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R&D and Implementation Outcomes From The U.S.-India Bilateral Center For Building Energy Research And Development Program

Reshma Singh[1]
Mary Ann Piette[1]
Ashok Gadgil[1]
Rajan Rawal[2]
Narendra Bansal[2]
Vishal Garg[3]
Jyotirmay Mathur[4]
Phil Haves[1]
Paul Mathew[1]
Christian Kohler[1]
Mahabir Bhandari[5]
Gail Brager[6]
Vivian Loftness[7]
Narendran Nadarajah[8]
Ronnen Levinson[1]
Rich Brown[1]
Andre Desjarlais[5]
Milind Rane[9]
Sanyogita Manu
Yash Shukla[2]
Mona Doctor-Pingel[10]

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[1]Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, California, USA

[2] CEPT University, Kasturbhai Lalbhai Campus,
University Rd, Navrangpura, Ahmedabad, Gujarat 380009, India

[3] International Institute of Information Technology, Hyderabad
Near DLF Building, Gachibowli, Hyderabad, Telangana 500032, India

[4] Malaviya National Institute of Technology, Jaipur
Jawahar Lal Nehru Marg, Jhalana Gram, Malviya Nagar, Jaipur, Rajasthan 302017, India

[5] Oakridge National Laboratory
1 Bethel Valley Rd, Oak Ridge, TN 37830, USA

[6] Center for the Built Environments
Wurster Hall, University of California Berkeley CA 94720, USA

[7] Center for Building Performance and Diagnostics
5000 Forbes Avenue, College of Fine Arts 201, Carnegie Mellon University
Pittsburgh, PA 15213

[8] Lighting Research Center at Rensselaer Polytechnic Institute
21 Union St, Troy, NY 12180, USA

[9] Department of Mechanical Engineering
The Indian Institute of Technology Bombay, Powai, Mumbai,
Maharashtra 400076, India

[10] Centre for Scientific Research,
Auroshilpam, Auroville, Bommayapalayam, Tamil Nadu 605101, India

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ABSTRACT

This paper explores the role of international partnerships to facilitate low-energy building design, construction, and operations. We present the strategic approach, joint research and development outcomes, and implementation activities of a unique U.S.-India program on buildings energy efficiency, the Center for Building Energy Research and Development. We discuss the collaboration successes in both countries despite their dissimilar building contexts, implementation challenges and opportunities. We highlight a range of R&D outcomes, such as novel tools and technologies developed and tested by the joint teams, with their technical energy savings potential, as well as results of capacity building and technology demonstrations. A deep-dive into key new scientific methods around building energy monitoring and benchmarking that could have a significant impact on high-performance of buildings in both countries is also provided. Finally, in addition to joint R&D successes, pathways to deployment, and lessons learned are discussed as key takeaways.

KEYWORDS

International collaboration,
Building energy efficiency,
Lifecycle performance model,
Integrated building physical and information systems,
Building energy technologies and tools,
Buildings research infrastructure and scientific methods

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1. INTRODUCTION

International collaborations are often required to solve critical global problems, as Glasbergen and Groenenberg [1] explain. International collaboration models specifically in buildings energy-efficiency can range from multi-lateral programs, which can broadly support global level codes and policies, bilateral programs that function at the national or regional scale, and institutional partnerships that function at the building or campus scale. Bilateral collaborations may be most effective in countries where built infrastructure is being newly developed and the energy demand is rapidly increasing. Such collaborations can provide opportunities to design, construct and operate high-performance buildings at the outset, rather than requiring more expensive retrofit solutions of an extant building stock [2].

There can be several benefits from such collaboration models – Parrish et al [3] affirm that international programs can build capacity, challenge the status quo, and create new resources in support of significant energy savings. Firstly, an international team can offer unbiased, scientific, innovative, and effective energy-efficiency research and development (R&D). Secondly, collaboration models that draw upon global expertise support knowledge transfer through lessons learned and insights, which in turn facilitate "leaps and breaks". The latter may be more effective as transformational advances, compared to incremental improvements through only in-country approaches. Thirdly, complementarity in learning through bi-lateral or multi-lateral R&D can create a powerful and synergistic approach to support the mutual evolution of building energy efficiency in the collaborating countries [3]. On the other hand, there may be certain challenges, such as cultural and policy differences, that make it difficult to understand the partner country's ways of working and implementation.

In this paper we present a case study of a unique United States and India building energy-efficiency program, the virtual Center for Building Energy Research and Development (CBERD). Awarded under the auspices of the U.S.-India Partnership to Advance Clean Energy (PACE), this program drew upon the complementarity of the R&D partners' experience and knowledge, to implement strategies for building lifecycle performance assurance while emphasizing solutions that leapfrog transitional technologies [4]. This paper provides a description, an overview of outcomes and lessons learnt, as well as future R&D directions from the five-year CBERD research program, The outcomes and implementation of the program are applicable to India with two-thirds of its building stock still to be built, as described in Section 1.1, as well to the U.S. with a primarily buildings retrofit paradigm.

1.1 Macro-Drivers

India's urbanization is a key driver of energy trends: an additional 315 million people, almost the entire population of the United States, are expected to be added to India's cities by 2040 [5]. Electricity demand is expected to triple from 1102 TWh in 2017 to 3606 TWh by 2040, making India the fastest-growing electricity market [5], boosted by rising incomes and new connections to the grid [6]. The peak electricity demand has been estimated as growing from 153 GW to 370 GW during the year 2031- 32 and to 448 GW during the year 2036-37 [7]. India's nationally determined contribution (NDC) goal is for reducing emissions intensity by 28%–33% in 2030 over 2005 levels [8]. As buildings represent a third of the nation's energy consumption, buildings energy efficiency must be regarded as a critical strategy for achieving that goal.

1.2 End Use Drivers

As India is poised to become the fifth-largest economy in the world, new buildings are being added at a significant rate, and building energy use is increasing exponentially. While U.S. buildings use ~40%, or 38

quads of the nation's 97 quads of energy consumption [9], Indian buildings already use 30% of the nation's 24 quads [5] of energy consumption. Projections indicate that the Indian commercial sector footprint alone could triple to ~1.9 Billion m^2 by 2030 over a baseline of 2010 [10]. Commercial buildings are responsible for 8% of national electricity use and this is growing at 8% annually.

With an active participation in the global economy, land pressure, and speed of construction of an aspirational, speculative market the Indian commercial building stock is becoming more international in form and function (Figure 1). Building energy use is increasing at an unprecedented rate due to multiple factors, including the rapid addition of a large, new construction footprint with high service levels, increasing urban temperatures, a trend towards highly glazed facades, enhanced computing and service levels, high occupant density, multiple shift operations, and most significantly, an explosive growth in mechanical space cooling.

1.3 Challenges and Barriers

The growth in energy intensive buildings is unsustainable given India's energy supply limitations, reliance on fossil fuel, and the massive environmental implications. Indian citizens face energy and environmental challenges, exacerbated by a rise in urban heat-related deaths, and air pollution-related diseases. Indeed, the cost of new office buildings in India is rising, not only from the perspective of the economics of construction and operations, but also due to environmental costs and associated productivity loss owing to unhealthy, polluted environments [11]. This cannot be solved though piecemeal, one-off strategies. For instance meeting the rapidly increasing cooling demand would require a consolidated set of strategies, with a integrated whole building approach ranging from envelope and passive design improvements during the design stage by architects, and enhanced cooling equipment design and delivery by mechanical engineers and air conditioning equipment manufacturers, to the integration of sensors, controls, and data-driven decision making for energy-efficient operations.

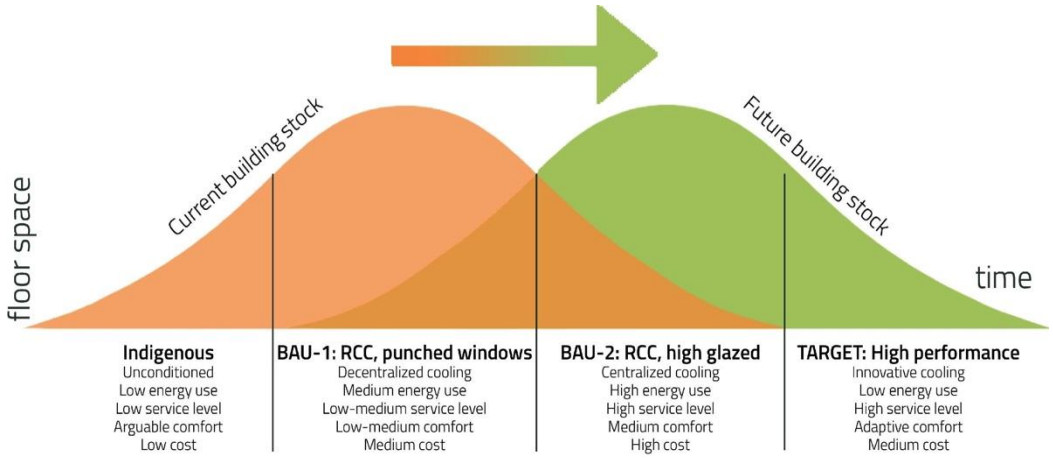

Figure 1: Characterization of commercial buildings in India

In characterizing the nature of the Indian building sector, the bulk of the existing commercial stock consists of buildings built with reinforced cement concrete construction and brick infill with operable, punched windows and external shade overhangs. (Business As Usual, BAU-1). These are typically not centrally air-conditioned, but fitted with *ad hoc*, decentralized air conditioning with occupant overrides to provide ostensibly higher levels of services. This lower grade space is usually built in smaller units (such as 1000 m^2 built up on 5000 m^2 plots). The construction cost of this building type is typically around INR 2000-3500/sqft (~USD $30-50/sqft). Recently, the trend is towards centrally air-conditioned buildings with a higher level of service, and a high amount of fully, single-glazed facades, and high plug and lighting loads (Figure 2). These "BAU-2" (Business As Usual-2) 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/ sqft (~USD 58-100/sqft) [11].

Figure 2: Typical facades of commercial buildings in India, showing the changing trends from thermally massive construction with punched windows to fully- glazed facades.

On the other side of the ocean, the U.S. Department of Energy reported that in 2014, 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. There is about 87 billion square feet of commercial space in the U.S., spread across more than 5 million commercial and institutional buildings [12]. Commercial electricity consumption accounts for about 36% of total U.S. electricity demand. From 2013 to 2040, commercial end-use intensity, measured in kWh per square foot, is projected to *decrease* by 8.8%. This decrease will be led by a significant decline in the electricity intensity of lighting, but is anticipated to also be offset by a significant *increase* in miscellaneous electric loads [13]. Hence there is also a need in the U.S. for a sustained effort towards operational savings in both existing buildings and new construction.

