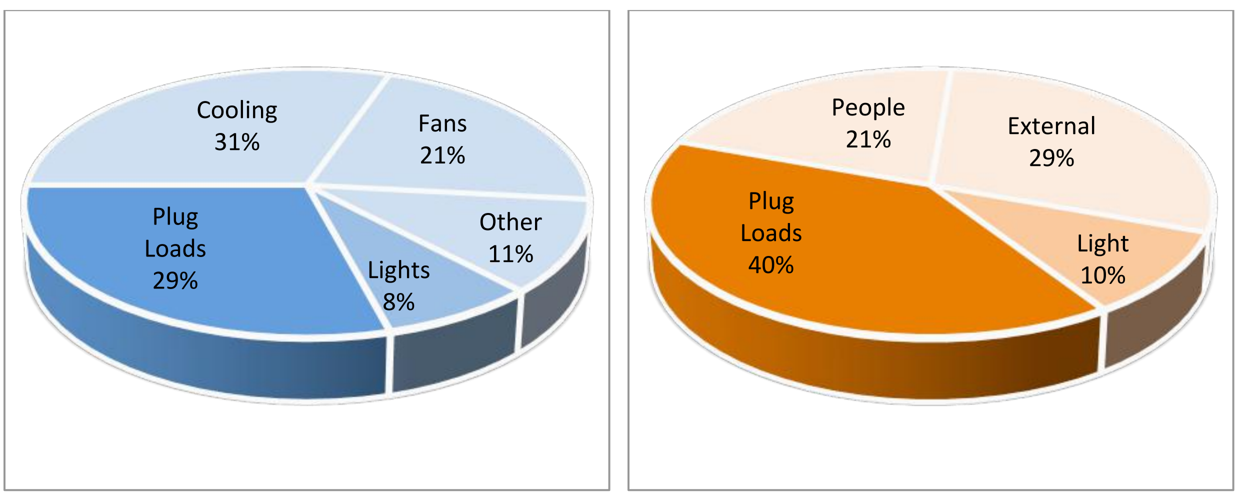


Figure 12: Plug loads and lighting loads shown as portion of the energy demand (left pie chart) and heat gains (right pie chart) for BP2

LESSONS LEARNED

- ***Plug loads and lighting represent a significant source of energy consumption and contribute to the internal heat gains and, hence, energy demand for space cooling.***
- ***The energy savings potential is substantial and is climate independent. Through this strategy, the EPI is reduced by about 40% in every city.***
- ***Daylighting controls greatly reduce the energy consumption for lighting, while maintaining the appropriate level of visual comfort for occupants.***
- ***Daylighting control is only possible and efficient if the envelope has been conceived to maximize natural light sources.***

BEST PRACTICE 3: NIGHT FLUSH

Another common way to reduce cooling demand is to use cool outdoor air when it is available to remove (flush out) the heat stored inside the building. In comparison to the previously mentioned solutions, this strategy does not affect heat gains or internal loads, but rather encourages heat losses to occur at an opportune time when the outdoor environment is cooler than the indoors. This generally may be the case at night, when the building is unoccupied, making it possible to increase air flow rate and drop the indoor temperature below the heating setpoint without creating discomfort. This solution is called “night flush;” it may make use of natural ventilation or mechanical ventilation. A meta-analysis for night flush was conducted to evaluate predicted savings using this strategy.

META-ANALYSIS 4: POTENTIAL SAVINGS FROM NIGHT FLUSH

For night flush to be efficient, the outdoor climate must show adequate diurnal variation and exhibit air temperatures below the cooling setpoint at night. The following study was done to evaluate the number of nights where various Indian climates meet this condition during unoccupied hours. The study assumed 25.5°C as a temperature trigger value. In other words, the maximum outdoor temperature under which the night flush is available is 25.5°C, which is the optimal operative temperature for comfort, assuming the relative humidity, the metabolic rate, and the clothing of the occupants (RH = 60%, met = 1.8, clo = 0.5).

Figure 13 presents the number of nights per month and the average number of hours per night when the outdoor temperature is low enough for night flush to be effective. Figure 14 presents the annual chart of the outdoor air temperature sampled hourly for each climate zone.

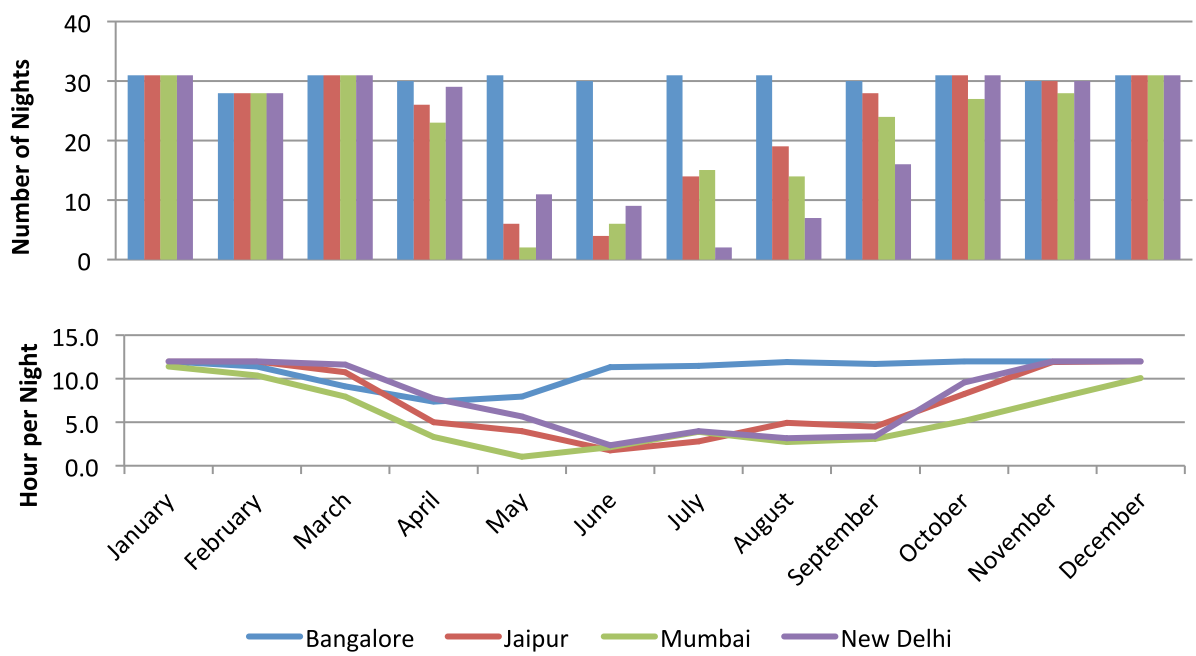


Figure 13: Number of nights (top) and average number of hour per unoccupied hours (bottom) for analyzing possibility of night flush

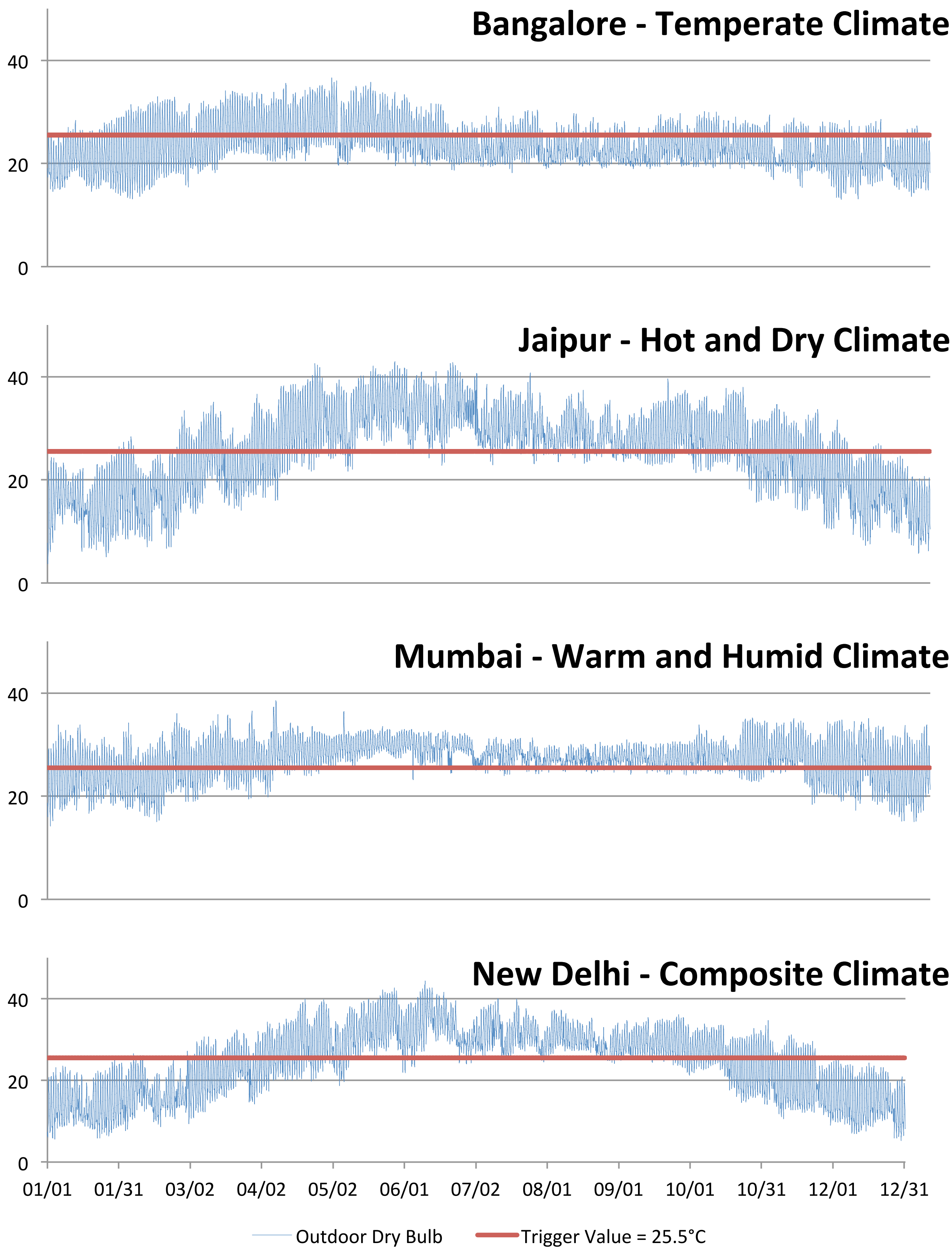


Figure 14: Annual outdoor air temperature variation and night flush trigger value

These results show that, theoretically, night flush can be recommended for the temperate climate of Bangalore, which has a consistently high fraction of nights, and hours per night, when the outdoor temperature drops under the trigger value. In the other climate zones, which have a high night flush availability in the winter but almost none in the summer when potential savings would be maximum, night flush is likely to have a smaller impact.

DRY BULB- vs. WET BULB-BASED NIGHT FLUSH

The primary concern associated with only considering the dry bulb temperature when ventilating outdoor air directly into the building is introducing humidity, or latent gains, into a dry environment. Outdoor air can increase the risks of condensation, mold, or hygrothermal discomfort. A solution to this problem is to change the control from a comparison of dry bulb temperature to a comparison of wet bulb temperature. The wet bulb temperature is an indicator of the total energy (enthalpy) content of the air, both sensible and latent—it can, therefore, prevent unwarranted ventilation of slightly cool, high relative humidity, outdoor air into the building.

The previous study was reproduced with the consideration of a wet bulb-based night flush, with a wet bulb limit of 20°C (corresponding to a dry bulb temperature of 25.5°C and a humidity of 60%, which is the optimal comfort condition). Results are shown in Figure 15.

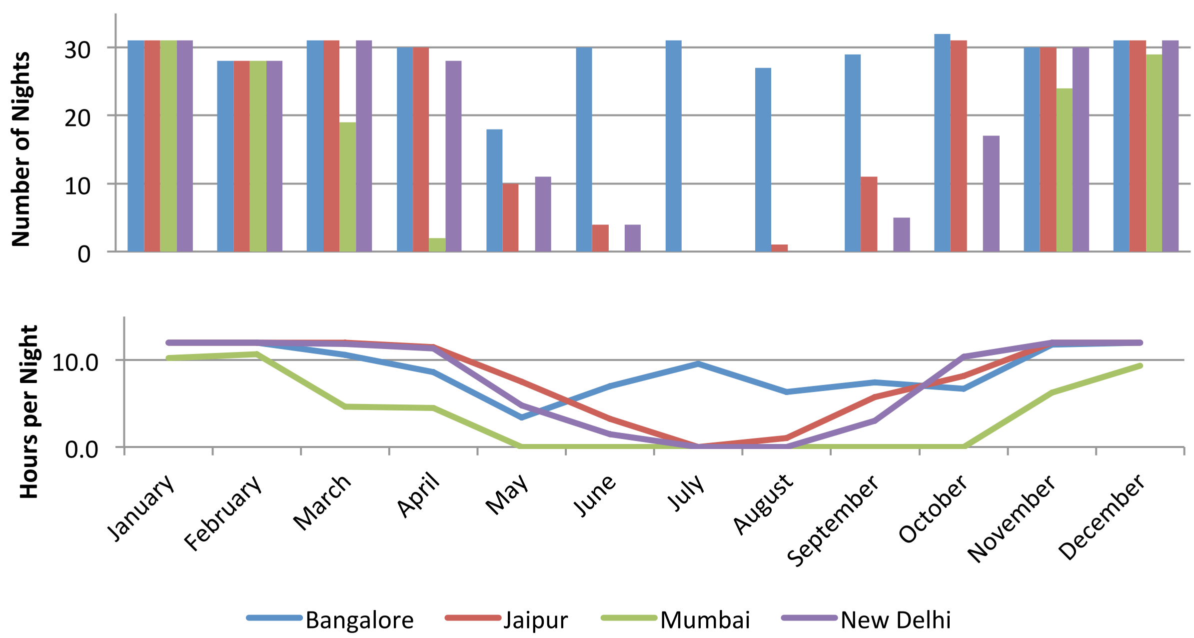


Figure 15: Number of nights (top) and average number of hours per unoccupied hours (bottom) for wet-bulb controlled night flush

Use of a wet-bulb limit on the night flush resulted in the unavailability of night flush in the summer for all cities but Bangalore. This effect is particularly pronounced in the monsoon season when the outside air has a very high relative humidity.