There are early adopters who are designing, building and operating high-performance commercial buildings, i.e. buildings that are highly energy-efficient while being smart and connected, and providing occupants healthy indoor environments.

While the cost differential between standard "BAU" buildings and high-performance buildings is decreasing in both countries due to a better market penetration of energy efficient materials and technologies, there exist a host of barriers that impede the widespread deployment of energy efficient buildings across the building stock, including:

1. **A skewed focus only on first costs and design-based decision making**. Developers, builders, architects, and engineers 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 payback and actual returns on investment.

2. **A fragmented building stakeholder ecosystem**. Buildings are typically designed, built, and operated in piece-meal stages and with siloed consideration of various building systems like HVAC, lighting, plug-loads, and construction methods. Systems operating at counter-purposes can lead to significant energy waste.
3. **The challenge of heterogeneity.** A wide diversity of building types, ownership, costs, services, and comfort levels exists within the commercial building typology, that requires a careful approach to envision and implement common approaches to energy conservation measures that would be pertinent across the built sector.
4. **The issue of regional transference.** Several building standards and systems have been transferred from western applications without accounting for the climatic, cultural, and economic context of India. For instance, de-rating of western equipment or contextualization of codes such as American Society of Heating, Refrigeration and Air conditioning engineers (ASHRAE) 90.1 code is seldom done during adoption to account for the Indian environment.
5. **A rapidly changing 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". Given the increasing penetration of renewable energy, smart buildings could provide several valuable services to the grid, including demand response and ancillary services. New buildings need to be grid responsive, integrating technologies such as smart metering, sub-metering, and data-driven decision-making with bi-directional communications

1.4 Opportunities and Policies

Commercial buildings in the United States and India have traditionally had significant differences in their construction, types of energy sources, and physical systems, but these boundaries are getting blurred. Also, both countries are starting to acknowledge the challenge of high energy use and wastage in their buildings, and have both established or adopted policies, programs (Table 1), and targets for achieving building energy efficiency.

Both nations have benefitted from bi-directional learning in building energy efficiency. The U.S. and India have had a history of collaborative energy projects such as the Asia Pacific Partnership and Clean Energy Ministerial (cleanenergyministerial.org). Recognizing that international collaborations should leverage precedents and require long-term engagement to be fully effective, the U.S. and Indian governments launched a five-year Center for Buildings Energy Research and Development (CBERD) in 2012.

The next section details the bilateral CBERD public-private partnership developed for building energy efficiency. This program identified common challenges in the building sector in both countries, and harnessed opportunities for cross-country technical assistance to develop building energy efficiency technologies, systems, and practices. This is a model that may be also applicable in other countries that have identified buildings energy efficiency as a goal.

Table 1: Technical opportunities, policies and programs relevant for building energy in India and the U.S.

Technological Opportunities	**In India** Technologies and strategies for primarily new construction, such as: 1. **Improved envelope and passive design** for reduction of external (solar) heat gain, (architects) 2. **Reduction of plug and lighting loads** for decreasing internal heat gain, (electrical engineers lighting designers, operators) 3. **Improvement of system efficiency for cooling delivery**, (mechanical engineers, architects, operators 4. **Integration of whole building and systems controls** (engineers, architects, operators) 5**. Building energy monitoring** and benchmarking of energy for data-driven decision-making (operators)	**In the U.S.** Technologies and strategies for primarily buildings retrofit , such as: 1. Enhancement of **grid-responsive** building operation, demand side management (operators) **2. Reduction of plug and lighting loads** for reduction of internal heat gain, (electrical engineers, lighting designers, operators) 3. Improvement of system **efficiency** for heating and **cooling** delivery, (mechanical engineers, architects, operators) 4. **Integration of whole building and systems controls** (engineers, architects, operators) 5. **Building energy monitoring and benchmarking** of energy for data-driven decision-making (operators)
Policy **Codes**	**In India** 1. National Building Code of India, 2016 (if local bye laws refer to it in whole or part)	**In the U.S.** 1. State- wise building codes, for e.g. Title-24 in California, 2015 IECC with amendments in Massachusetts etc. 2. ASHRAE Standard 90.1 – Energy Standard for Buildings Except Low-Rise Residential Buildings 3. ASHRAE Standard 62.1 – Ventilation for Acceptable Indoor Air Quality 4. ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy
Voluntary building energy related codes and green building rating systems	**In India** 1. Energy Conservation Building Code 2. TERI-GRIHA Green rating system 3. IGBC Green rating system 3. LEED (GBCI) Green rating system	**In the U.S.** 1. USGBC LEED and WELL Building rating system 2. Living Building Challenge 3. Architecture 2030 challenge 4. Utilities incentive and rebate programs

2. CBERD U.S.-INDIA PROGRAM ON BUILDING ENERGY EFFICIENCY

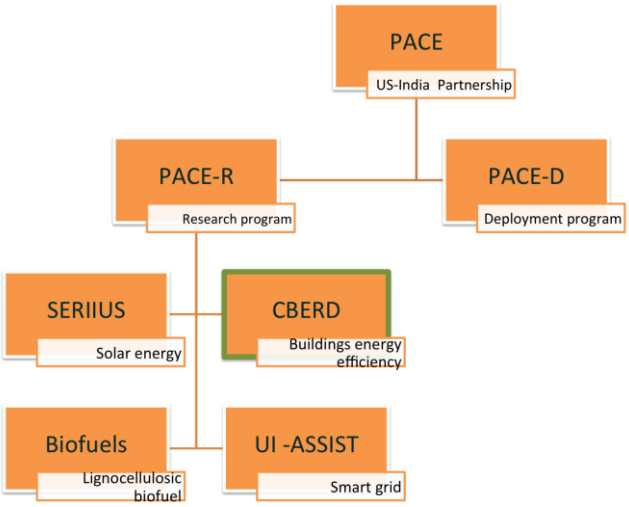

Figure 3: The Partnership to Accelerate Clean Energy program framework

The bilateral U.S.-India Partnership to Advance Clean Energy (PACE) was announced in 2009 though a Memorandum of Understanding signed between (former) U.S. President Barack Obama, and (former) Indian Prime Minister Manmohan Singh. The PACE program had two components: Research (PACE-R), and Deployment (PACE-D) [14] (U.S. DOE, 2015). The U.S. Department of Energy and the Government of India funded PACE-R jointly through the creation of the virtual Joint Clean Energy Research and Development Center (JCERDC) [15]. Four distinct joint research advancement tracks have been launched since 2012: solar energy, building energy efficiency, biofuels, and most recently, smart grids (Figure 3). Through a competitive solicitation in 2012, the U.S.-India joint Center for Buildings Energy Research and Development (CBERD) was selected as the consortium for the building energy efficiency track, and this program was operational from 2013-2018.

As an initiative at the highest governmental level, the vision of CBERD has been to solve complex, critical global problems in the building energy efficiency space by leveraging interdisciplinary, bilateral public-private collaboration. CBERD's goal was to deliver robust R&D solutions focused on providing significant, measurable improvements in the energy efficiency of buildings in both the United States and India. The CBERD leadership developed third key strategies to achieve this goal, as follows:

- **First, a technical strategy of developing a strong R&D scope to address key barriers to building energy efficiency** in both countries. This would be achieved through building energy R&D utilizing integrated building physical systems and building information systems targeting both first and operational cost savings to deliver deeper energy efficiency,
- **Second, a management strategy of developing a synergized collaborative team to deliver and transfer outcomes** that would leverage existing research efforts in both nations. The team consisted of each nation's premier energy-efficiency experts at multiple national laboratories, academic institutions, private industry, and non-profits, thus providing an unparalleled capability both to conduct the research and to enable pathways to deployment and technology transfer.
- **Third, a prioritization strategy**, to target both immediate and near term mitigation benefits, i.e. 2018-2050. These prioritized set of joint outcomes would include new building energy software tools, novel prototype technologies, scientific methods, physical research infrastructure, peer reviewed publications, and scientific two-way researcher exchanges

The CBERD consortium brought under one virtual roof, world-class researchers and scientists from academia, industry, and government laboratories, and institutional partners, from both India and the United States. CBERD was a tightly integrated 3X3 model with government, research and industry being the three key players. In the U.S., the Department of Energy's International Affairs and Building Technologies Offices provided program oversight. In India, the Department of Science and Technology, and the Indo-U.S. Science Technology Forum provided oversight. The joint CBERD Management Office (CMO) led by Lawrence Berkeley National Laboratory (LBNL) in the U.S. and the Centre for Environmental Planning and Technology (CEPT) University in India developed the management and organizational structure. LBNL

already participated in the Climateworks Global Buildings Performance Network, an organizational partnership between the U.S., E.U., China, and India for mutually beneficial work in building energy codes and labels [16], the Clean Energy Ministerial, for advancing technical expertise in energy efficient appliances in 23 countries [17], and the U.S.-China Clean Energy Research Center for Building Energy Efficiency (CERC-BEE) with an aim to position the United States and China for a future with very low energy buildings resulting in very low CO2 emissions [18]. On the Indian side, the lead partner, CEPT, was the only institution in India to enjoy the status of Centre of Excellence in Solar Passive Architecture and Green Buildings (granted by India's Ministry of New and Renewable Energy). It had contributed to the Indian Energy Conservation Building Code (ECBC) and the two green-rating programs: the Indian Green Building Council's (IGBC's) LEED program and the GRIHA (Green Rating for Integrated Habitat Assessment).

The CBERD consortium was comprised of eleven research institutions, each selected for its expertise in specific R&D and network. LBNL's U.S. partners included Oak Ridge National Laboratory (ORNL) for their expertise and test labs in advanced materials and HVAC, University of California, Berkeley (UCB) for their world-leading expertise in occupant thermal comfort, Carnegie Mellon University (CMU) for their expertise in building performance and diagnostics, and Rensselaer Polytechnic Institute (RPI) for their expertise in lighting tools and technologies. CEPT University's India partners included the International Institute of Information Technology Hyderabad (IIIT-H), selected for their expertise in building information technologies, Malaviya National Institute of Technology Jaipur (MNIT-J) for their expertise in building energy simulation and HVAC, Indian Institute of Management Ahmedabad (IIM-A) for their grid-responsiveness research, Indian Institute of Technology Bombay (IIT-B) for their HVAC labs and expertise, and Auroville Centre for Scientific Research (CSR) for their creative design and monitoring of passively-cooled buildings. Thirty industrial partners and organizations collaborated with CBERD to co-develop and demonstrate advanced building tools and technologies (Figure 4).