However, studies have shown that control of ventilation based on enthalpy or wet bulb using humidity sensors is unreliable due to the propensity of humidity sensors to drift out of calibration, though traditional wet-bulb sensors can be reliable if they are well maintained. As shown by Taylor and Cheng (2010) for HVAC economizers, an alternative approach is to control on dry bulb temperature but with a lower limit to ensure that the resulting relative humidity in the occupied space is acceptable (e.g., below the 68% required to sustain mold growth).

BEST PRACTICE 3 (BP3) MODELS

The BP3 models were overlaid on the BP2 models with the night flush added to the control sequence. Night flush is triggered whenever the outdoor temperature is lower than the indoor temperature and is turned off when the indoor operative temperature drops below 24°C, which corresponds to the heating setpoint required to maintain acceptable comfort for 80% of the occupants. If spaces were cooled further, it would either the heating demand or discomfort. The control is specific to each zone, and the rated air flow rate is 5 air changes per hour, taken as a minimum for natural ventilation (Table 13).

Natural Ventilation Control Sequence	**Rated Air Flow Rate**	5 ACH (air changes per hour)
	Trigger Rule	Outdoor Dry Bulb < Zone Mean Air Temperature - 1
	Minimum Operative temperature	25°C

Table 13: Night flush BP3 model parameters

In this model, night flush is performed through natural ventilation. It means that the fan consumption does not increase during night flush. This would correspond to opening the window at night and considering that the air is distributed evenly in all the zones until the threshold is met. The advantages and disadvantages of natural vs. mechanical night flush are addressed later.

RESULTS AND DISCUSSION

The results in Table 14 are presented in comparison with the BP2 models.

City Climate	Bangalore Temperate		Jaipur Hot and Dry		Mumbai Warm and Humid		New Delhi Composite	
Model Name	BP2	BP3	BP2	BP3	BP2	BP3	BP2	BP3
EPI [kWh/m²]	64	61	90	89	82	80	93	92
Savings	4%		1%		2%		1%	
Uncomfortable hours (Ratio of Total Occupied Time) (%)								
West	0	0	1	1	0	0	1	1
North	0	0	1	2	0	0	1	1
East	0	0	1	1	0	0	1	1
South	0	0	1	1	0	0	1	1
Core	0	0	2	2	0	0	3	3

Table 14: EPI and comfort value for BP2 and BP3

As expected, Bangalore is the only climate zone that shows a significant savings by using night flush. It is important to note that the results presented are only valid for the control sequences used, but a more aggressive sequence (that would not take early morning discomfort into account) could bring more savings. Nonetheless, considering that implementing night flush adds little to no additional cost, if the ventilation system is sufficiently sized, a savings of 2 kWh/m² is still significant in warm, humid climates such as Mumbai.

Figure 16 provides insight on how night flush helps to reduce the cooling load by increasing the heat losses when available. Note that the total heat gains remain unmodified.

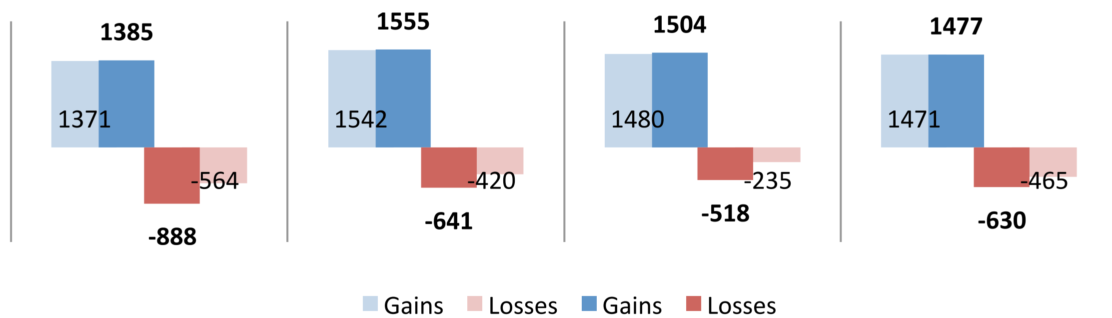


Figure 16: Heat gains and losses summary for BP2 and BP3

MODELING ENTHALPY-BASED NIGHT FLUSH

As presented in the meta-study, it is also possible, using the right sensors, to trigger night ventilation when the wet bulb temperature (instead of the dry bulb temperature) is lower outdoors than indoors. This type of control prevents the introduction of moist air that can create condensation, mold, or hygrothermal discomfort.

In an alternative version of the night flush model, we changed the control sequence to only consider the wet bulb temperature difference between the inside and outside to trigger the ventilation. The indoor temperature set point remained 25°C dry bulb, as it would create heating demand in the early morning to cool the space further.

This control sequence had minor effect on the heat loss introduced in the building; the difference in the total EPI is negligible as shown in Table 15.

City	Bangalore		Jaipur		Mumbai		New Delhi	
Control	Dry bulb	Wet bulb	Dry bulb	Wet bulb	Dry bulb	Wet bulb	Dry bulb	Wet bulb
Heat Loss [GJ]	888	894	641	640	518	511	630	638
Total EPI [kWh/m^2/year]	61.1	62.5	88.8	89.1	80.1	80.2	92.0	92.4

Table 15: Comparison of dry bulb- and wet bulb-based night flush with simulation results

ABOUT THE USE OF MECHANICAL NIGHT FLUSH

In this project, savings brought by passive night flushing was modeled by opening windows or having a ducted air flow rate without the use of fans. In many situations around the world, passive ventilation is the most efficient method for night flushing, as it allows ventilation with “free” cool air. In other cases, natural ventilation using operable windows might not be recommended, for the following reasons:

- It requires automated (too sophisticated) or manual (inconvenient) windows operation
- It might not be recommended for ground floor spaces, to avoid intrusions
- Small- or large-particle pollution in some cities requires the use of filters before ventilation.

Mechanical ventilation alleviates those risks. However, attention must be given to fan consumption, to ensure that it does not exceed the savings. Generally, this requires high-performance fans and an air network designed to minimize pressure losses—and, additionally, a control sequence that only triggers the night flush when the temperature difference is large enough to justify the energy used by the fans.

In this case study, where natural ventilation resulted in little to no savings, mechanical night ventilation would only increase the EPI. Even in Bangalore, where the total cooling equipment consumption was reduced by 27%, the savings partly came from nights where night flush only cooled down the buildings by a fraction of a degree, where it would be counterproductive to turn on energy-consuming fans.

For instance, when the same control sequence was modeled with mechanical ventilation that has a pressure drop of only 350 Pa and a high fan efficiency of 90%, the savings in Bangalore were nullified. However, cooling consumption in BP2 was already low to begin with.

LESSONS LEARNED

- **Night flush is very efficient in a temperate climate (such as Bangalore).**
- **Other Indian climates, that are warmer at night than Bangalore, show much lower savings, but they are still not negligible, considering that the implementation and operation cost is low with an existing ventilation system.**
- **This solution enhances the heat losses when possible in a diurnal cycle, and the savings add to those from previous solutions that independently reduced heat gain or energy consumption from plugs and lights.**
- **Changing the control sequence from a dry bulb-based to a wet bulb or enthalpy-based night flush does not affect the total EPI.**
- **Mechanical night flush is possible, but attention must be given to the ratio of the fan consumption to the potential savings.**

BEST PRACTICE 4: MIXED-MODE BUILDING

Mixed-mode buildings use natural ventilation whenever possible and use mechanical cooling only when natural ventilation is insufficient or inappropriate. In a changeover mixed-mode space, the mechanical cooling can be turned off and replaced by natural ventilation with operable windows, and then turned on again to meet cooling loads when necessary. Mixed-mode can also refer to buildings that have some spaces that are always naturally ventilated (e.g., lobbies, stairwells) connected to air-conditioned spaces–referred to as concurrent mixed-mode. Some mixed-mode buildings use both changeover and concurrent modes.

Mixed-mode, whether it is changeover or concurrent, generally requires the use of operable windows, and the problems of security, outdoor pollution, and pests must be considered.

As discussed in the previous section, in hotter and/or more humid climates, natural ventilation can provide comfort in fall, winter, and spring but less frequently in summer, making these climates suitable for mixed-mode operation. Mixed-mode buildings are common in India, and they achieve high performance (Steemers and Manchanda 2009), in part because the occupants control mixed-mode operations by opening and closing windows. When the occupants control their own comfort (and thereby energy consumption), they tend to accept a broader range in terms of comfortable indoor temperature since they expect it. Applied to modeling, this means implementing a new comfort model to replace Fanger's PMV, as detailed in the meta-analysis below.

META-ANALYSIS 5: COMFORT CALCULATION IN MIXED-MODE BUILDINGS

In this section, comfort is evaluated in spaces that can be naturally ventilated when outdoor conditions are sufficient but still rely on mechanical ventilation the rest of the time. ASHRAE-sponsored research has demonstrated that occupants of buildings that are naturally ventilated during occupancy are comfortable over a much wider range of temperatures, compared to occupants of air-conditioned buildings, primarily because the higher degree of personal control shifts their expectations and preferences (Brager, Ring and Powell 2000).

Studies have also shown that in naturally ventilated spaces, where windows are operable, and occupants choose their own comfort, the occupant's thermal sensation is strongly dependent on the outdoor temperature over the last few days, which serves to influence clothing levels. The temperature history also appears to influence comfort expectations, which are then not entirely determined by body heat balance. For this reason, the latest version of ASHRAE Standard 55 recommends that users employ the Brager adaptive comfort model (De Dear and Brager 2001) for naturally ventilated spaces.

ADAPTIVE COMFORT MODEL

In ASHRAE Standard 55-2013, the adaptive comfort model is recommended for occupant-controlled naturally conditioned spaces that meet the following criteria:

- No mechanical cooling systems and no heating system in operation

- Metabolic level between 1.0 and 1.3 met
- Occupants are free to adapt their clothing within a range at least as wide as 0.5 to 1.0 clo
- The outdoor temperature is in the range of 10°C to 33.5°C.

This model has proven to be more accurate than the PMV model in spaces where occupants have a direct impact on their environment. This is the case in offices with operable windows. Furthermore, the range of comfortable indoor temperature is broader than the limits proposed by Fanger, since adaptation has a primary role in comfort as defined in the adaptive model. To be conservative, the criterion preventing the use of the cooling and heating system should limit the use of the adaptive comfort model to only the time when the space is being naturally ventilated. However, it is currently an open question as to whether the broader acceptable temperature range of the adaptive comfort model can carry over into mechanical cooling, at least in the short term.

Switching from one comfort model to another can lead to high energy consumption results since the setpoint temperatures would vary at each transition. Therefore, in a zone using natural ventilation, we always used the adaptive comfort model, even when the air is mechanically cooled (e.g., a changeover mixed mode operation).

LITERATURE REVIEW

One of the primary principles of adaptive theory is that the outdoor climate context matters. In the warm climate cities, occupants voted "neutral at higher temperatures" in both conditioning types, with a more distinct pattern for naturally ventilated buildings. Higher airspeeds and adaptive clothing are two contributing factors to this distinction (Singh, et al 2018). In a 2014 study conducted through the U.S.-India Center for Building Energy Research and Development (www.cberd.org), the comfort temperature of 1800 respondents was identified to be 27.21 °C for all seasons. The effects of seasonal variations on neutral temperature were also determined; respondents felt neutral at 25.6 °C, 27.0 °C and 29.4 °C during winter, moderate and summer seasons, respectively. Acceptable humidity and air velocity were 36% and 0.44 m/s for all seasons. Thermal acceptabilities for 90% and 80% of the occupants were higher than the limits defined by comfort standards (Dhaka, et al. 2014).

There are a few studies that address the accuracy of both Fanger and adaptive comfort models when applied in Indian climate (Indraganti, Ooka and Rijal 2013) (Singh, Mahapatra and Atreya 2011) (Deb and Ramachandraiah 2010), but no studies were found that evaluate the viability of Fanger's PMV model in naturally ventilated spaces. Work by Indraganti (Indraganti, Ooka, et al. 2014) has shown that the occupants of office buildings in a hot climate zone, whether they are naturally ventilated or air conditioned, have a higher neutral temperature (at which comfort is optimum) than predicted by both the PMV model (that is used to define the adaptive comfort model used in the National Code of India) and ASHRAE's adaptive comfort model. Nonetheless, for naturally ventilated buildings, the ASHRAE adaptive comfort model was found to be accurate, with most of the neutral temperature fitting within the range of 80% of comfort, even when the prevailing outdoor air temperature is higher than the 33.5°C limit proposed in Standard 55.

Regarding the model used for a mixed-mode building, a study conducted in Sydney (Deuble and De Dear 2012), which has a cooler climate and lower seasonal variation, shows that the adaptive model has a better overall accuracy than the PMV model. In this study, the PMV model presents good results when the spaces work in air-conditioning mode but fail to correctly predict comfort in naturally ventilated (NV) mode; Brager's adaptive comfort can be extended to the air-conditioning mode with a good accuracy. It is still questionable whether those results are transposable on other climate and different types of mixed mode (for instance, where the air-conditioning hours might be predominant compared to NV).

APPLICATION TO THIS STUDY

The adaptive comfort model was used in this study for spaces that could be naturally ventilated. The control sequence of the mechanical ventilation in those spaces was modified to account for the adaptive behavior of the occupants. In spaces that are only mechanically ventilated, Fanger's PMV model was used, and the control sequence remained unchanged.