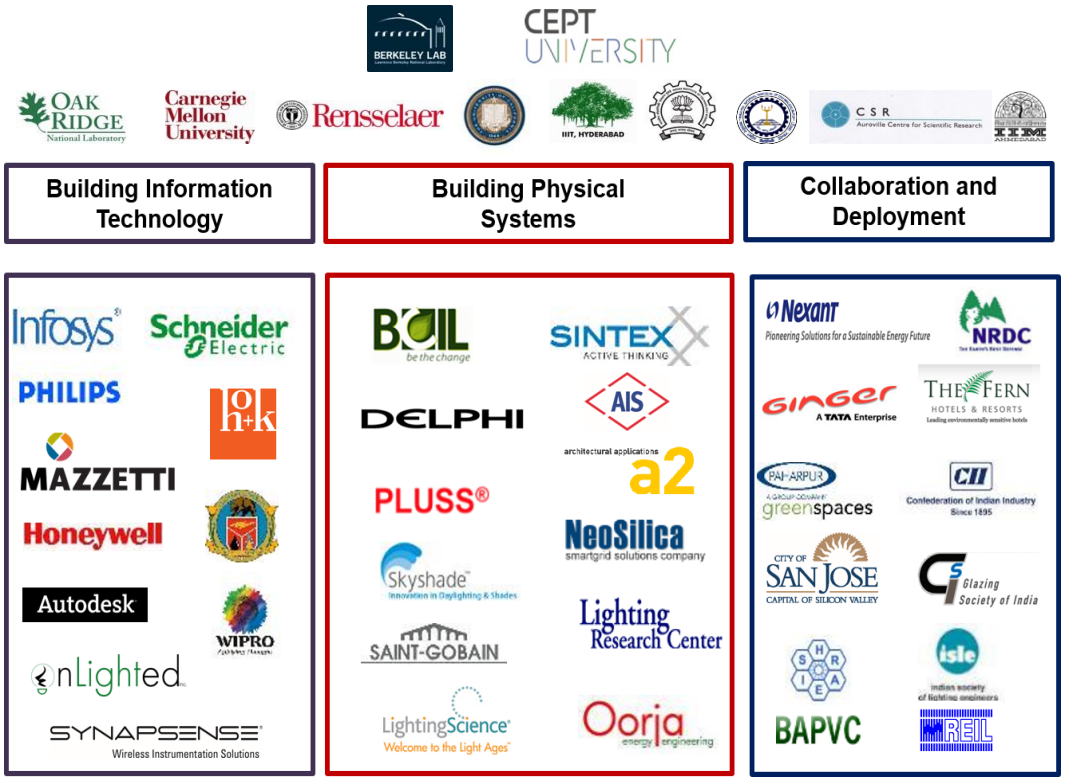

Figure 4: CBERD research and industry partners

The CBERD model integrated operating efficiencies–in the management, reporting, and dissemination of the research–by working closely across the ocean. R&D activities were mapped to leverage partner strengths to benefit both India, with its new construction paradigm, and the U.S., with a focus on retrofits (Figure 5). For instance, we identified the Indian team strengths in the areas of physical building systems and software, and the U.S. teams' R&D strengths in areas such as advanced mechanical and lighting systems and controls.

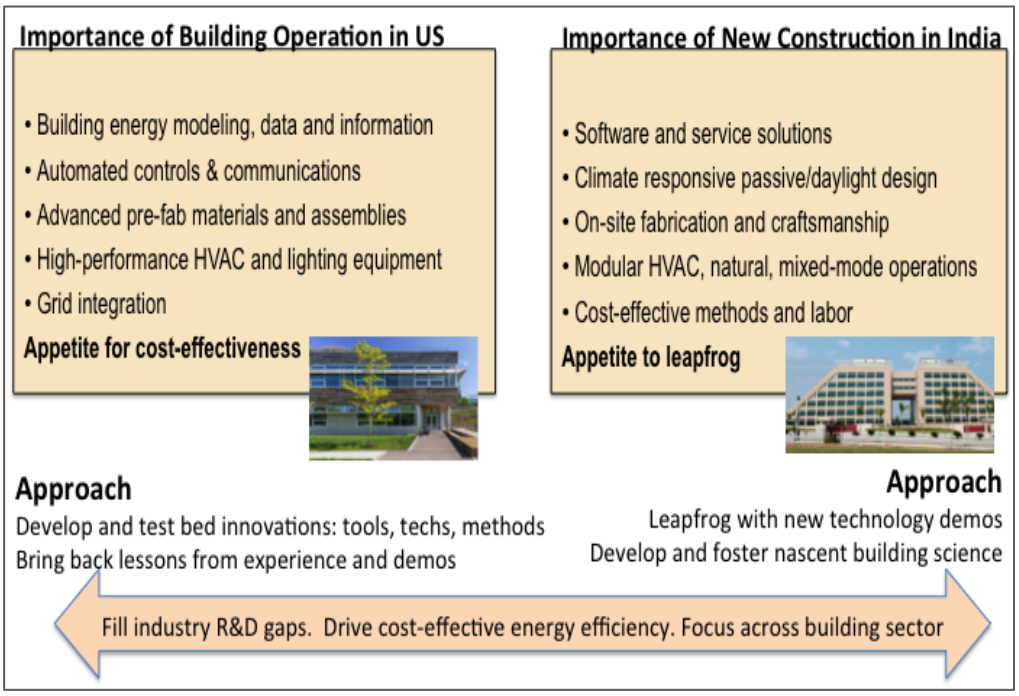

Figure 5: Dovetailing the CBERD consortium's strengths

Three key sets of activities were developed under CBERD, focused on near energy-efficiency potential:

(1) **Applied building science: New knowledge creation and dissemination**

- Basic science and research including thermal - optical performance characterization of materials and technologies,
- Development of joint peer reviewed papers, workshops, and technical reports
- Dissemination activities through industry and academic partners

(2) **Deployable R&D products**

- Software tools/modules for building energy efficiency
- Novel building materials and technology prototypes
- Methods, guidelines, and best practices for public use

(3) **Capacity building**

- New research infrastructure at Indian partner institutions by leveraging U.S. expertise and experience
- Testing of methods and technologies at real buildings and test beds in India, in collaboration with industry collaborators
- Researcher exchanges to encourage the bilateral transfer of knowledge

3. THE CBERD RESEARCH APPROACH

The team formulated a primary research question: *Is there an effective approach for prioritizing joint research and development activities that could enable and accelerate building energy efficiency in both countries*? To answer this, the team considered various perspectives over multiple brainstorming sessions that would bridge the gap between research and development, and implementation. The greatest challenge for developing a common approach seemed to be the significant dissimilarities in the building ecosystems, such as the disparate developmental stage of buildings: primarily new construction in India and retrofit in the US; dissimilar supply fuel mix, construction type and services; and incongruent costs and market adoption levels of various systems and technologies. However, there were some striking similarities-ranging from a trend towards high service level buildings in India that were starting to become similar to those in the U.S., and a similarly fragmented stakeholder ecosystem with a siloed approach that reduced interoperability between technologies, thereby leading to lost efficiency opportunities. The most critical common problem was the large gap between design and operations, i.e. buildings in both countries seldom provided energy performance per the intended design. It is only if operational energy savings are realized that true efficiency and therefore emissions mitigation is achieved, otherwise an intended design savings remains only a number on paper. Hence targeting operational building energy savings through a cost-effective integration of systems provided a common opportunity to address the challenge of widespread adoption of energy efficiency across the building stock in both countries.

Based on these findings, the team developed a hypothesis: *A life cycle performance assurance framework that integrates building information systems with building physical systems can enable deeper whole building energy savings.* The hypothesis was developed into an approach for defining the five-year research, as described next.

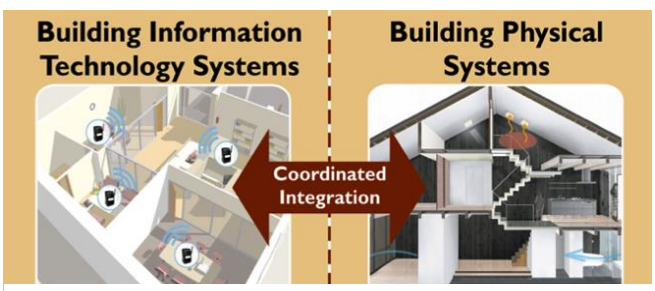

Figure 6: Coordinated integration between building physical systems and building information systems for effective building energy efficiency

Whole-building system integration throughout the building's lifecycle- design, build, and operate-can potentially assure high performance in terms of energy efficiency, cost, and comfort. To achieve this, it is critical to ensure coordination between the buildings' physical systems and information systems at each stage of the life cycle (Figure 6).

Building physical systems include the building envelope (wall, windows, roof), heating ventilation and air conditioning (HVAC), plugs, lighting, and thermal comfort technologies. Building information systems provide information and control of the building physical systems across the building life-cycle. First, by performing building energy simulation and modeling at the design phase, one can estimate the building's energy performance and code compliance. This is especially relevant for certain energy conservation measures (ECMs) that may not seem immediately attractive, but may become so through data analysis. Second, by building in controls and sensors for communications, one can track real-time performance at the building phase, relative to the original design intent. Third, by conducting monitoring-based commissioning and benchmarking during operations, one can ascertain building performance, compare a building to its peer buildings, and provide operational feedback. Thus, the use of building information systems provides indicators at all three stages of the life cycle, i.e. design-build-operate, to help predict, commission, and measure the performance of the whole building systems and components. This was integrated as the CBERD Lifecycle Performance Assurance Framework (Figure 7).

The approach also implemented a cross-cutting thrust on a triple bottom line framework, that includes energy (environmental), social (human health and productivity), and economic (cost savings) benefits, as a basis for

investments in building energy efficiency strategies. The objective was that this comprehensive framework would help decision makers consider beyond first cost, to encompass operational expenses, return on investment, as well as environmental and social costs while taking investment decisions.

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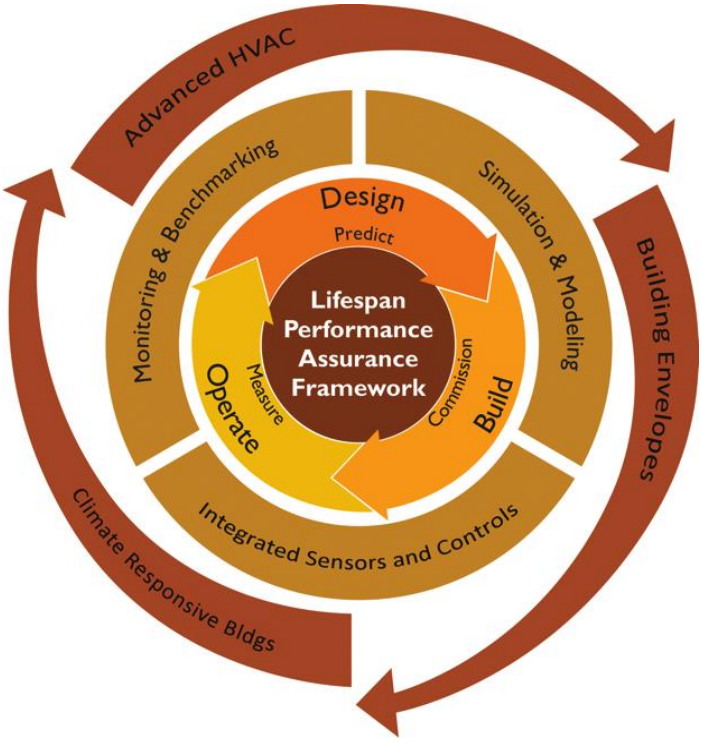


Figure 7: The CBERD 'Whole building lifecycle performance assurance' approach

A sequential process was identified to integrate the systems and target cost-effective energy efficiency in order to transcend the gap between design and operations to achieve lifecycle performance assurance. Firstly, whether in the U.S. or India, lower embodied energy can be attained through no-cost or low-cost energy conservation measures (ECMs) that lower the first costs of construction and equipment. For instance, careful selection of regional, low-embodied energy building materials, assemblies, and equipment that use less energy and fewer resources to make, transport and build can reduce first cost and environmental cost.

However, the CBERD program focus was on the research gaps, as mentioned earlier, i.e. operational energy costs (Figure 8). This started with ECMs that reduce the energy *demand* for services such as space cooling, lighting, and appliances, and then focusing on improving the *supply*, i.e. efficient and decarbonized delivery of these services. This essentially involved reduction of heat gains: both internal heat gains, by reduction of latent loads, lighting, and equipment loads, as well as external heat gains, by designing the envelope with windows and shading assemblies that optimize glare-free daylighting, better insulation and solar reflectance of the opaque surfaces, mixed-mode operations and controlled infiltration. Only when the demand load was reduced to an optimum level, would active ECMs such as improved energy supply equipment –HVAC equipment and plant design, and system monitoring and controls–be considered.

Hence, the CBERD team focused on the operational savings through R&D of building physical systems starting with passive and envelope systems, followed by plug and lighting load reduction, and finally advanced HVAC and lighting delivery. An integrating backbone of building information systems and

technologies was used, i.e. building energy simulation and modeling during 'design', integrated sensors and controls during 'build', and monitoring and benchmarking during the 'operate' phase to provide information and control of the physical systems, and help straddle energy efficiency across stakeholders throughout the the building lifecycle. A final step would be the use renewable energy to achieve net-zero buildings (but this was outside the CBERD program scope). Based on the above approach, the team developed a R&D portfolio methodology, as described in Section 4 below.

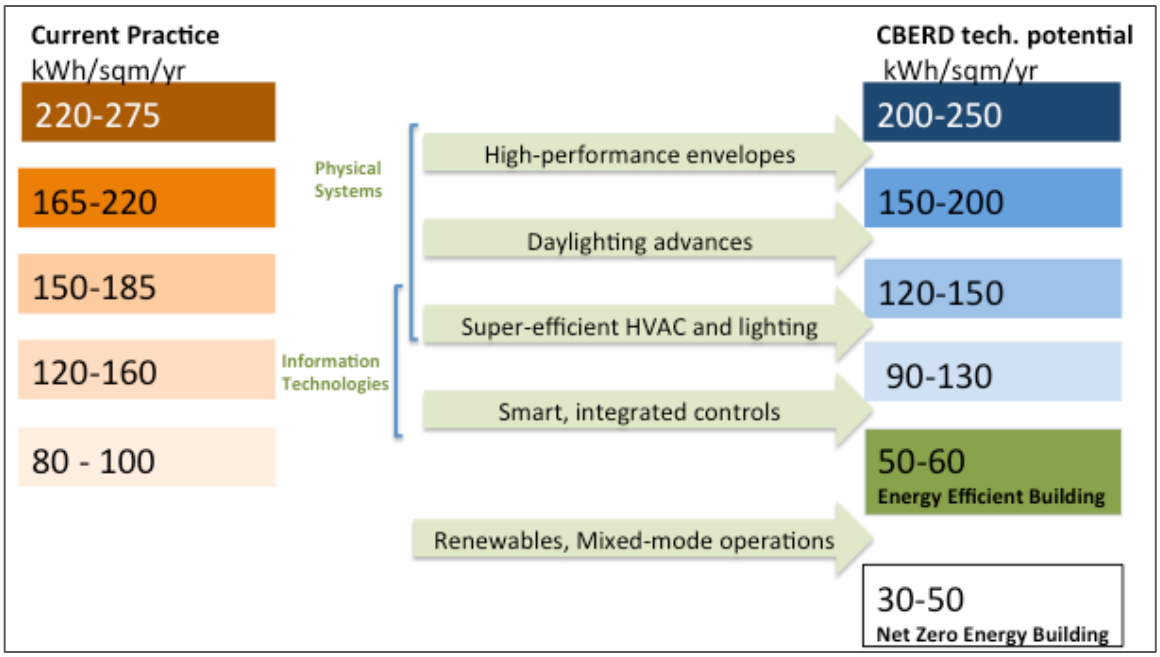


Figure 8: Sequential strategies for providing operational energy savings. The EPI (kWh/sqm/yr) numbers are illustrative benchmarks from current practice and technical potential targets.

4. METHODOLOGY

The CBERD methodology was comprised of three main thrusts:

4.1. Develop building energy simulation software: Develop simulation software tools jointly to compare design alternatives for passive, envelope, windows and shading strategies, evaluate energy codes, and use artificial intelligence to provide model predictive control for energy-saving operation of cooling systems. Design stakeholders (architects and engineers) would use these types of software tools once they would be tested and iterated upon.

4.2. Build and test building energy –related hardware: Co-develop (with industry partners) prototype technologies and materials with the intent that these R&D outcomes can help fill industry gaps. These include equipment that can address the largest demand loads (i.e. cooling, lighting, and plugs, and operational controls). These could potentially be productized and deployed by the private sector through technology iterations.

4.3. Implement strategies for capacity building and scientific methods: This included capacity building by developing research infrastructure, joint publications, two-way researcher exchanges, and bilateral transformation of methods to share lessons learned from each country.

As described in section 2.2, joint teams that dovetailed the strengths of the public and private partners conducted the R&D activities based on the above methodology and developed the outcomes. The results are discussed in section 5.

5. RESULTS AND DISCUSSION

In both India and the U.S. selecting and bundling the appropriate energy-efficiency measures to achieve building energy performance targets depends on know-how of materials, tools, and technologies; cost of integration and implementation; and impact on energy savings. The actual operational energy savings depends on both the development as well as adoption of relevant tools and technology strategies relevant for the immediate term implementation, as well as capacity-building and policy-push of scientific methods that can enable greater adoption over the longer-term. The technical savings potential of the portfolio of energy efficiency R&D projects was assessed in both countries.

5.1 Technical Targets For Building Energy

5.1.1 Technical energy reduction **target in India***:* A technical energy savings potential of 200 TWh/year by 2030 was identified in Indian commercial buildings, which almost exclusively use electricity (primarily grid, with diesel generator backup), with liquefied petroleum gas (LPG) as a secondary fuel used only for cooking. This assumes that 66% of the building footprint that would be extant in 2030 still needed to be built [10], and there is a ~38% potential for energy savings [4]. A significant portion of these savings is dependent on reduction in cooling loads through envelope design with high-performance windows and shading assemblies, cool surfaces to mitigate solar heat gain, mixed-mode operations and high thermal mass/phase change materials to reduce peak loads, and alternate low-energy cooling strategies such as non-compressor-based and radiant cooling. These are befitting of India's warmer climate, it's labor-intensive reinforced cement concrete (RCC) construction, and the new construction paradigm (Figure 9).

5.1.2 Technical energy reduction **target in the U.S**.: A technical energy savings potential of 1160 TWh/year by 2030 (was identified in U.S. commercial buildings. This is an 18% savings in the buildings sector (that includes both electricity and natural gas), and is dependent on the deployment of retrofit energy conservation measures, such as integrated sensors and controls, reduction of plug loads, energy management and information systems, and efficient HVAC units. This is based on the assumption that in the U.S., where most of the building stock is already built, energy efficiency measures can potentially impact 30% energy savings in new construction, 20% energy savings through retrofits between 2013-2020, and 30% energy savings through retrofits between 2021-2030 (assuming that half of the building stock will be retrofitted by 2030) (Figure 9).