NATURAL VENTILATION POTENTIAL IN INDIAN CLIMATE

The following study evaluated potential savings achieved through natural ventilation operations in Indian buildings. Results show the number of hours for which natural ventilation could be used to replace mechanical ventilation and potentially create a comfortable indoor environment as predicted by Brager's adaptive model.

The following assumptions were made:

- The rolling comfortable temperature range is determined with the following linear equations, corresponding to an indoor environment comfortable for 80% of occupants (De Dear and Brager 2001):

$$Upper\ limit\ (°C) = 0.31 * T_{OA} + 21.3$$
$$Lower\ limit\ (°C) = 0.31 * T_{OA} + 14.3$$

- The outdoor air temperature used to determine the comfortable temperature range is the exponentially weighted running mean of the daily mean outdoor temperature as defined in ASHRAE Standard 55 (ASHRAE 2013) (Indraganti, Ooka, et al. 2014):

$$T_{RM}(today) = 0.8 * T_{RM}(yesterday) + 0.2 * T_m(today)$$

Where T_m is the daily mean outdoor temperature in °C. This weighted running mean has a half-life of approximately 3.5 days, meaning that the weight of each value falls by a factor of two over that period.

When buildings are operating in natural ventilation mode, the operative temperature is considered equal to the outdoor temperature. It is likely that the operative temperature will be different, as it depends on multiple factors that are not usually considered here, including the diffusivity of walls, air flow rate, internal gains, and solar radiation. Those factors differ from one building to another. Nonetheless, this study gives an idea of the natural-ventilation potential for India's different climates. Figure 17 shows where outside air temperature would allow for naturally ventilated zones that are comfortable under a prevailing outdoor air temperature of 25°C.

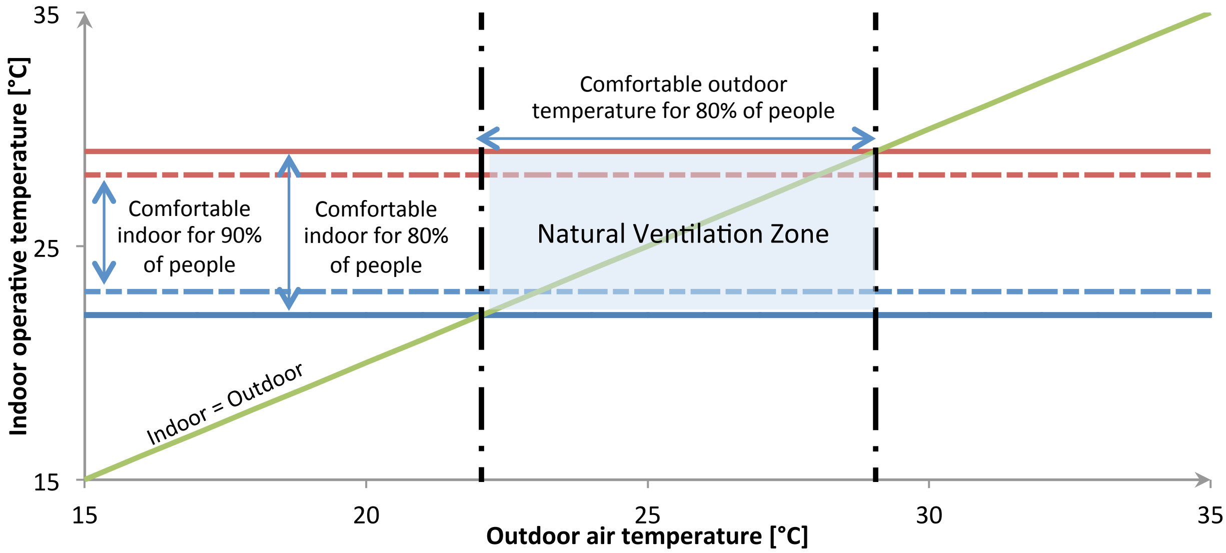


Figure 17: Adaptive comfort model, comfortable range for a prevailing outdoor air of 25°C

Regarding humidity, there is no standard that defines the acceptable range or the effect of humidity on adaptive comfort in naturally ventilated buildings. Empirical studies performed in naturally ventilated spaces in hot-dry and hot-humid climates (Nicol 2004) (Toe and Kubota 2013) conclude that the impact of humidity in hot conditions is relatively small and mostly affects the comfortable range around the optimal indoor temperature rather than changing the optimum value. However, these studies did not use ASHRAE's adaptive comfort model but instead developed their own adaptive comfort equation. Those equations are most likely climate specific and not entirely applicable to this study's four climates. It is difficult to trace back the effect of humidity on comfort when using ASHRAE's model; therefore, the following results do not take humidity into account.

The results in Figure 18 were obtained by applying the previous assumption to the weather data of the four different cities of this study . In these charts, the natural ventilation mode can be considered whenever the dry bulb outdoor air temperature is within the range of comfort. This range is determined with Brager's adaptive comfort equation using the prevailing outdoor air temperature (plotted in red). It is already clear that the temperate, and warm and humid climate, should be a good fit for naturally ventilated spaces because of their small annual variation and a prevailing outdoor temperature that remains inside the acceptable indoor temperature. On the other hand, the hot and dry climate of Jaipur and the composite climate of New Delhi show high annual and daily variations that often bring the outdoor temperature outside of the comfortable range. The potential savings brought by a naturally ventilated mode are therefore relatively smaller.

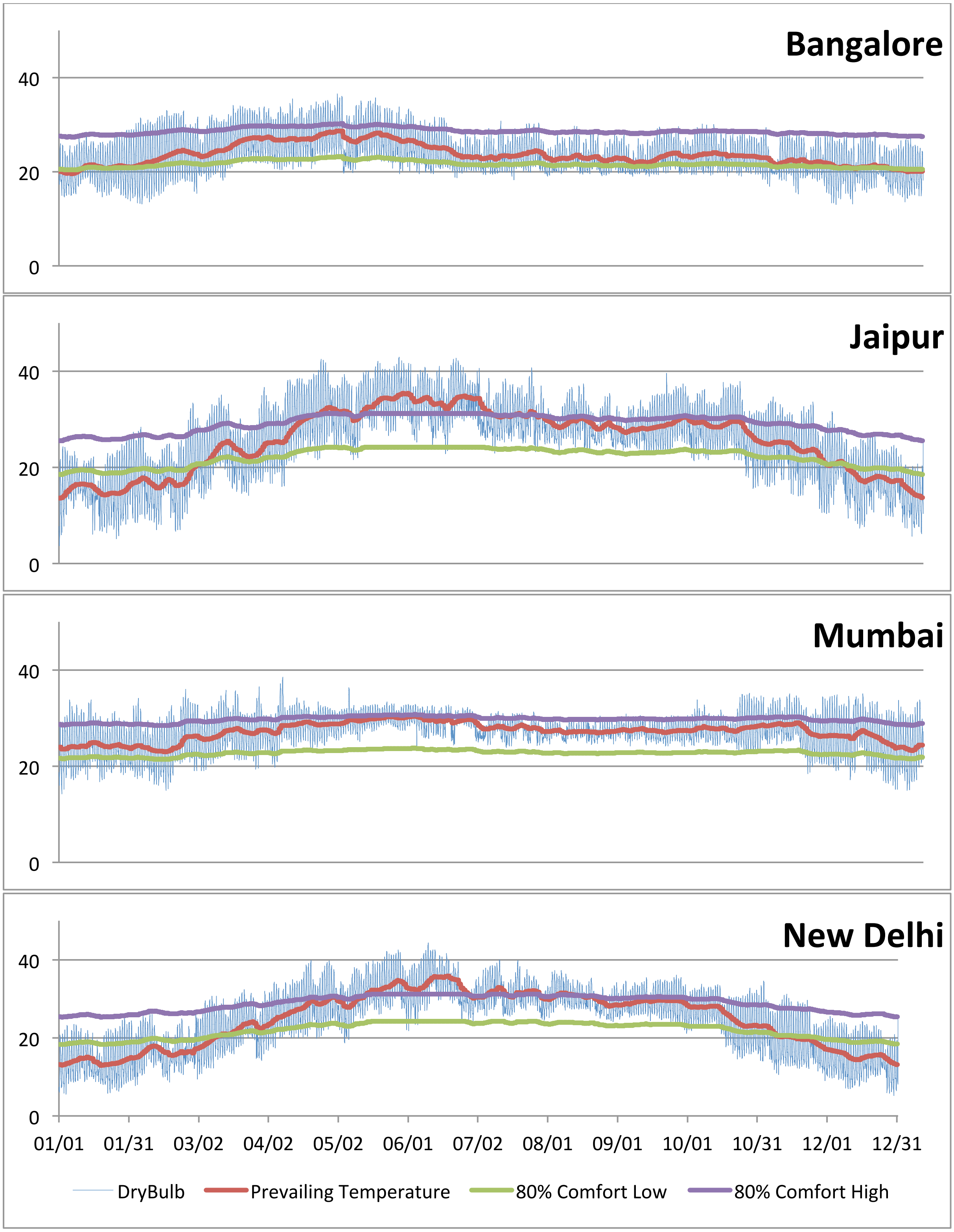


Figure 18: Annual outdoor air temperature variation and associated rolling comfort range

Accounting only for the occupied hours (7 am to 6 pm on weekdays), the number of hours per month where the spaces could be operated in naturally ventilated mode can be determined (Figure 199). The previous observations are validated even when only accounting for occupied hours: in Bangalore and Mumbai, the outdoor temperature fits within the adaptive comfort range for, respectively, 64% and 52% of the occupied hours, while this condition occurs only 38% of the occupied time in Jaipur and New Delhi. The difference is even more noticeable during the summer (June to August), when the cooling load is the highest, with an average value of 78% and 73% for Bangalore and Mumbai, and 34% and 30% for Jaipur and New Delhi (Figure 19).

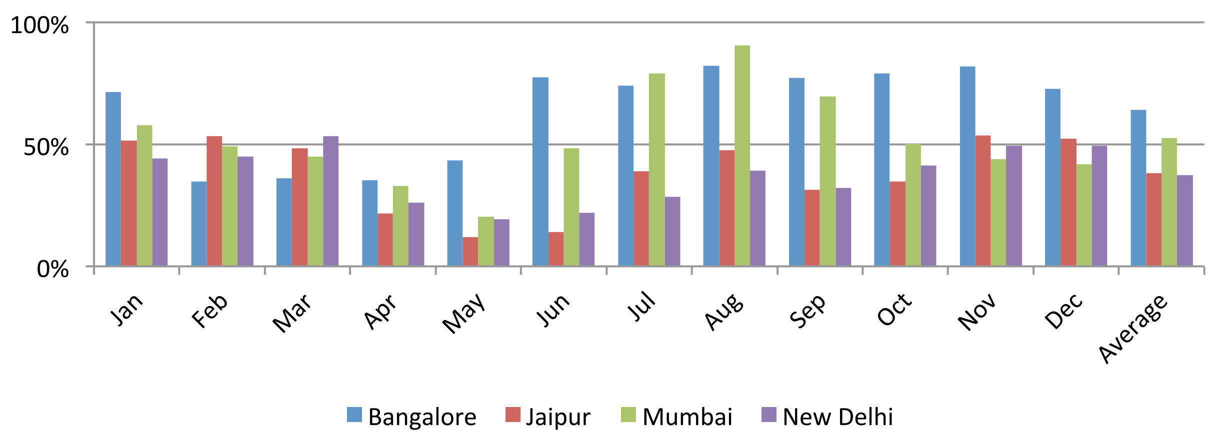
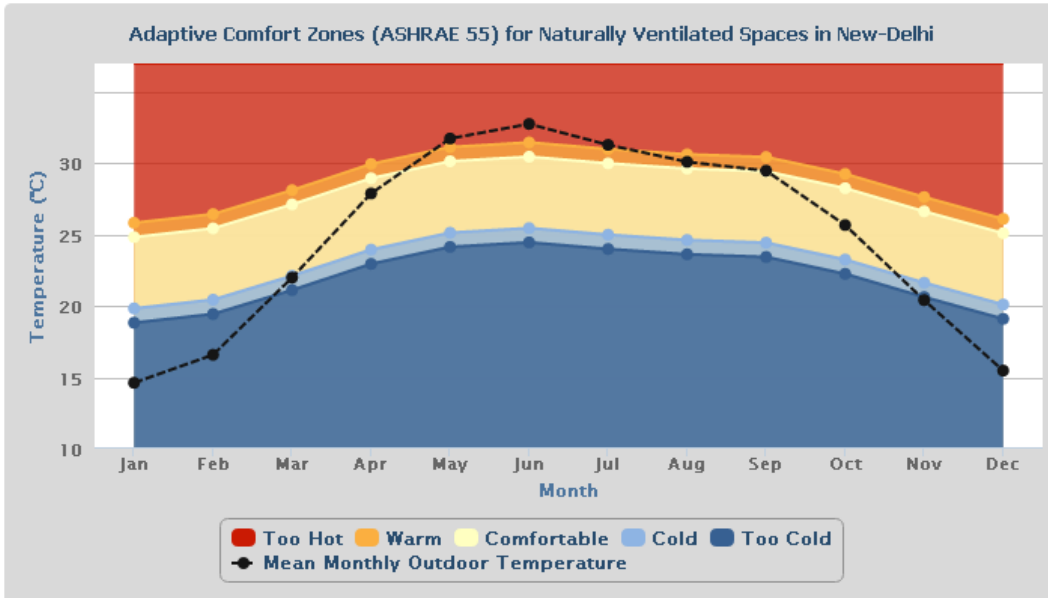


Figure 19: Ratio of occupied time when outdoor air temperature fits within the comfort range

The details of the numbers of hours per month where natural ventilation is possible, along with the ratio to the total number of hour per month, are presented in Appendix B.

ONLINE TOOL FOR NATURALLY VENTILATED SPACES

The Center for Advanced Research in Building Science and Energy (CARBSE) has developed an online tool that allows this study's results to be reproduced for several cities in India. The tool can create annual charts that determine if the outdoor air temperature is perceived as comfortable, as per Brager's adaptive comfort model, and how many hours per months are suitable for naturally ventilated buildings, similar to the study presented in this report (CARBSE s.d.). The data obtained with this tool corroborate the results found in the study (Figure 20).