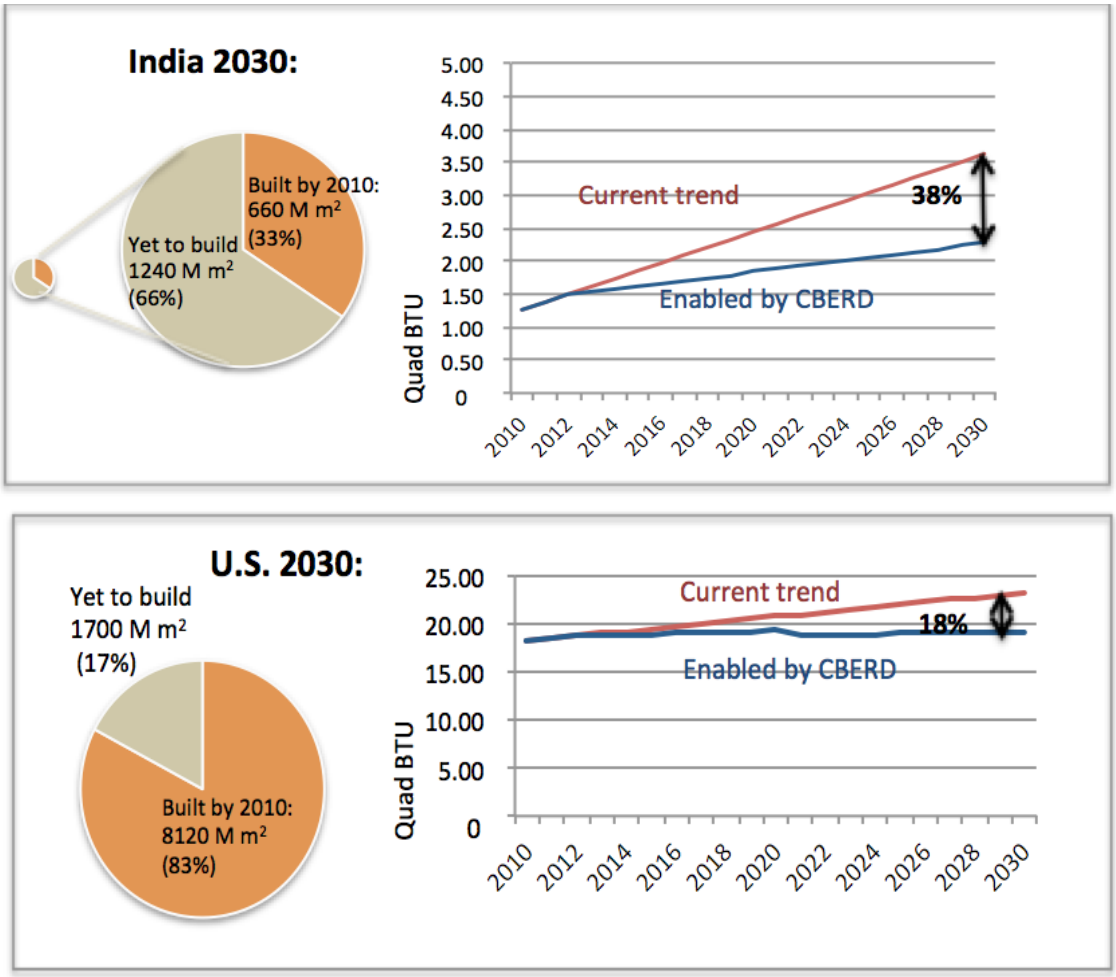


Figure 9: Technical potential for commercial building energy savings in both nations. (1 Quad BTU~293 TWh)

5.2 Tools, Materials, And Technologies

The key CBERD outcomes included building energy software tools, building energy technologies and materials, energy efficiency methods, development of research infrastructure, and establishment of scientific exchanges. These are briefly described below, followed by a deep-dive into a key method: building energy monitoring and benchmarking.

5.2.1 Building energy software tools for energy efficient design

Five joint building energy software tools were developed as new tools or enhancements, namely (i) Early Design Optimization Tool eDOT, (ii) COMFEN- India with Non-coplanar Shading Calculator enhancement, (iii) Cool Roof Calculator, (iv) Model Predictive Control for radiant cooling, and (v) ECBC Code Compliance ruleset. Four of these are can be publicly deployed with further product development, to be used by practitioners for building design and building operation (Figure 10).

The early design optimization tool **eDOT** can be primarily used for early stage envelope and windows design decisions for whole building energy saving predictions [19]. This is especially relevant in India, where decisions in new construction regarding thermal mass, orientation and glazing are critical. The projected energy savings enabled by this tool are 120 GWh of energy per year in India, based on a conservative whole buildings savings potential of ~ 5%, and market penetration of 20% (averaging over the next 15 years).

COMFEN-India, predicts daylighting, solar control, and energy savings, with India-specific construction material, windows glass libraries, and climate. It expands upon the free, online software tool Commercial Fenestration (COMFEN) developed by Berkeley Lab as a simple, user-friendly, single-zone façade analysis tool based on the EnergyPlus and Radiance simulation engines (Figure 10) (https://windows.lbl.gov/software/comfen).

The web-based **Non-coplanar Shading Calculator** integrates with the U.S. DOE software tool COMFEN**,** and calculates the resultant solar heat gain coefficient (SHGC) of twenty types of shading designs, i.e., fins, overhangs, and perforated shading devices [20]. With this tool a user can calculate the summer- and winter-weighted SHGC for a certain window and compare that to a different window (i.e., with a different coating) with an overhang, enabling them to analyze and performance trade-offs for window or glazing technologies and exterior shading elements.

The Cool Roof Calculator tool calculates energy savings and life cycle costs for solar reflecting envelope materials and optimizes roof insulation [21] as both a new construction and retrofit opportunity, making it relevant for both countries. The **Model Predictive Control** (MPC) software toolchain uses artificial intelligence and radiant cooling strategy [22] to help solve this complex controls challenge and bridge the design-operations gap. **ECBC Code Compliance Ruleset** for the Indian Energy Conservation Building Code (ECBC) is incorporated in performance-based compliance software, and implemented in DOE's OpenStudio modeling environment. This enables architects, owners, and urban local bodies to create automated prototype models at a reduced modeling time and cost, and overcome a key technical barrier in the widespread implementation of ECBC-i.e. the lack of automated compliance tools. This tool can have a significant impact for the implementation of the ECBC code in India, and is also directly adaptable to the ASHRAE 90.1 code, making it pertinent for the U.S. as well.

Figure 10: Illustration of a CBERD tool: COMFEN with the non-coplanar shading module integration

5.2.2 Materials and technologies for operational energy savings

Several prototype technologies and materials (Figure 11) were co-developed or improved, typically with industry partners, and can provide significant energy savings. Four of these are being patented.

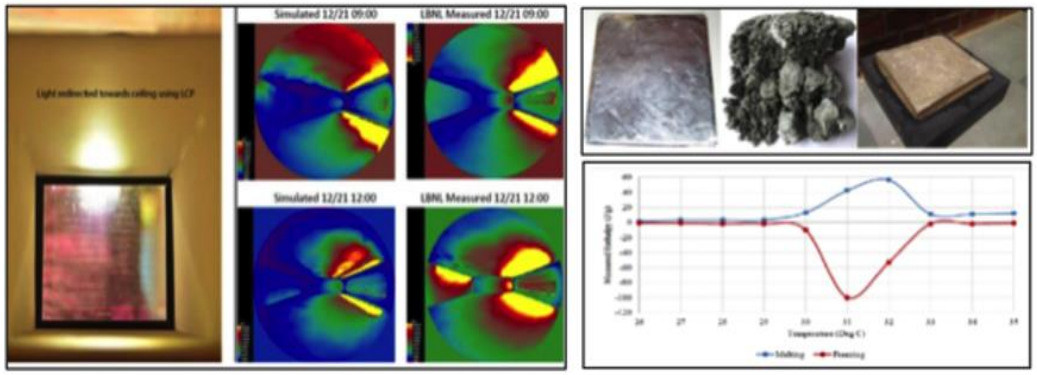
The performance evaluation of **laser-cut glazing panels** (LCPs) was conducted to help enhance the redirecting ability of the panels manufactured by industry partner Skyshade, for deeper daylight penetration into buildings. Simulations also revealed that the use of LCPs distributed daylight uniformly along the depth of the space, increasing the depth of penetration to up to 12m from the opening with illuminance greater than 100 lux, and enabled maximum lighting energy savings of up 69-75% for a building with 30% window to wall ratio, with windows placed in the south direction [23].

Phase-change materials were tested to provide thermal storage, enable peak load shifting and enhance comfort [24]. Energy and comfort benefits of 5%–10% were estimated, based on simulation model results for climates of Ahmedabad, India and Charleston, SC and test bed experimentation at CEPT University, following ASTM C1784 guidelines. PCM tiles, cement concrete, and cement plaster with encapsulated PCM can suit both U.S. and Indian construction types.

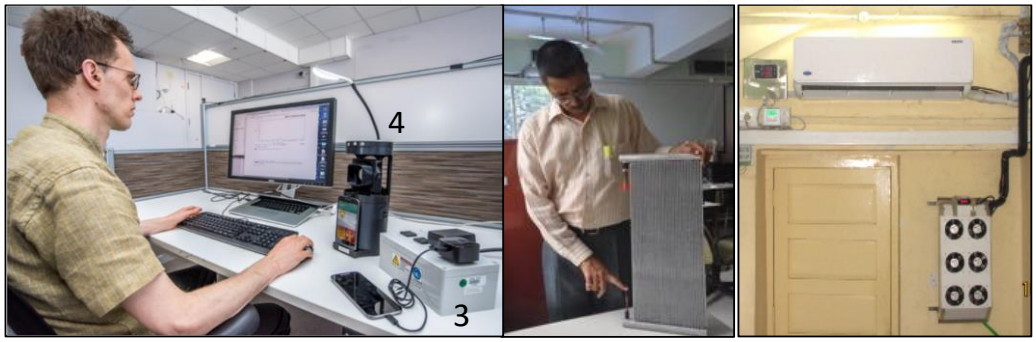
An **Intelligent System using Personalized Automated Control for Energy Efficiency iSPACE** was developed a patent-pending internet of things (IoT) smart workstation device. It has a sensor suite**, smart plug strip** for identification of plugged in devices, distributed controls using the Volttron transactive controls software [25] that enable grid interaction, and personalized comfort. Test results revealed 80% peak load savings, and 57% average savings during a load reduction event.

For mechanical cooling energy efficiency, two new technologies are worth mentioning. The first was a **new Microchannel Heat Exchanger** (MCHX) component that can be integrated into small unitary HVAC systems 0.75 to 2 tons (TR) in size that are common in India. Co-developed with industry partner Delphi, this improved MCHX enables coefficient of performance (COP) improvement by 7%–15%, reduction in mass and cost by ~30% as compared to a conventional fin tube evaporator, as well as reduction in refrigerant inventory to facilitate use of a flammable, environmentally friendly refrigerant such as R290, and easy recycling of the heat exchanger [26]. In the context of India's air conditioner crisis, by 2030, peak load due to room ACs alone will be 150 GW, i.e. three times California's peak load [27]; such a system can be highly relevant, and has already been integrated into a 1.5 TR 5 Star Split AC.

The second technology, a **Dedicated Outdoor Air System (DOAS),** decouples latent and sensible loads in a building, potentially leading to significant HVAC energy savings. The CBERD team developed configurations such as indirect evaporative water cooler, air-to-air heat recovery, and solution heat exchanger configurations. The tests for these new configurations showed 20% energy savings, with half the pressure drops and parasitic power consumption as compared to conventional systems [28]. Being modular in construction, these technologies can be deployed cost effectively in both Indian and U.S. buildings.



(1) Laser cut panels (LCP) redirecting light towards the ceiling with simulated and measured results. (2) Phase change materials. Top: ceiling tiles, cement concrete, and cement plaster. Bottom: Testing thermal properties of PCMs



(3) Smart Strip, and (4) i-SPACE Smart Hub for workstations (left). (5) Novel microchannel heat exchanger design of a 1.5 TR split unit

(6) Dedicated Outdoor Air System: indirect evaporative cooling of fresh air using exhaust air (left), with various components and sub-systems (right)

Figure 11: Technologies jointly developed by the U.S.-India team

5.3 Capacity Building And Scientific Methods

5.3.1 Capacity Building. U. S. partners provided technical assistance on the design and construction of new building energy test beds and apparata at the Indian partners' institutions, which will be an important ongoing resource for future studies. In addition to over 100 publications and reports on the research findings, fifty two-way research exchanges helped researchers gain international experience, mutual understanding, access to new ideas, and training on test beds. These knowledge creation and transfer activities are anticipated to have robust impact over the next years.

5.3.2 Scientific method for climate responsive buildings. Analyses conducted within an adaptive comfort framework, of new data acquired from physical monitoring of passive strategies, field based indoor environmental quality surveys, chamber thermal comfort studies, mixed-mode case studies, and air movement analysis showed significant key findings:

- Passive strategies such as solar chimneys with evaporative coolers, cavity walls, and ventilated double roofs were highly effective at creating comfortable indoor thermal conditions that were aligned with the India Model for Adaptive Comfort (IMAC) (Figure 12). In our analysis and computer modeling of data from two U.S. buildings in mild climates using thermal mass and nighttime ventilation, we found that the mass was sufficient and the night ventilation was overcooling the buildings, and would have less significance when there are low internal loads and heavy mass.
- 85% of surveyed occupants from twelve mixed-mode and air-conditioned buildings across three climate zones of India reported a high level of thermal satisfaction, significantly higher than what we see in U.S. buildings [29]. Air movement was fairly successful at keeping people comfortable in chamber test studies, with the exception of the very warmest conditions of 32°C and 80% RH. The high levels of satisfaction, frequency of use, and confidence in the effectiveness of using windows and fans (especially in combination) revealed opportunities to judiciously combine both natural ventilation and low-energy mechanical systems in a well-designed "mixed mode", that can improve both energy and comfort performance [30] [31].

These findings have been adapted into the second version of the Indian Energy Conservation Building Code released in 2017 [32] and can have a significant impact on mitigation of cooling energy consumption in India.

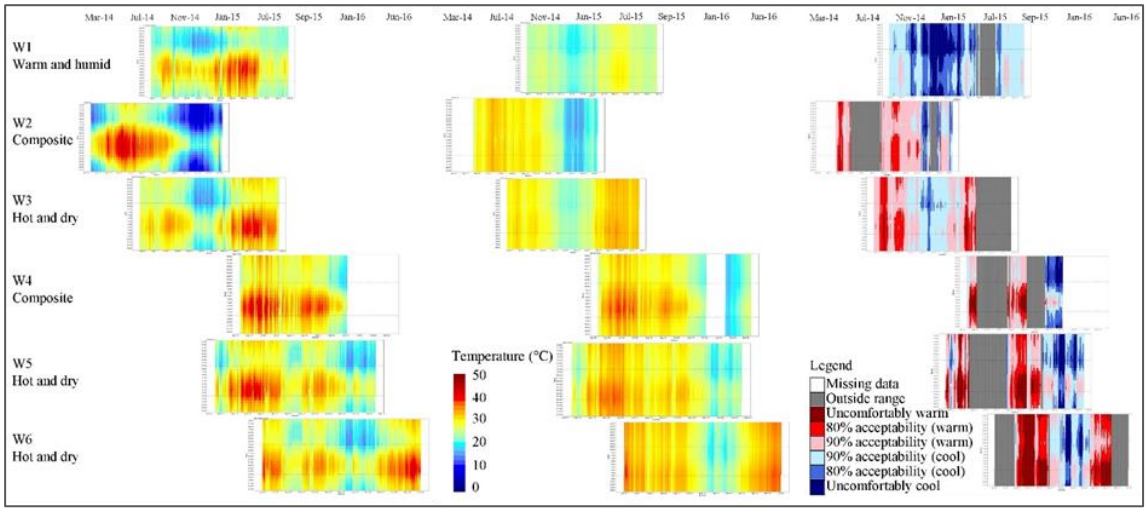


Figure 12: Heat maps plotted for outdoor temperature, indoor temperature and indoor temperature binned according to the IMAC-NV acceptability bands, for three Indian climate zones

5.4 Detailed Technical Outcome: Operational Energy Data Benchmarking and Monitoring

As discussed, operational energy savings is the most significant pathway to building energy efficiency. We discuss in detail below the two core aspects of acquiring and using energy data to enable operational savings.

5.4.1 Energy benchmarking

The nascent state of building energy benchmarking in India afforded an opportunity to develop methods and tools that build on U.S. experience where energy benchmarking has gained significant traction through voluntary and mandatory programs at the local, state, and federal level, most notably through Energy Star. One particular lesson from U.S. and European benchmarking efforts is that even basic data required for benchmarking can sometimes be difficult to obtain with a reasonable degree of accuracy (e.g. gross floor

area, number of occupants). Furthermore, benchmarking scores are rarely, if ever, presented with uncertainty information to help apply these results appropriately. The team developed benchmarking methods that address these two challenges through a "graduated" tiered approach to benchmarking that allows tradeoff between data inputs and accuracy. Lower tiers have fewer user inputs and wider uncertainty due to less context-specific information, and vice versa for higher tiers [33]. The study used the hotels and hospitals building energy datasets from a previous USAID program called ECO-III (USAID, 2011), to develop and evaluate three methods for graduated benchmarking: Independent models, Constrained Regression models, and Single model (Figure 13), with criteria to evaluate the suitability and internal consistency of these methods for graduated benchmarking.

The result was a national energy benchmarking database framework for India, including data needs and fields that also were developed. This graduated methodology is relevant to various levels of available data, provides benchmark scores with error bars allowing users to apply them appropriately, and is ready for uptake by future benchmarking programs in India.

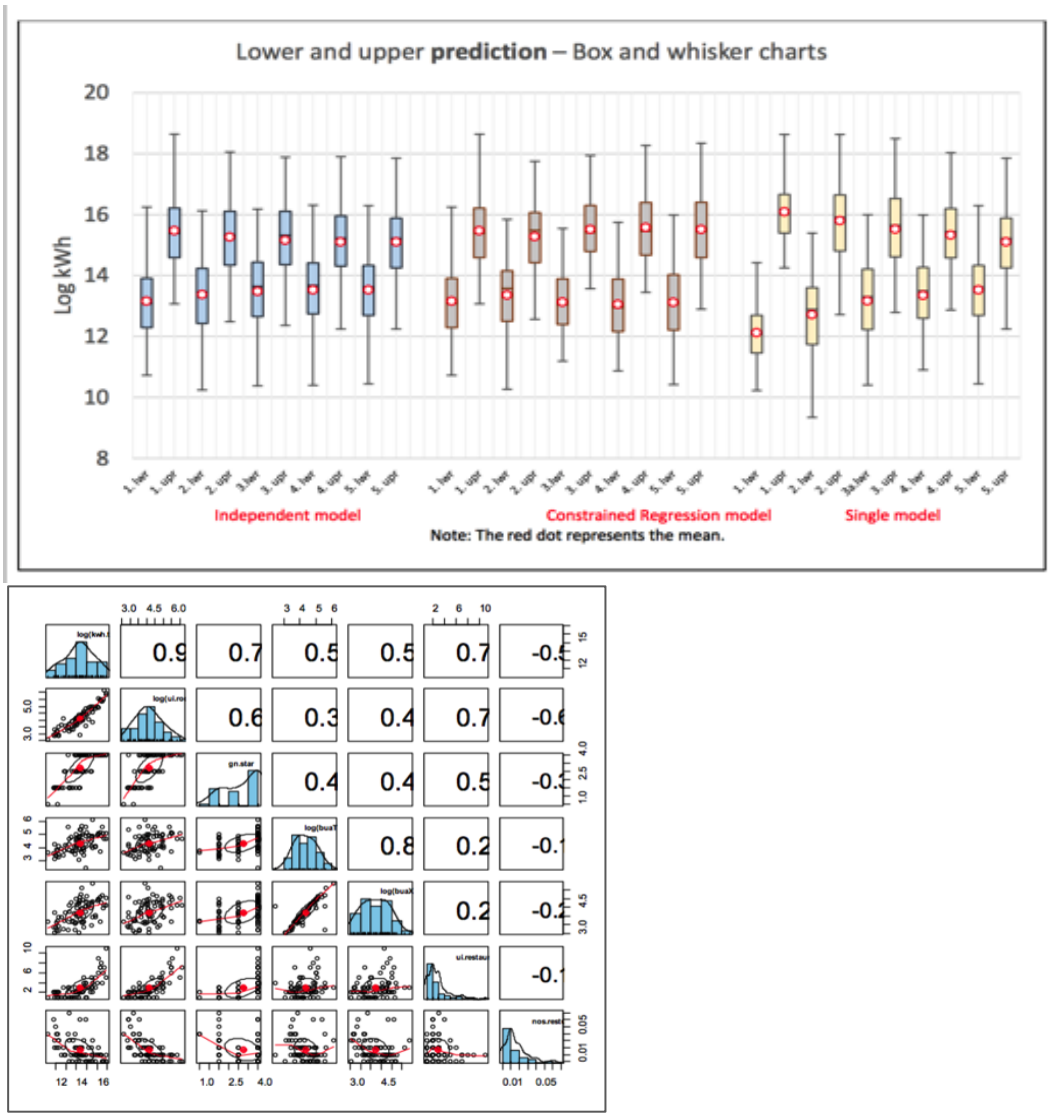


Figure 13: Graduated benchmarking method: (Left) Box and whisker charts showing lower and upper prediction in the three types of chart. (Right) Correlation matrix of USAID's ECO-III hotels dataset

5.4.2 Energy Monitoring

Energy information systems (EIS) are performance-monitoring solutions that acquire, store, analyze, and display building energy data [34]. EIS track energy cost and consumption patterns, identify system- and component-level energy use and waste, and benchmark performance against the building's past performance or similar buildings. Facility managers can then take data-driven actions and reports for tighter schedules and controls, repairs, audits, and upgrades. Building owners can derive insights into their quarterly and annual operational costs, enabling better investment decision making for efficiency retrofits. EIS are commercially available and growing in technical capability, but high transaction costs– skill and time required to configure, install and use EIS–limit their market reach. The CBERD project thereby focused on scalable, cost effective "EIS in a box" packages that were informed by pain points identified in the U.S. and a future Indian EIS market, that are being driven by the roll out of the smart meter initiatives and policies. The results were simplified, low-cost EIS packages—"EIS-in-a-box"—with broad applicability across the specific sectors, rather than needing high customization at a building-by-building level. We derived the technical requirements for two tiers (entry and advanced) of EIS packages for hotels, hospitals and office facilities (established as high growth sectors through a market segmentation study) based on organizational business drivers [19], each with three predefined components (Figure 14).