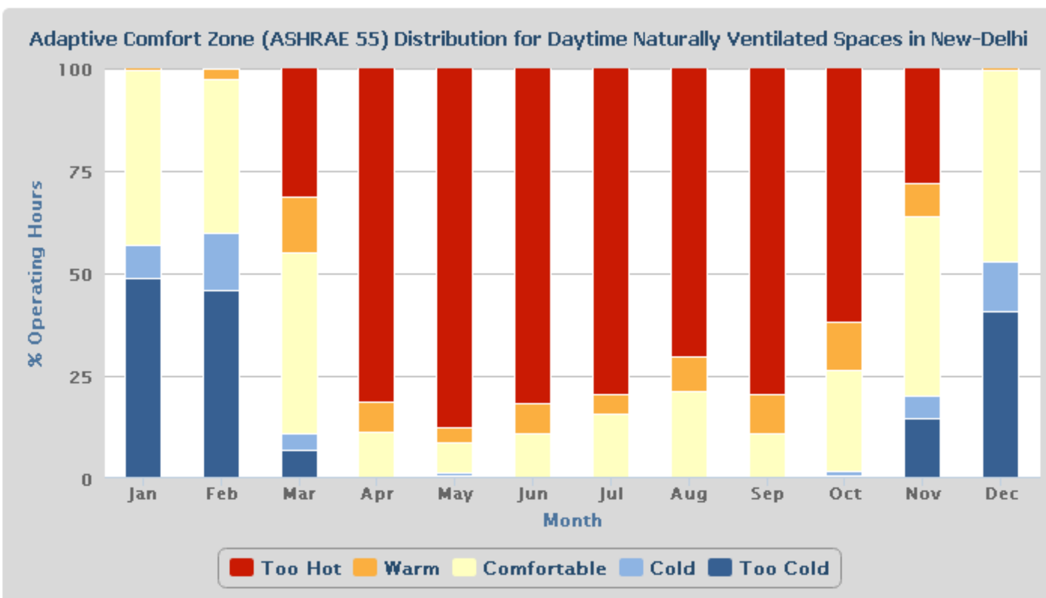


Figure 20: Comfort analysis tool (http://www.carbse.org)

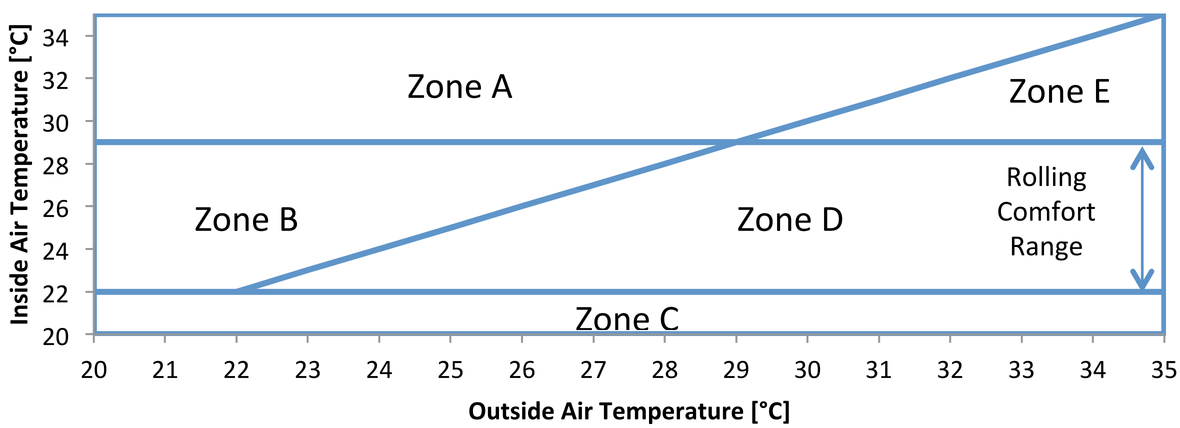
BEST PRACTICE 4 (BP4) MODELS

Mixed-mode strategy can only be used in spaces with windows, implying only the south- and north-oriented zones in this model. For the other zones the previously introduced Fanger comfort model and control sequence were used, including night flush. In spaces using the adaptive comfort model, the control sequence of the mechanical ventilation was updated to account for the new setpoints. Natural ventilation was turned on and off in the model to maintain the indoor operative temperature within the 80% acceptance zone. When the building was not occupied, the heating and cooling setpoints for both the mechanical ventilation and natural ventilation dropped to 15°C and 30°C, respectively.

Mixed-mode Control Sequence South- and North-oriented Spaces	**Heating setpoint**	During occupancy	0.31 * T_{OA} + 17.8
		Out of occupancy	15°C
	Cooling setpoint	During occupancy	0.31 * T_{OA} + 19.8
		Out of occupancy	30°C
	Trigger Rule	$T_{OA} < T_{IN} - 2$	
	Minimum Operative Temperature	Occupancy Heating Setpoint	
	Maximum Outdoor Air for NV	Occupancy Cooling Setpoint	
	Air Flow Rate	5 ACH	

Table 16: BP4 model updates

The control sequence in the mixed-mode zone is represented in Figure 21. At each time interval, depending on the outdoor and indoor air temperatures, the control sequence will detect in which zone it should execute mechanical ventilation and which ones to operate the windows.



	Windows	Comfortable	Mechanical Cooling	Mechanical Heating
Zone A	**Open**	No	No	No
Zone B	**Open**	**Yes**	No	No
Zone C	Closed	No	No	**Yes**
Zone D	Closed	**Yes**	**If Needed**	**If Needed**
Zone E	Closed	No	**Yes**	No

Figure 21: Illustration of the control sequence associated with mixed mode

RESULTS AND DISCUSSION

To clarify the impact of the mixed-mode operations compared to a simple night flush, the results were compared to the BP3 model (Table 17).

City Climate	Bangalore Temperate		Jaipur Hot and Dry		Mumbai Warm and Humid		New Delhi Composite	
Model Name	BP3	BP4	BP3	BP4	BP3	BP4	BP3	BP4
EPI [kWh/m²]	60	53	89	83	80	72	92	84
Savings	12%		7%		9%		8%	
Uncomfortable hours (Ratio of Total Occupied Time)								
West	0%	0%	1%	2%	0%	0%	1%	3%
North	0%	1%	1%	0%	0%	0%	1%	0%
East	0%	0%	1%	2%	0%	0%	1%	3%
South	0%	4%	1%	3%	0%	2%	1%	2%
Core	0%	0%	2%	1%	0%	0%	3%	2%

Table 17: EPI and comfort value for BP3 and BP4

The results validate the previous study. The solution proposed here has a lower influence on Jaipur and New Delhi performances. Once again, the results are only valid under the condition that the ASHRAE's adaptive comfort is applicable in India. If hotter temperatures are acceptable, the savings might greatly increase. In all climate zones, the savings are primarily realized from an increase in the temperature setpoint from the initial comfort model to the adaptive comfort model. Even without the introduction of fresh outdoor air, cooling demand is lowered. Therefore, the main interest of mixed-mode spaces lies in the effect on an occupant's perception of comfort more than on the actual introduction of free, cold air.

Figure 22 shows the two methods of savings obtained through the mixed-mode approach: (1) reducing the cooling demand by increasing the comfort for the hotter environment and (2) reducing the need of mechanical ventilation. The charts show the initial and actuated cooling demand for each climate as well as the mechanical cooling demand and the heat losses created by the natural ventilation mode.

LESSONS LEARNED

- **Naturally ventilated spaces are perceived as being more comfortable for occupants.**
- **Mixed-mode operation, similarly to night flush, increases heat losses when available, but is conducive to higher temperatures. It is therefore adapted to a hotter climate.**
- **This solution is efficient in a warm and humid climate (Mumbai) where the diurnal and annual temperature variation is low. Occupants are thermally adapted to the outdoor temperature.**
- **Savings add up to solutions that reduce heat gains or energy demand from plugs and lights but mix with savings that come from night flush.**
- **Thermal comfort in mixed mode or naturally ventilated spaces can be enhanced using ceiling and pedestal fans. A combination of operable windows and fans is a cost-effective strategy used in a significant portion of Indian buildings.**

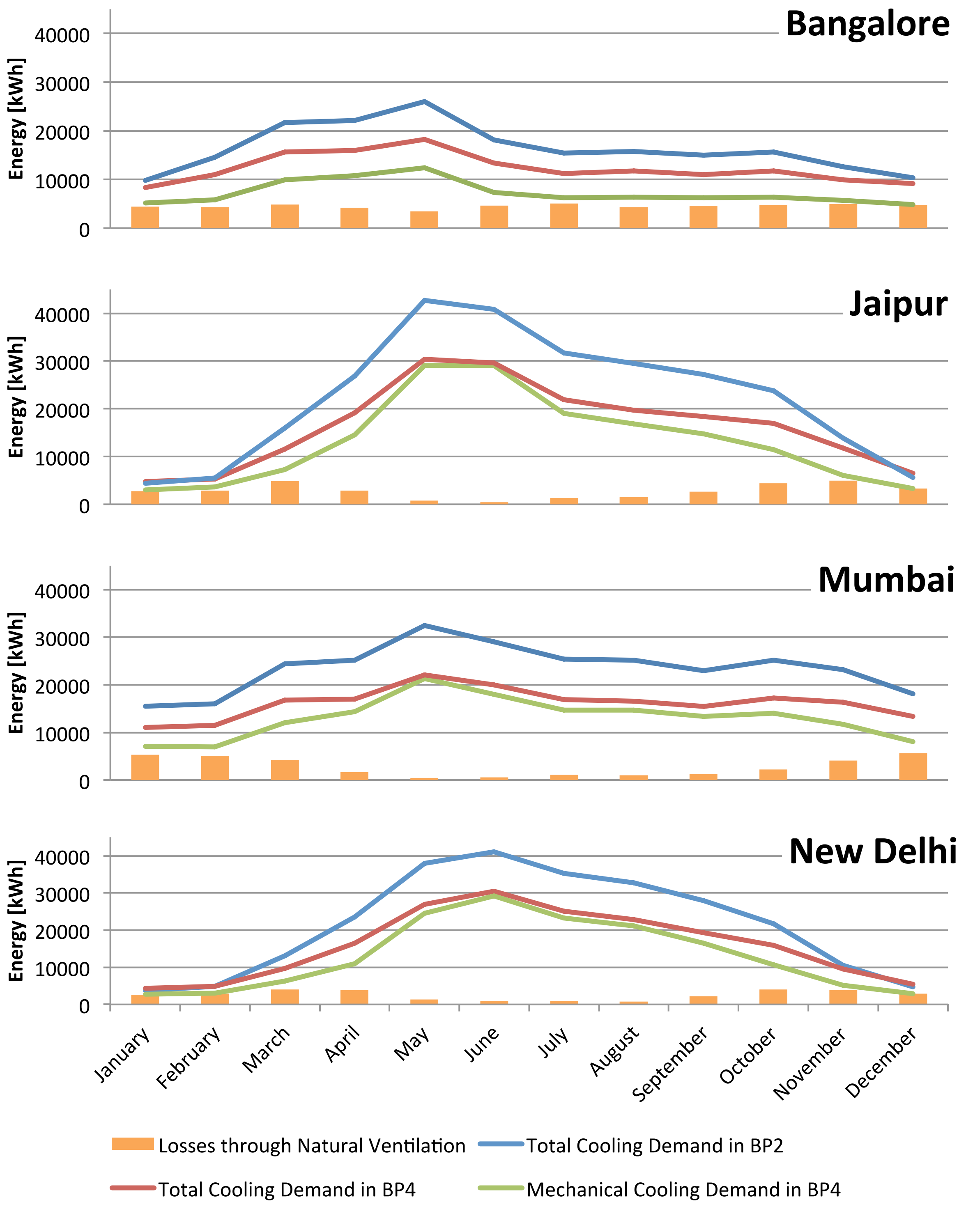


Figure 22: Initial, actuated, and mechanical cooling demand and heat losses through natural ventilation in BP4

BEST PRACTICE 5: RADIANT COOLING

In this section, we investigate the energy savings potentially brought by replacing air conditioning with a hydronic cooling system using radiant ceiling panels.

HYDRONIC COOLING

There are multiple advantages of using hydronic (water-based) cooling systems:

- Decoupling ventilation and cooling allows the ventilation system to be downsized. Ideally, the ventilation would only renew fresh air, while radiant panels would process the entire cooling load. But in this model building, a cooling coil is still necessary to bring down the temperature of the outdoor air being brought indoors.
- The high thermal capacity of water and better convection coefficient makes it possible to use smaller equipment for distribution and heat transfer than is possible with air systems. For the same amount of energy transported, a water pump consumes less energy than an airflow fan.
- Even after reducing the solar and equipment heat gain, more than 50% of the gains are radiant and cannot be directly removed with air-based cooling (Figure 23). A quick change in the radiant load can increase discomfort until it is removed through convection into the air. A radiant system has a direct influence on the radiant temperature and can create a more homogeneous and comfortable environment by cooling the walls and floor. Hence radiant cooling is a form of thermally activated building system (TABS).

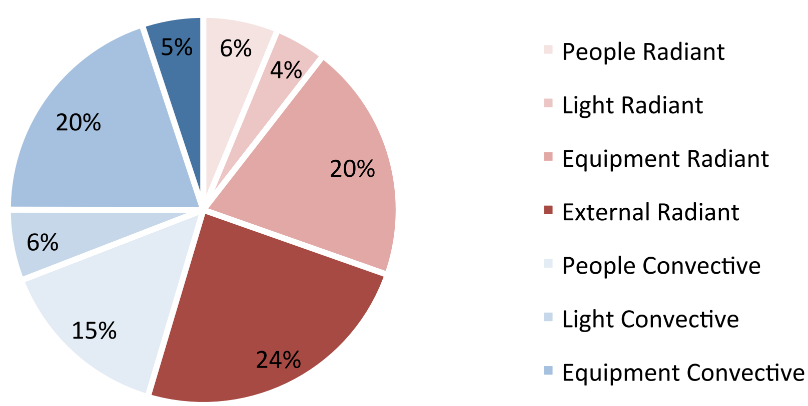


Figure 23: Fraction of convective and radiant loads in BP2 total heat gains

There may be some disadvantages as well. For instance, chilled water radiant cooling requires large installations that may not fit every building footprint. Ideally, the radiant panels are placed in the ceiling to benefit from air stratification, which can be difficult to accommodate in retrofit. There is also a higher first cost for a radiant system than there is for an air-based cooling system. Radiant slabs, when included in the original building design, are generally cheaper than radiant ceilings. In more humid climates, there is a need to avoid condensation on the panels and the associated pipework, either by controlling the dew-point temperature of the space or by limiting the chilled water temperature.

BEST PRACTICE 5 (BP5) MODELS

The BP2 model was used as a base to build the radiant systems model BP5. There is no night flush or mixed-mode control in the BP5 model. The control sequence for the air system remained the same as a BP2.

The new radiant system consisted of radiant panels in the suspended ceiling. Radiant ceiling panels provide more flexibility for architectural layouts than radiant slabs, though they are more expensive. The panels were modeled as hydronic tubes transporting chilled water embedded in a thin gypsum board with low thermal mass, with an insulation layer to reduce the heat transfer with the ceiling plenum. The chilled water was generated with a chiller connected to a cooling tower. This system may not be identical to existing systems in India, but it provided quick and simple modeling results regarding the energy savings that can be achieved with a hydronic radiant system. Table 18 provides the BP5 model parameters. The temperature in the chilled water loop was maintained at a constant 16°C. The equipment was sized to cover the cooling load with a temperature rise of 4 K. The water flow rate in the panels was controlled to maintain the operative temperature of the spaces under 25.5°C, which was deliberately lower than the air-conditioning setpoint, to ensure that the air system was turned on when the radiant system failed to meet the setpoint.

Ceiling panels	Lower layer	Gypsum 13mm, 0.16 W/m·K
	Upper layer	Insulation 130mm, 0.065 W/m·K
Water loop control sequence	Supply Water Temperature	16°C
	Rated Temperature Rise	4 K
Ceiling panels control sequence	Cooling Setpoint	25.5°c
Chiller	Nominal COP	5

Table 18: Radiant system based BP5 model parameters

RESULTS AND DISCUSSION

In Table 19, the BP2 model is used as a comparison to the BP5 model.

City Climate	**Bangalore Temperate**		**Jaipur Hot and Dry**		**Mumbai Warm and Humid**		**New Delhi Composite**	
Model Name	BP2	BP5	BP2	BP5	BP2	BP5	BP2	BP5
EPI [kWh/m²]	64	62	90	86	82	72	93	88
Savings	4%		4%		12%		5%	
Uncomfortable hours (Ratio of Total Occupied Time) (%)								
West	0	0	1	1	0	0	1	1
North	0	0	1	1	0	0	1	1
East	0	0	1	1	0	0	1	1
South	0	0	1	1	0	0	1	1
Core	0	0	2	3	0	0	3	4

Table 19: EPI and comfort value for BP2 and BP5

Table 19 shows that, overall, the BP5 model performed better than BP2. In terms of end use consumption (Figure 24), both cooling and ventilation energy were reduced. This is because the two were decoupled, bringing down the flow rate required to address the load and consequently reducing the amount of hot outdoor air going through the cooling coil. Despite cooling demand being essentially the same in both models, and the equipment having the same efficiency, in the case of air-conditioning, the introduction of additional outdoor air required to meet the demand, further increased the cooling load. The energy demand for pumps was increased in the models with radiant cooling, but the savings in cooling equipment consumption largely canceled the increase in consumption.

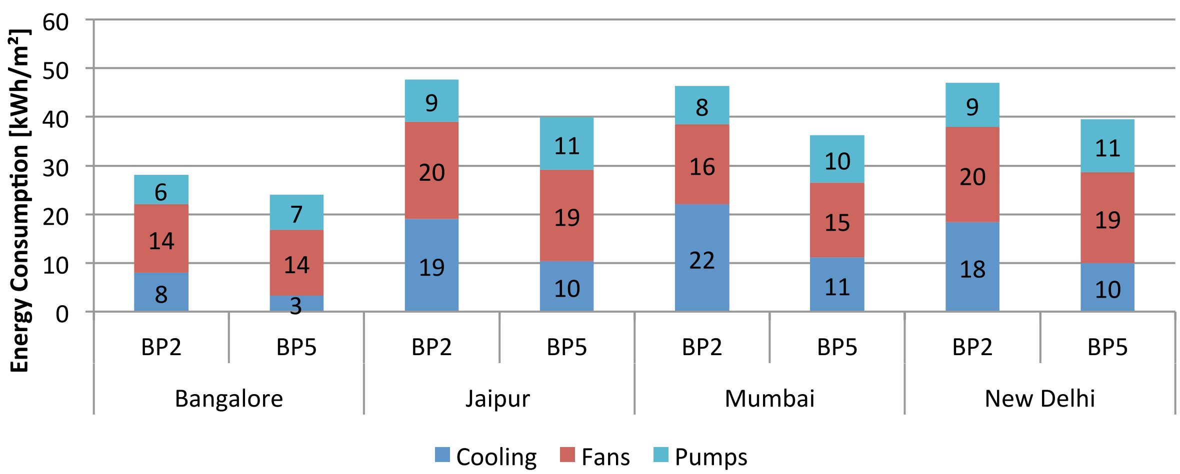


Figure 24: HVAC consumption of BP2 and BP5

Radiant cooling is an effective cooling solution, but it is a bigger investment than a conventional air-conditioning system. It also needs sophisticated controls, especially in a humid climate such as Mumbai, to avoid condensation. Since it lowers the energy consumption of the HVAC system, radiant cooling is especially efficient for buildings with high cooling loads.

LESSONS LEARNED

- **An important part of heat gain is transferred to the building through radiant transfer. It is optimal to reduce those gains with radiant-based cooling.**
- **Cooling through radiant ceilings reduced energy consumption in all climates in this study.**
- **The savings created by this solution are achieved because the ventilation is decoupled from the cooling. Water systems consume less energy to transport the same amount of energy than air systems.**
- **Construction first costs and operation costs (not accounting for energy cost savings) of radiant cooling are assumed to be higher than those for a conventional air-based HVAC system.**

BEST PRACTICE 6: BEST HVAC SUITE

For this model, night flush was added to the radiant system presented in BP5 to further reduce energy consumption with a simple addition to the control sequence of the ventilation system and operable windows. Additionally, cooling equipment performance was increased: from an initial COP of 5, chillers were upgraded to premium devices with a COP of 7.

BEST PRACTICE 6 (BP6) MODELS

This model provided the best energy-efficiency results in terms of all the solutions in this study considering the constraints of building size and work scope presented in the first section. The BP6 model is compared to the baseline ECBC model (Table 20) to highlight the total energy savings brought by the overlaying of all the strategies, BP1 through BP5. Figure 25 shows that the BP6 suite of solutions provides reduction in energy consumption for every end use. The whole-building savings reach 79% compared to BAU and 64% compared to ECBC.

City Climate	Bangalore Temperate		Jaipur Hot and Dry		Mumbai Warm and Humid		New Delhi Composite	
Model Name	ECBC	BP6	ECBC	BP6	ECBC	BP6	ECBC	BP6
EPI [kWh/m²]	125	60	146	82	144	69	146	85
Savings	52%		44%		52%		42%	
Uncomfortable hours (Ratio of Total Occupied Time) (%)								
West	0	0	1	1	1	0	1	1
North	0	0	1	1	1	0	1	1
East	0	0	1	1	1	0	1	1
South	0	0	1	1	1	0	1	1
Core	0	0	1	3	1	0	1	4

Table 20: EPI and comfort value for ECBC and BP6

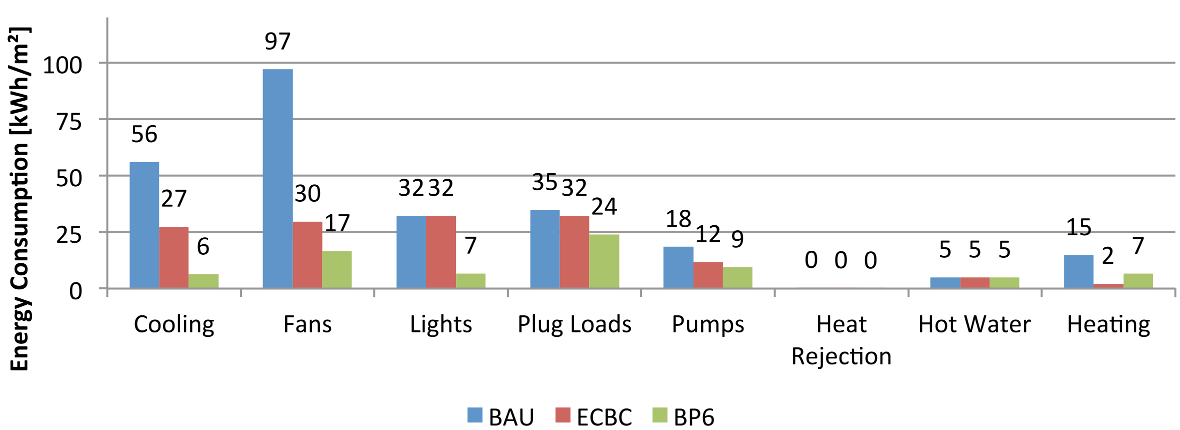


Figure 25: Comparative end-use energy consumption for BAU, ECBC, and BP6

BEST PRACTICE 7: VRF SYSTEM

For this solution, savings provided by variable refrigerant flow (VRF) was investigated. VRF is an HVAC technology that uses a refrigerant loop for space cooling. The loop comprised an outdoor unit that contained a condenser and cooling towers for heat removal as well as one or multiple evaporators in the different conditioned spaces to cool the indoor air.

VRF SYSTEMS

Like radiant ceiling panels, the benefit of VRF systems results from decoupling ventilation and cooling. The main difference is that the cooling process still requires fans to create air movement, as well as pumps to circulate the refrigerant from the outdoor unit to the indoor evaporators. Therefore, it does not achieve the full savings that can come from using water, which has a higher heat capacity than refrigerant as a cooling medium, which leads to lower pumps consumption to deliver the same amount of cooling power. Nonetheless, having an individual cooling unit for each zone enables the central equipment size to be reduced; especially fans that still account for 21% of the energy demand in BP3 (night flush), used as a reference. Moreover, the VRF system is assumed to have a lower construction and operating cost than a radiant system, with more decentralized control, and can be a good alternative in retrofit since a radiant system is more difficult to adapt to an existing design.

BEST PRACTICE 7 (BP7) MODELS

The BP7 model used BP3 (night flush) as a reference. The cooling coil was removed from the initial air loop, and individual evaporators installed in every thermal zone. A single condensing unit (i.e., compressor + condenser) provided cold liquid refrigerant for all evaporators. The new system was auto-sized to meet the cooling load when the ventilation provides air at a temperature of 16°C. The setpoints and control sequences remained the same. See Table 21 for further details.

Individual evaporators	Fan Pressure Drop	100 Pa
Condensing unit	Constant COP	4

Table 21: BP7 model parameters

RESULTS AND DISCUSSION

Table 22 compares the BP2 model to the BP7 model.

The VRF system showed energy savings in all climates. The energy savings in Bangalore were relatively smaller, since the night flush had already reduced the cooling energy demand to a low value. On the other hand, this solution is less comfortable than a radiant system in hot climates. This is because ventilation with outdoor air is still necessary to remove the indoor pollutants and, without a cooling coil in the air loop, the supply air can be hot, creating peak cooling demand.

City Climate	Bangalore Temperate		Jaipur Hot and Dry		Mumbai Warm and Humid		New Delhi Composite	
Model Name	BP2	BP7	BP2	BP7	BP2	BP7	BP2	BP7
EPI [kWh/m²]	64	61	90	78	82	69	93	80
Savings	5%		13%		18%		14%	
Uncomfortable hours (Ratio of Total Occupied Time) (%)								
West	0	0	1	2	0	1	1	2
North	0	0	1	2	0	1	1	3
East	0	0	1	2	0	1	1	2
South	0	0	1	1	0	1	1	2
Core	0	0	2	2	0	1	3	3

Table 22: EPI and comfort value for BP2 and BP7

The savings were partially due to a reduction in fan energy demand, but primarily from a reduction of the chiller energy demand. Previously, when only one zone required cooling, the chiller had to cool the entire building's supplied air. Therefore, the cooling energy supply would be higher than the sum of individual zones cooling demand. In BP7, the condensing unit provided the exact cooling duty needed by the individual evaporators, thus reducing its energy consumption. The end-use energy consumption for BP2 and BP7 is shown in Figure 26.

While the VRF models show bigger savings than the radiant models, those results might not hold for buildings with a higher thermal mass than the envelope modeled in this analysis and/or when the radiant loop is embedded in the slab. The conclusions of this report is that both solutions help with decoupling ventilation and cooling, which have a significant effect on the cooling consumption and a thorough analysis during the design of a building will help determine which solutions to adapt in specific constraints.