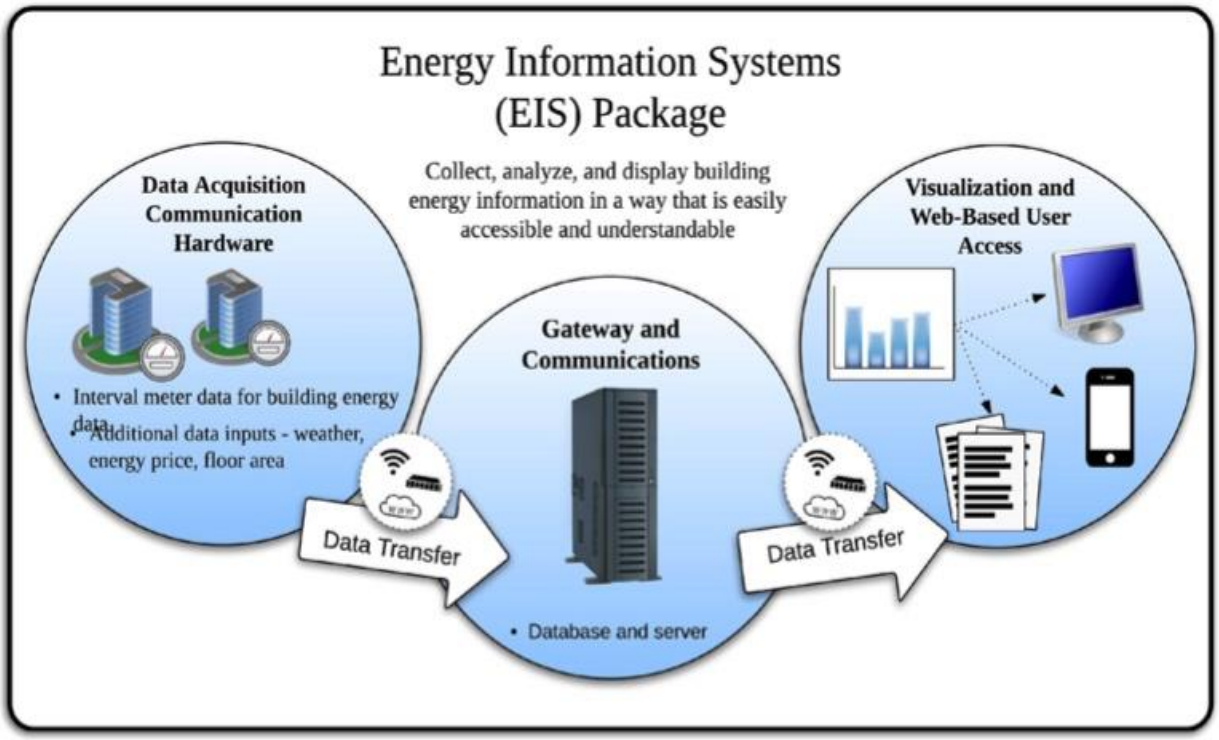


Figure 14: The three components of an EIS-in-a box [19].

- Data acquisition from critical end uses and spaces, communication through sub-meters, and gateway connectivity
- Streamlined data architecture with back-end software allowing data access, storage, and analysis
- Front-end visualization with performance metrics for key stakeholders and user notifications, enabling insights and actions (Figure 15).

These packaged solutions can reduce cost by up to 30% as compared to current custom solutions, and were demonstrated in six buildings-hotels, hospitals and offices with industry partnership from Schneider, Wipro Eco-Energy (United Technologies). Given the emphasis on building retrofits in the U.S., and the smart meter states initiatives in India, the potential impact on energy monitoring and benchmarking is an annual energy savings of 68.4 trillion Btu (TBtu)/year in the United States and 6.7 TBtu/year in India.

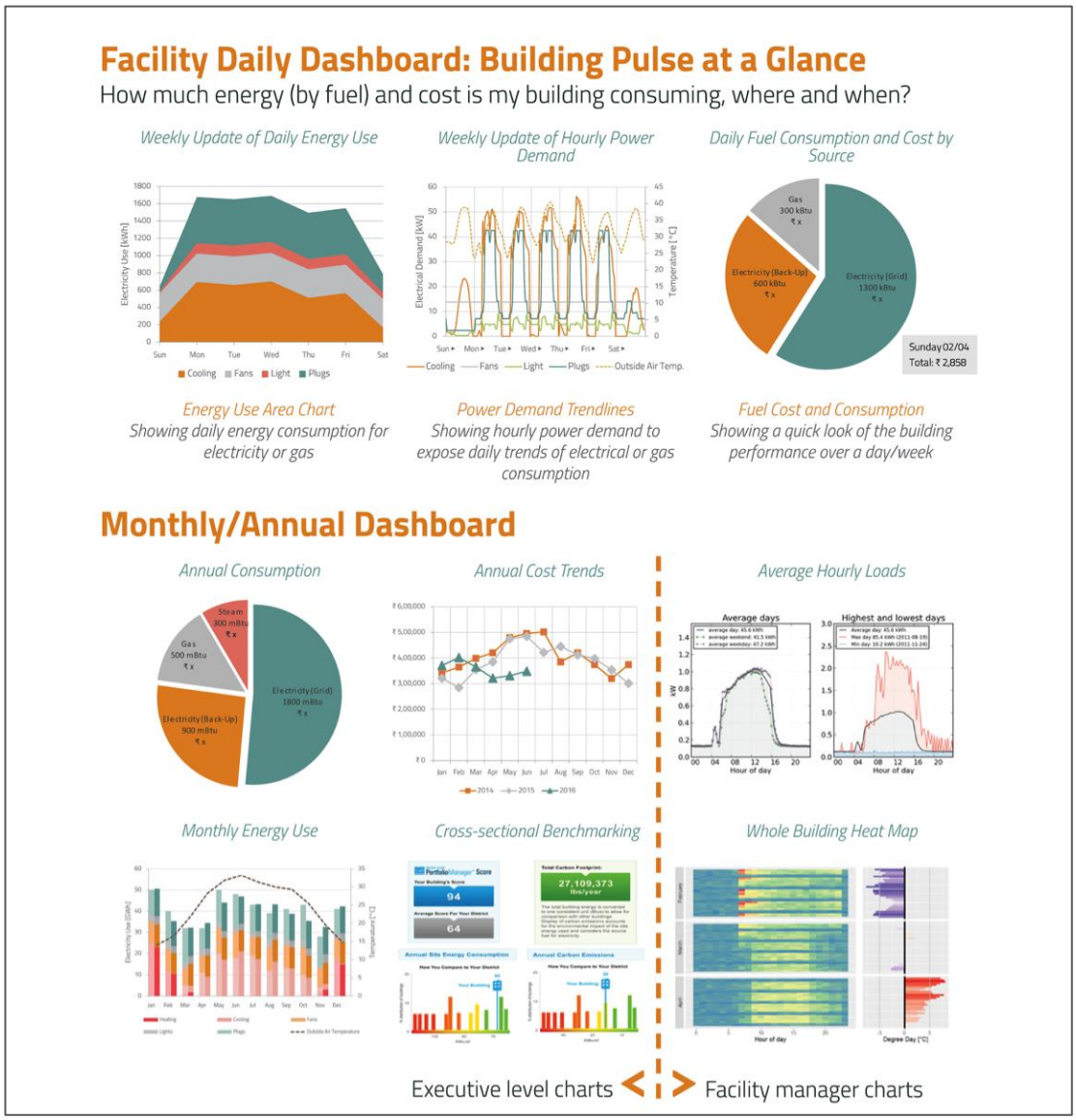


Figure 15: Visualization charts developed with operational energy data, to be used by facility managers and executives to make data-driven decisions such as schedule, control, repair, audit, and retrofit [19].

While these monitoring and benchmarking areas mentioned above are an illustration of the R&D results and potential benefit of this particular set of methods and technologies, the following section outlines overall potential benefits of the CBERD program, lessons learned, and pathways for future activities.

6. CONCLUSIONS: BENEFITS OF THE CBERD PARTNERSHIP AND FUTURE DIRECTIONS

6.1 Potential benefits of the CBERD R&D

CBERD was architected to thrive in today's fast-evolving building energy landscape. For instance, India has rapidly changed in the past decade from having a population of 400 million+ without energy access, to the present where several states have power surplus and aggressive renewable energy deployments. Key energy issues in India have transformed the status quo from a problem of 'unreliable grids' with blackouts and brownouts as the norm, to designing and implementing a leapfrog 'smart grid' that can manage renewable energy and intermittency, regional grid connections to make power production more cost-efficient, installing smart meters, and improving billing efficiency. However, the explosive growth in space cooling energy use, rapidly growing building energy footprint, and rising urban temperature will continue to challenge India's energy systems.

In the United States, the energy efficiency challenges are different, focused on cost effective methods for retrofitting the country's already-existing buildings, and responsiveness to the grid. In both countries, building energy efficiency consists of complex science, engineering, business and economic challenges, with the gap between design and operations and a siloed, non-integrated approach being the key technical barriers. [36]. The U.S.-India CBERD partnership has promoted innovation to address these challenges by harnessing the collective knowledge of research partners, market intelligence of private sector partners, and wisdom of policy-makers to help shape the research agenda, develop robust methods and technical outcomes, and share best practices.

CBERD's R&D strategy to integrate information technology with building physical systems across the building life cycle led to deployable outcomes from the program. CBERD design tools such as eDOT, enhanced-COMFEN, and the ECBC automated baselining ruleset have been designed as platforms not just to gain green ratings or code compliance, but to enable the designer's participation in strategies for energy efficiency early enough in the design process to make them pragmatic. The performance gap between design and operations that has plagued the building industry is also addressed through a new model predictive controls tool, as well as energy benchmarking and monitoring. These methods are ready for use in policy as well as empower designers to identify and validate energy efficient strategies to their clients. For use in the building phase, prototype equipment and materials such as micro-channel heat exchangers, enhanced radiant systems and DOAS solutions, phase change materials, laser cut glazing, and cool materials are ready for productization and deployment by the private sector. For the operations phase, packaged, scalable EIS-in-a-box solutions addressing the paucity of building energy performance data, to provide cost effective smart metering, billing validation, and data driven energy efficiency actions, are already being used in the demonstration buildings in India and will also be piloted in the American Society of Healthcare Engineers (ASHE) member facilities.