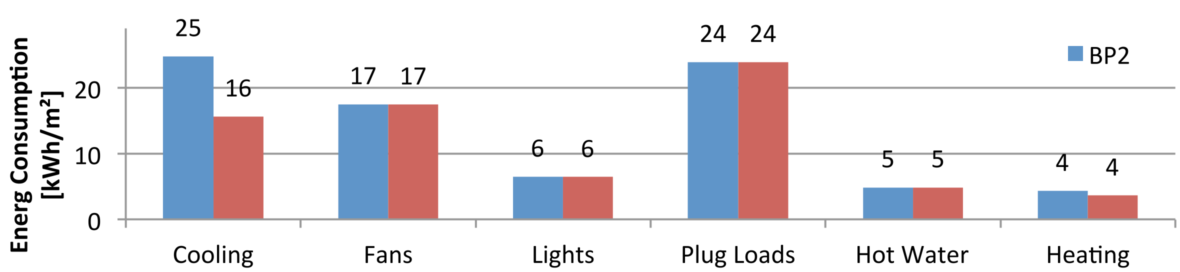


Figure 26: End-use energy consumption for BP2 and BP7

LESSONS LEARNED

- **A VRF system may provide a good energy-savings alternative, especially for smaller sized facilities in temperate climate. If high-performance evaporators and condensers are used and sufficiently sized, the performance may even be comparable to a radiant cooling system.**

CONCLUSIONS

This work provides insight on the relevance of particular energy-efficiency strategies in specific climate zones. In the real world, the energy consumption of a building is greatly dependent on its use and the external environment in which it operates. Therefore, it is difficult to compare the performances of two different buildings and determine the effect that efficiency improvements in one building would have on a different building under different conditions. Building simulation allows for the development of models for a certain building typology (e.g., class A offices) to understand the effect of each energy-efficiency strategy, for an “apples-to-apples” comparison.

Therefore, even though every building is different and would ideally have a customized simulation study conducted for its strategies, this work provides higher-level, climate-based guidance about which strategies may have a greater chance of success and which ones could be less effective in each climate. This is especially seen in the envelope and HVAC strategies. Appendix C, Global Results, shows charts of the comparative energy consumption and annual heat gains/losses in the four climate zones across the models BAU, ECBC, and Best Practices models BP1 through BP7.

- In all climates, most of the energy savings can be achieved by reducing solar heat gains and internal heat gains. The former can be done by reducing the amount of glazed surfaces and installing performant windows that have lower heat transmission. The latter can be done through the installation of energy-efficient equipment and lighting and use of plugs and light-control strategies.
- In a temperate climate like Bangalore (or Pune) it may not be worth the investment to add radiant panels or VRF systems since a higher level of energy benefits can be derived through more cost-effective mixed-mode operations, if the pollution can be controlled.
- The models for hot dry climates, such as Jaipur or Ahmedabad, show that a VRF system can achieve 13% savings over a well-designed VAV system when both systems have a good envelope and reduced lighting power density and plug loads (BP2).
- In hot and humid areas such as Mumbai, Chennai, or Kolkata, the best-modeled performance is achieved with a well-designed and performant radiant system. Nevertheless, mixed-mode buildings and VRF systems also obtain good savings and might be more cost effective.
- In a composite climate such as New Delhi, Chandigarh, or Hyderabad, a VRF system model provides the best results, saving 14% over a well-designed VAV system, when both systems have a good envelope and reduced lighting power density and plug loads (BP2).

This study also indicates the practical limits of energy-savings potential for energy-efficiency strategies. Through a series of cost-efficient improvements, it was possible to reduce the EPI by 72% compared to a standard building design, and by about 50% compared to the 2007 energy code standard. For example, as shown in Appendix C for Jaipur, the BP7 model saves 72% over the BAU baseline and 47% over the ECBC baseline. This shows that buildings in India can strive towards more aggressive targets than those provided in the ECBC.

Table 23 summarizes the different improvements proposed and the results in performance they brought on average in all four climates (in comparison with the previous model they were built on). It is important to note that the savings are dependent on the order they are introduced, since they were implemented incrementally, with BP3, BP5, and BP7 based on BP2. Taken alone, the ratio observed might be higher than the one presented in Table 23.

	Windows Orientation	Shadings	Reducing Peak Load	Daylighting	Night-Flush	Mixed-Mode	Radiant Cooling	Radiant COP 7	VRF
Model	**BP1**		**BP2**		**BP3**	**BP4**	**BP5**	**BP6**	**BP7**
Reference	**ECBC**		**BP1**		**BP2**	**BP2**	**BP2**	**BP2**	**BP2**
Bangalore	9%	+0%	30%	+19%	4%	16%	4%	5%	5%
Jaipur	6%	+1%	24%	+14%	1%	7%	4%	8%	13%
Mumbai	6%	+1%	26%	+17%	2%	12%	12%	16%	15%
New Delhi	6%	+1%	22%	+13%	1%	9%	5%	8%	14%

Table 23: Average savings summary

The simulation also validates the results of the first *Best Practices Guide for High-Performance Indian Office Buildings* report (Singh, Sartor and Ghatikar 2013) and provides insight on the effect of each solution. For instance, in the first model (BP1), a significant proportion of the energy savings can be achieved by reducing the solar gains, which are a dominant component of the cooling loads. Considering the natural and urban environment of the building, shading is a good way to solve this challenge. With reduced solar gains, internal gains become a proportionally more significant contributor to the total heat gain. Potentially, this can be addressed by shifting certain plug loads or equipment (e.g., chiller coupled with thermal storage) to the night, when cooling is not required.

The conclusions of this work are optimistic. The simulation data provide support to benchmarked energy performance data collected from various office buildings in India that use a variety of energy-efficiency strategies, generating a more robust set of target metrics for office buildings. These metrics are provided in Best Practices Guide version 2.

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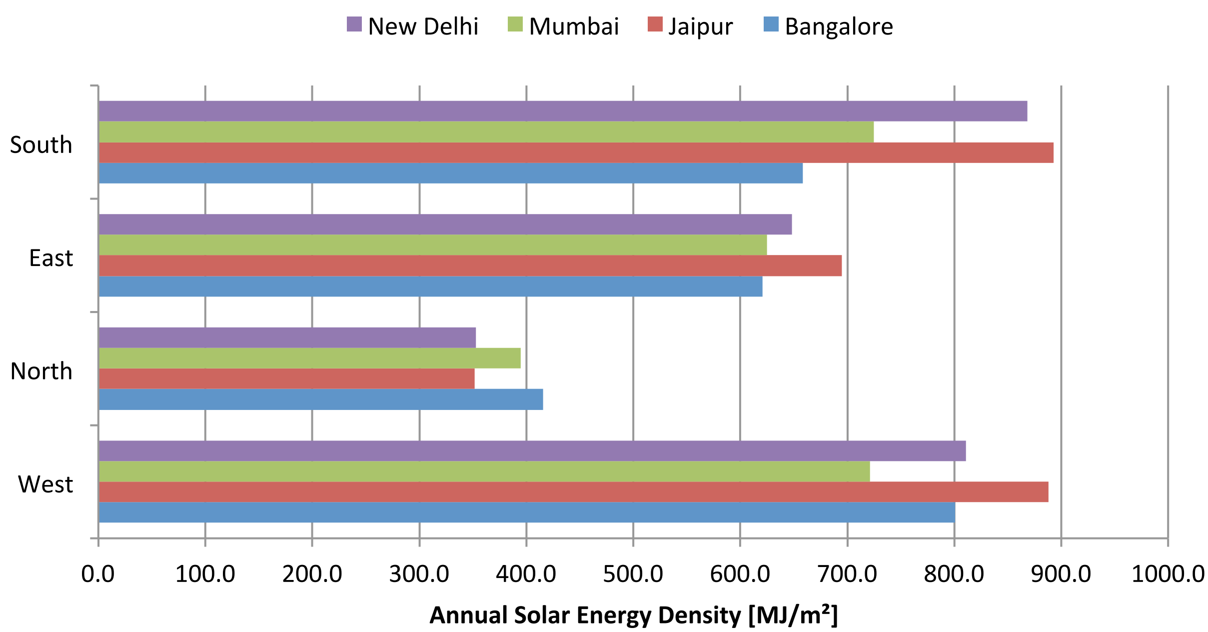
APPENDIXES

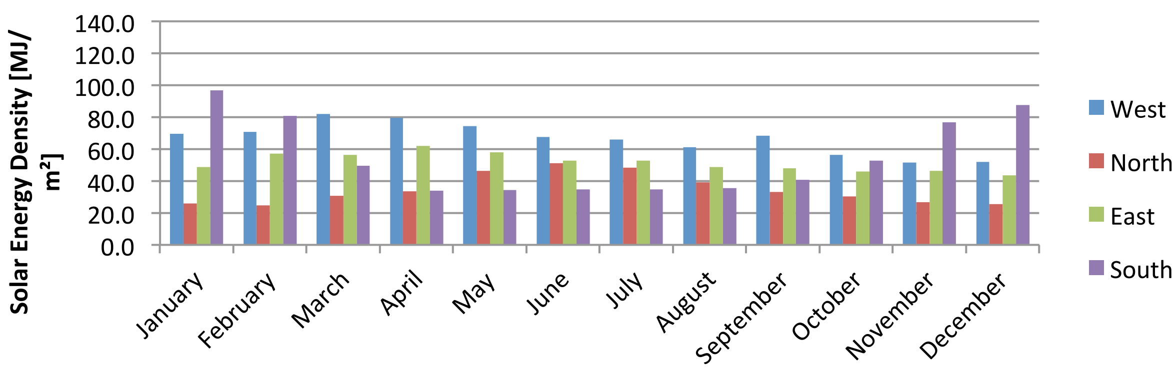
APPENDIX A: SOLAR LOADS

ANNUAL SOLAR ENERGY DENSITY PER ORIENTATION

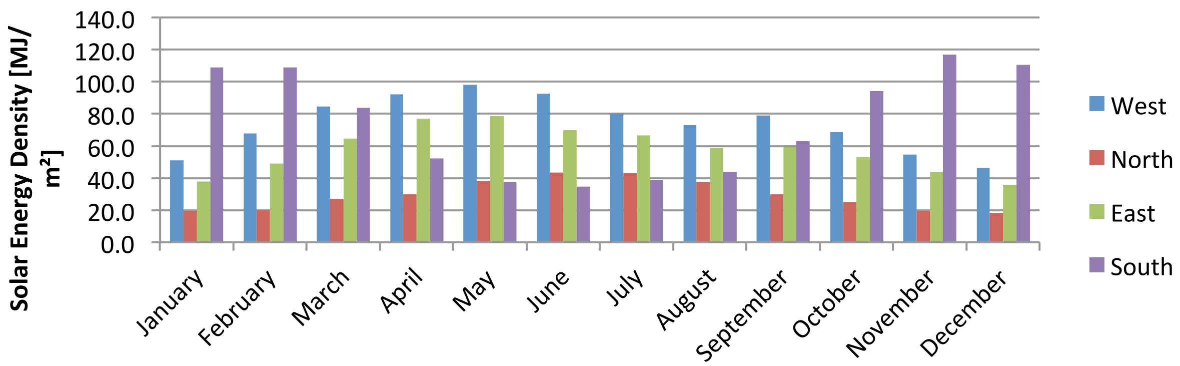


SOLAR ENERGY DENSITY PER MONTH

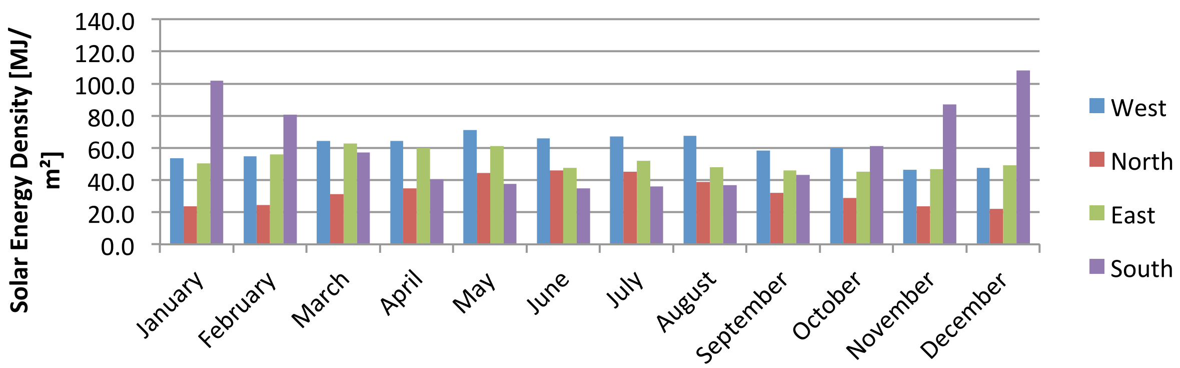
BANGALORE



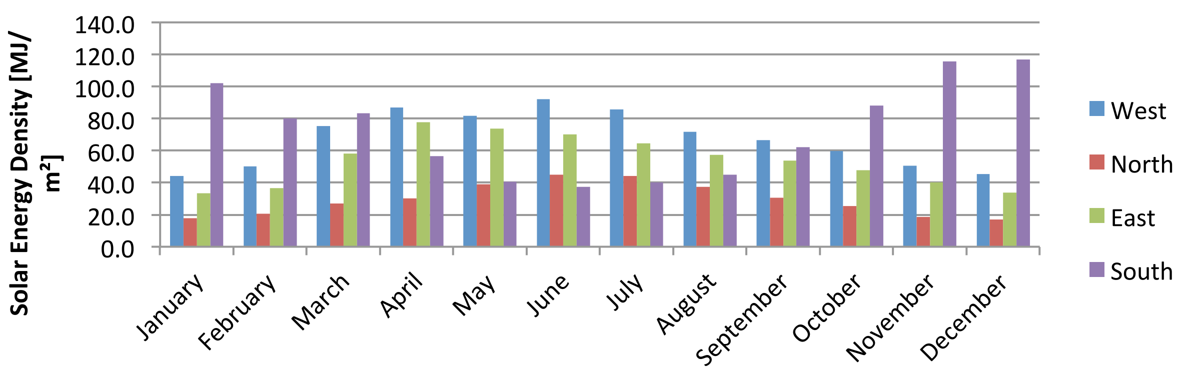
JAIPUR



MUMBAI



NEW DELHI



APPENDIX B: MIXED-MODE COMFORT

MIXED-MODE HOURS AND RATIO PER MONTH

	Bangalore	Jaipur	Mumbai	New Delhi
January	333	197	368	164
	45%	**26%**	**49%**	**22%**
February	222	203	312	164
	33%	**30%**	**46%**	**24%**
March	381	312	462	304
	51%	**42%**	**62%**	**41%**
April	411	302	459	314
	57%	**42%**	**64%**	**44%**
May	434	226	446	301
	58%	**30%**	**60%**	**40%**
June	425	228	528	257
	59%	**32%**	**73%**	**36%**
July	465	463	666	371
	63%	**62%**	**90%**	**50%**
August	446	520	709	476
	60%	**70%**	**95%**	**64%**
September	439	435	610	446
	61%	**60%**	**85%**	**62%**
October	443	351	550	353
	60%	**47%**	**74%**	**47%**
November	365	261	394	193
	51%	**36%**	**55%**	**27%**
December	303	195	328	185
	41%	**26%**	**44%**	**25%**
Total	4,667	3,693	5,832	3,528
	53%	**42%**	**67%**	**40%**

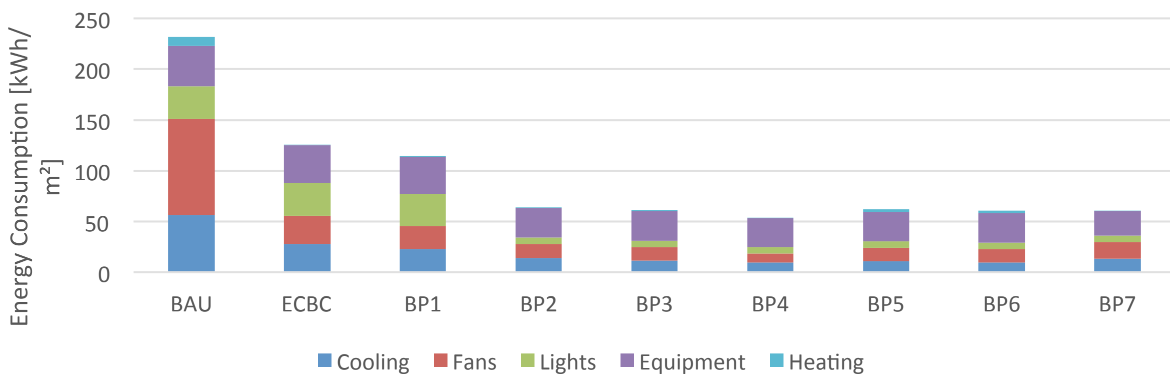
MIXED-MODE HOURS DURING OCCUPANCY AND RATIO PER MONTH

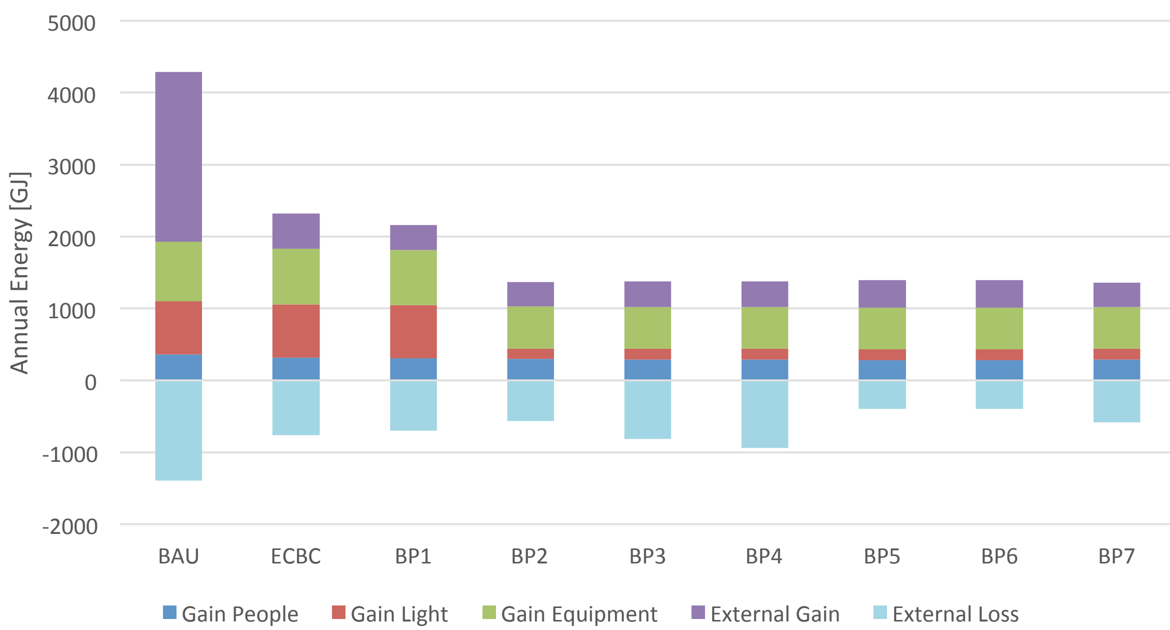
	Bangalore	Jaipur	Mumbai	New Delhi
January	266	192	215	164
	72%	**52%**	**58%**	**44%**
February	117	179	165	151
	35%	**53%**	**49%**	**45%**
March	134	180	167	199
	36%	**48%**	**45%**	**53%**
April	127	78	119	94
	35%	**22%**	**33%**	**26%**
May	162	45	76	72
	44%	**12%**	**20%**	**19%**
June	279	51	174	79
	78%	**14%**	**48%**	**22%**
July	276	145	294	106
	74%	**39%**	**79%**	**28%**
August	306	177	337	146
	82%	**48%**	**91%**	**39%**
September	278	113	251	116
	77%	**31%**	**70%**	**32%**
October	294	129	187	154
	794	**35%**	**50%**	**41%**
November	295	193	158	178
	82%	**54%**	**44%**	**49%**
December	271	195	156	184
	73%	**52%**	**42%**	**49%**
Total	2,805	1,677	2,299	1,643
	64%	**38%**	**52%**	**38%**

APPENDIX C: GLOBAL RESULTS

BANGALORE: END-USE ENERGY CONSUMPTION – HEAT GAINS AND LOSSES

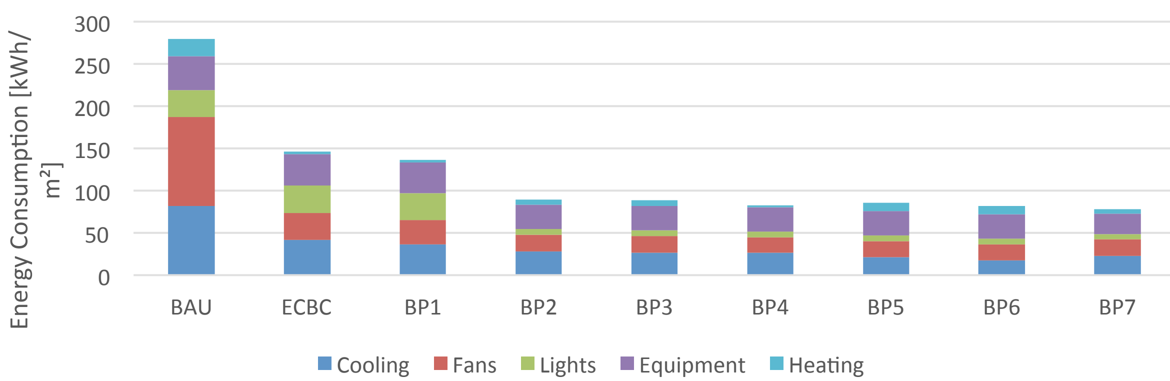
	BAU	ECBC	BP1	BP2	BP3	BP4	BP5	BP6	BP7
Cooling	40	18	14	8	6	4	3	2	9
Fans	95	28	23	14	13	9	14	14	16
Lights	32	32	32	6	6	6	6	6	6
Plug Loads	35	32	32	24	24	24	24	24	24
Pumps	16	10	8	6	6	5	7	7	0
Heat Rejection	0	0	0	0	0	0	0	0	5
Hot Water	5	5	5	5	5	5	5	5	0
Heating	9	0	0	1	1	0	2	2	1
Total	232	125	114	64	61	53	62	60	61

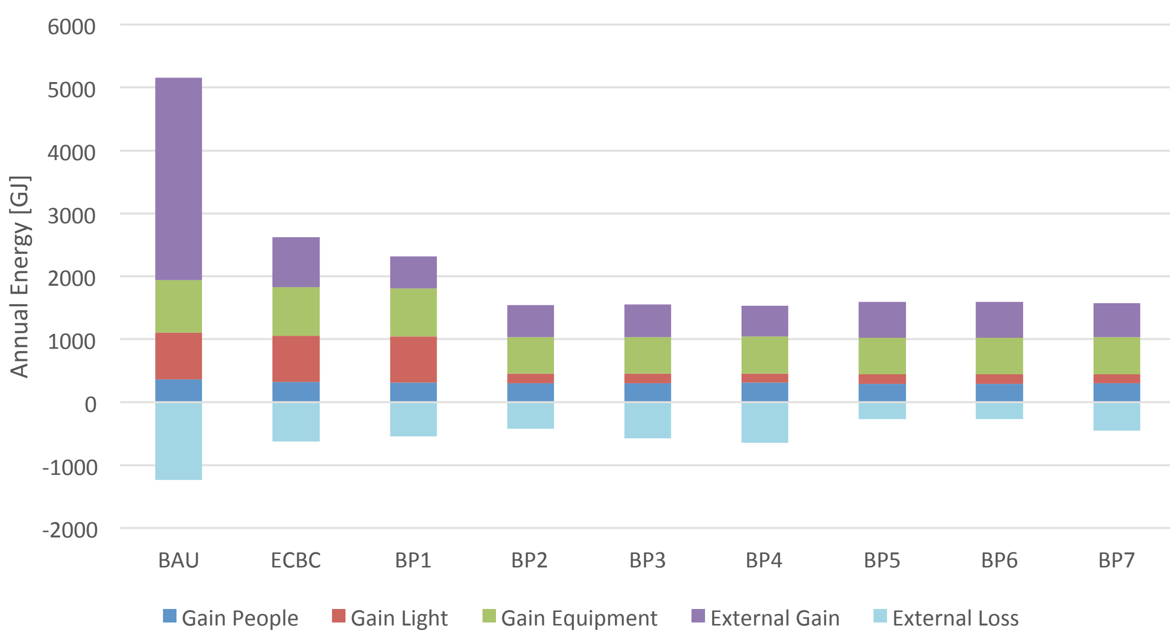




JAIPUR: END-USE ENERGY CONSUMPTION – HEAT GAINS AND LOSSES

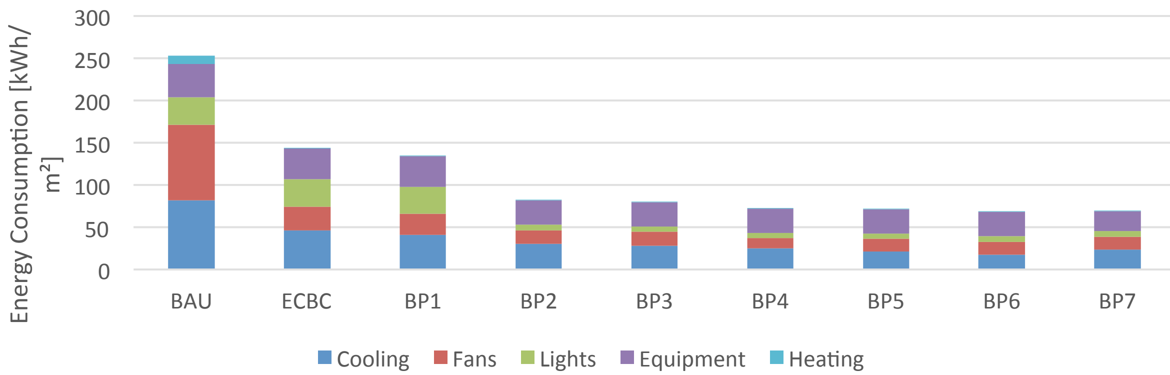
	BAU	ECBC	BP1	BP2	BP3	BP4	BP5	BP6	BP7
Cooling	63	30	26	19	18	18	10	7	18
Fans	105	32	28	20	20	18	19	19	19
Lights	32	32	32	7	7	7	7	7	6
Plug Loads	35	32	32	24	24	24	24	24	24
Pumps	19	12	11	9	9	9	11	10	0
Heat Rejection	0	0	0	0	0	0	0	0	5
Hot Water	5	5	5	5	5	5	5	5	0
Heating	21	3	3	6	7	2	10	10	5
Total	280	146	136	90	89	83	86	82	78

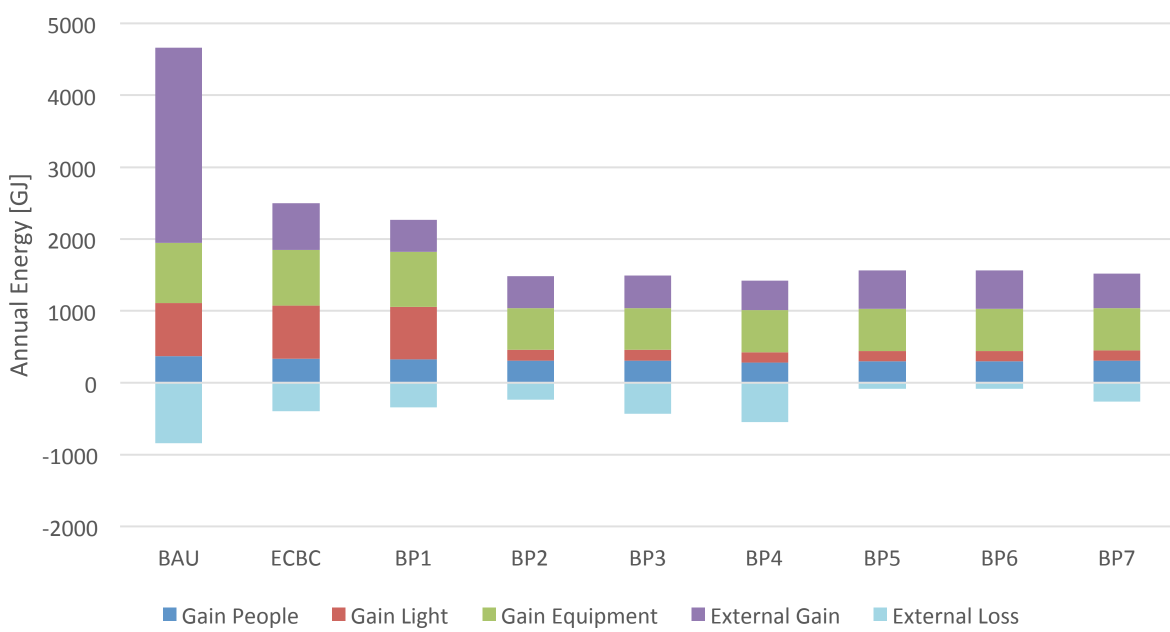




MUMBAI: END-USE ENERGY CONSUMPTION – HEAT GAINS AND LOSSES

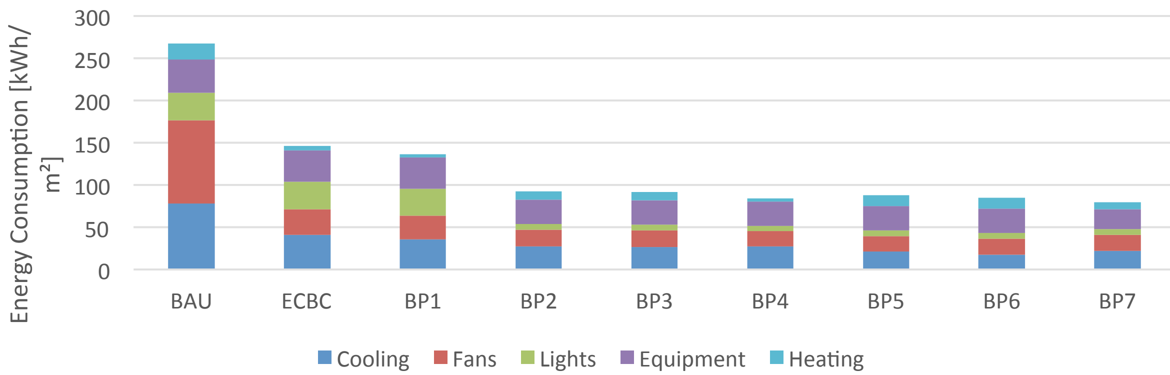
	BAU	ECBC	BP1	BP2	BP3	BP4	BP5	BP6	BP7
Cooling	63	34	30	22	20	18	11	8	19
Fans	89	28	25	16	16	12	15	15	15
Lights	32	32	32	6	6	6	7	7	6
Plug Loads	35	32	32	24	24	24	24	24	24
Pumps	19	12	10	8	8	7	10	9	0
Heat Rejection	0	0	0	0	0	0	0	0	5
Hot Water	5	5	5	5	5	5	5	5	0
Heating	9	0	0	0	0	0	1	1	0
Total	253	144	134	82	80	72	72	69	69

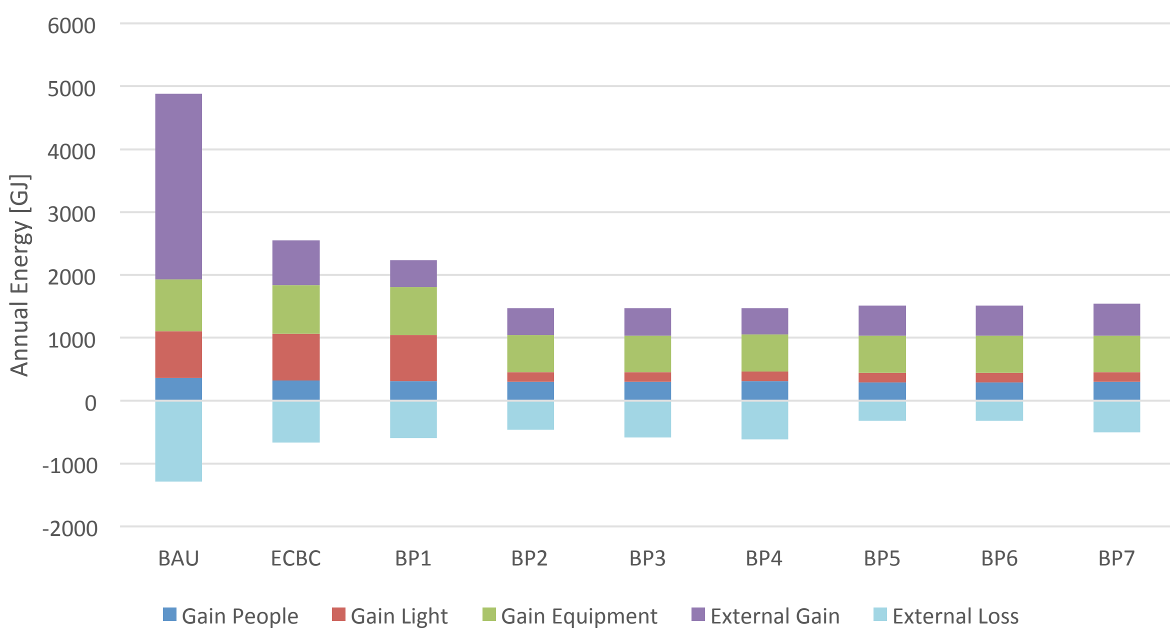




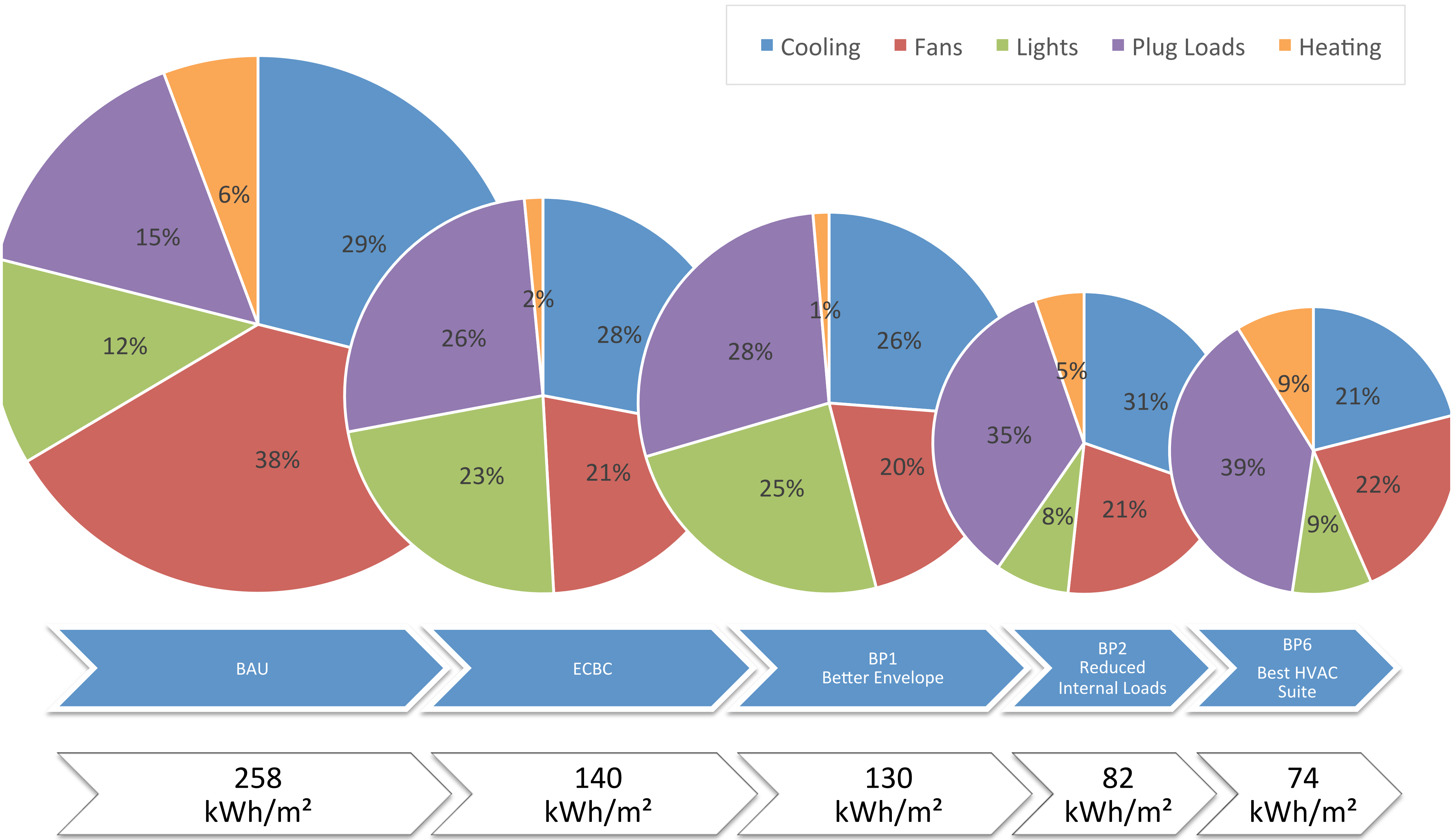
NEW DELHI: END-USE ENERGY CONSUMPTION – HEAT GAINS AND LOSSES

	BAU	ECBC	BP1	BP2	BP3	BP4	BP5	BP6	BP7
Cooling	58	28	25	18	17	18	10	7	17
Fans	99	31	28	20	20	18	19	19	19
Lights	32	32	32	7	7	7	7	7	7
Plug Loads	35	32	32	24	24	24	24	24	24
Pumps	19	12	11	9	9	9	11	11	0
Heat Rejection	0	0	0	0	0	0	0	0	5
Hot Water	5	5	5	5	5	5	5	5	0
Heating	19	5	4	10	10	4	13	13	8
Total	268	146	137	93	92	84	88	85	80

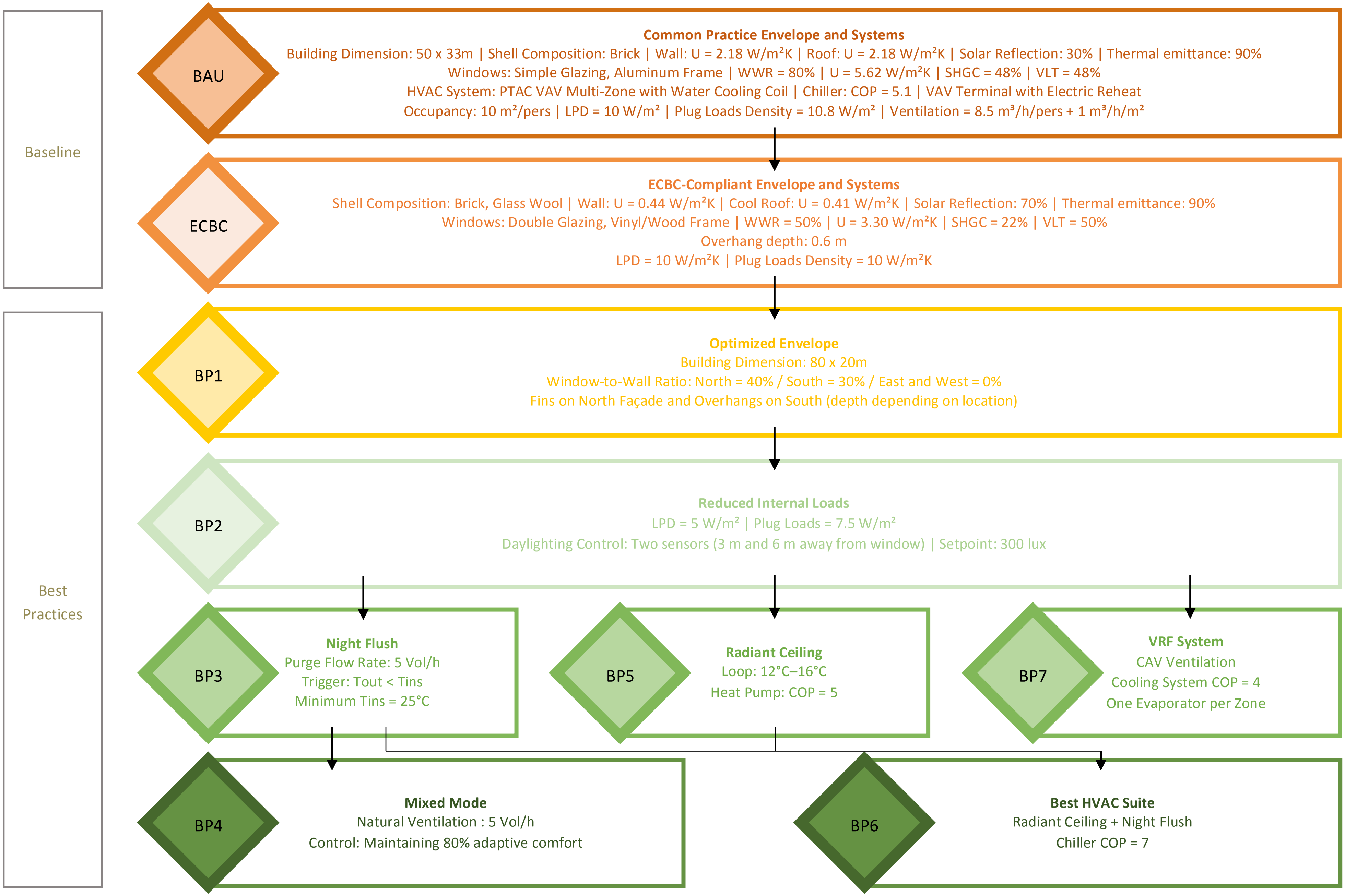




GLOBAL RESULTS: AVERAGE ON ALL CLIMATES



APPENDIX D: WORK FLOWCHART



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