A CBERD cross-cutting study that includes energy (environmental), social (human health and productivity) benefits and economic cost savings, revealed that using this triple bottom line (TBL) framework with can influence decision makers to move beyond first-cost decision making to support investments in high performance, energy efficient technologies. Decision maker responses, tested during this effort, confirmed that when TBL information is provided, decisions to invest shift in favor of high performance, energy efficient technology. Policies and regulations with TBL enable robust, mainstream investments in both nations. [35].

Additionally, the team explored the future of grid responsiveness, and has successfully developed the I-SPACE smart hub prototype with transactive controls as a building-to-grid integration solution to address issues of peaks and renewable intermittency. CBERD's climate responsive adaptive comfort approach has

already been integrated into India's ECBC v.2 2017, while the Triple Bottom Line methodology for energy efficiency decision-making is already being tested as a USGBC LEED pilot.

6.2 Lessons Learned

The CBERD international partnership has adapted global best practices, policy and standards to local Indian contexts, and provided capacity building, educational opportunities, and scientific exchanges. In India, this has helped overcome cultural challenges, ushering in a new culture of big team science collaboration, and cultivating a new generation of researchers and scientists. This has provided an impetus to advance building science in India, as evidenced by the creation of a cohesive CBERD India team and a new "BHAVAN" fellowship dedicated for the first time to building energy efficiency. In the U.S., it has enabled not only a global perspective on technology applications and market adaptability of building tools and technologies, but also helped build close ties with our partners across the ocean. Also, given the equal funding, the dollar was leveraged manifold in terms of access to skilled scientists, researchers and technical staff that had the appetite to learn and innovate, in collaboration with the U.S. team.

However, there were certain areas that, in hindsight, could have been built into the model as additional time and resources to further advance the outcomes. First, given the challenges of cultural and time differences, more frequent, dedicated face-to-face interaction between private and public partners in both countries would be greatly beneficial to a bilateral program, and resources should be assigned adequately. Second, while the products developed were tested separately, conducting integrated testing of the different products in a test bed or a real building would have provided a validation for the technical targets achieved through simulation. Third, a robust strategy for seamless hand-off for tech transfer to industry partners or a broader private sector ecosystem for productization and pilots could have been developed. Similarly, a closer integration with strong policy organizations would have been more beneficial for transfer of the documented results of the scientific methods. These could be achieved through a tighter coupling between the 'Research' and 'Deployment' aspects of the PACE structure at the onset of the program.

6.3 Pathways towards deployment and impact

Bilateral collaborative programs such as CBERD, being at the national level, can evolve into three types of deployment pathways: technology transfer, policy adaptation, and education with capacity building.

R&D prototype products may be developed further by collaborators such as industry partners, or for uptake by the broader market through use of the free, online design-operations tools and methods such as eDOT and EIS, or by licensing of technologies such as the cooling equipment, and I-SPACE controls. This will enable technology transfer. Scientific methods such as the validation of the adaptive comfort model, the triple bottom line framework, or the graduated benchmarking approach can be adapted into strong policy to benefit the state of the building stock, existing and new, and help to leapfrog over transitional systems. The capacity building activities through development of research infrastructure and researcher-educational exchanges have created benefits that will be realized over several years, as the building science in India grows—in fact, one of the key successes of CBERD has been the unprecedented recognition of building science as a real science track in India.

Several of these outcomes are relevant for application in both U.S. and Indian buildings. CBERD research has leveraged bidirectional learning between the U.S. and India based on traditional expertise in both countries. These approaches—testing, data collection and demonstrations in India, ranging from mixed-mode operations, adaptive thermal comfort standards, cool materials, and energy information systems—cut across both countries, which are at different developmental stages of their built environment.

A cornerstone of CBERD is the co-development of equipment, materials and technology, and its cost-effective testing and field validation through demonstrations. This development has been done through joint collaboration of U.S. and Indian partners, by developing new building hardware and software technologies, and collaborating with industry. This has also generated new intellectual property through a model U.S.-India IP agreement. Co-developed technology prototypes include laser cut window panels, phase change energy storage materials, smart plug load strips, I-SPACE IoT device, and HVAC equipment, which have been tested cost-effectively in India. The context of India's relative affordability and robust service ecosystems can also act as catalysts for reverse innovation. These tested technologies and best practices, such as passive cooling and mixed mode operations, have important applications in the U.S building ecosystem for deep energy savings.

6.4 Future directions

With the strong foundation of all of these efforts, the CBERD partnership has challenged the status quo for building performance, driven by a triple bottom line framework of energy cost efficiency, occupant comfort, and environmental sustainability. We have identified technologies that can support a technical target of 18% energy savings in the U.S. and 36% energy savings in India. The program has provided leapfrog opportunities through cross pollination activities, gaining of insights from new data facilitated through the bi-lateral activities, and outcome-oriented deployable results. CBERD has developed and demonstrated a broad range of technologies that can help ensure that the energy use of buildings is lower than it would have been without this portfolio of work. It will be possible to create impact only with further development and deployment activities of the outputs described above to higher technology readiness levels, as well as developing tighter integration with the market and policy stakeholders. The complex buildings value chain will need to be addressed by building stakeholders for the deployment of cost-effective and scalable solutions with robust applications in an expanded market, for reduced energy use in buildings and decreased carbon emissions. Taking CBERD outcomes to this next level can drive the acceleration of these combinatorial passive-active, high tech-low tech tools, technologies and methods using to achieve deep levels of building energy efficiency and meet the upcoming challenges.

ACKNOWLEDGEMENTS

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ANNEX: AN OVERVIEW OF CBERD DISSEMINATION AND OUTREACH

The CBERD team presented at various funder and stakeholders reviews and disseminated outcomes at various international and domestic fora. Some of the key events are detailed below:

1) Program Reviews and Stakeholder Fora

i. *Annual Peer Reviews* 2017, 2016, 2015, 2014. CBERD was reviewed at the BTO Peer Reviews every year. In 2017, CBERD was reviewed to be complimentary and aligned with BTOs goals and objectives of developing, demonstrating, and accelerating the adoption of technologies, techniques, tools and services that are affordable and enabling high-performing, energy-efficient new and existing buildings. Reviewers remarked that CBERD allows both countries access to each other's buildings experts to collaboratively face building efficiency challenges. Reviewers mentioned that the project staff *collaborates and coordinates with industry, academia, and other stakeholders to a great extent and that funding this activity provides insights into new and different facilities, sites, populations, and energy markets*. Similarly, the Indian team presented semi-annually at Project Monitoring Committee reviews and included the feedback in the ongoing R&D activities. For future work the reviewers suggested including a market penetration strategy, showcasing field-testing the CBERD tools and technologies, and identifying technology and materials applications in both countries based on differences in climate, building construction, grid pricing patterns, and fuel types.

ii. *CBERD Annual Stakeholders Fora*: Each year the team hosted a U.S. and an India Stakeholder Forum, presenting the activities and ongoing results to stakeholders in the energy efficiency space. Stakeholders included sponsors, industry partners, collaborators, policy, non-profit, academia. (*Figure AN1*). For instance, in August 2017, LBNL hosted a U.S. CBERD Stakeholder Forum attended by a range of stakeholders, such as DOE Building Technologies Office BTO's Amir Roth and Gina Lynch, the Indian Deputy Consulate General, CBERD research staff across all U.S. partner institutions including Oak Ridge National Lab, Carnegie Mellon University, and University of California, Berkeley. We also hosted visiting CBERD India PIs, from CEPT University (Ahmedabad), International Institute of Technology (Hyderabad), IUSSTF BHAVAN fellows, and U.S. industry partners and collaborators Phillips, Architectural Applications, American Society of Healthcare Engineers, Daikin, Mazzetti, Natural Resources Defense Council (NRDC) and Center for Strategic and International Studies. U.S.-India research and industry partners co-presented ongoing CBERD work, identified pathways for tighter integration with demonstrations and markets, and ideas for expansion into potential future work. This engagement at the annual stakeholders forum was valuable to keep the CBERD activities sharply focused on ground realities and opportunities in both countries. (*Figures AN2 and AN3*)

iii. *CBERD quarterly webinar series*: The CBERD U.S. task leads presented quarterly webinars to the corresponding DOE Building Technologies Office's Technology Managers (TMs). Feedback from the TMs has been valuable and addressed through further detailing and execution of ongoing activities.

Figure AN1: CBERD Joint Funder Forum conducted at LBNL in FY 2015. Pictured are DOE's Karma Sawyer and Govt. of India's Dr. Sanjay Bajpai, IUSSTF's Dr. Rajeev Sharma and Vandana Sharma with a few of the U.S. and India CBERD team members.

Figure AN2: FY17 CBERD U.S. Stakeholder Forum conducted at LBNL in August 2017. DOE Program Managers Amir Roth and Gina Lynch with CBERD research and industry collaborators from India and the U.S..

Figure AN3: Interactive discussions between industry and research partners on ongoing and future CBERD R&D and deployment-facing activities. CBERD PIs Dr. N.K. Bansal (India) and Dr. Ashok Gadgil (U.S.) jointly present the program to the Stakeholders at the FY 17 CBERD U.S. Stakeholder Forum conducted at LBNL in August 2017.

2) Dissemination and outreach

CBERD launched a public website that provides a public platform for the dissemination of CBERD products. Please see www.cberd.org.

Researchers from CBERD were invited to several meetings and conferences. CBERD also hosted several program-wide dissemination events and workshops. Selected outreach events in 2016-17 are described below: (starting from most recent)

i. FY 18: Greenbuild, Mumbai, Nov 2017, invited by U.S. Green Building Council (USGBC)

U.S. CBERD Program Director Reshma Singh led a workshop session about the CBERD program, outcomes, and best practices for Indian high-performance buildings. The event was the first *Greenbuild India* held in Mumbai, which hosted acclaimed national and international dignitaries from across industries and the government. Greenbuild is hosted by USGBC, the developer of the LEED and WELL certifications, and a key green building rating system in India. During this trip Singh also led a day-long CBERD dissemination workshop for undergraduate and graduate students of architecture at the Indian Institute of Technology (IIT) Roorkee (*Figure AN4*).

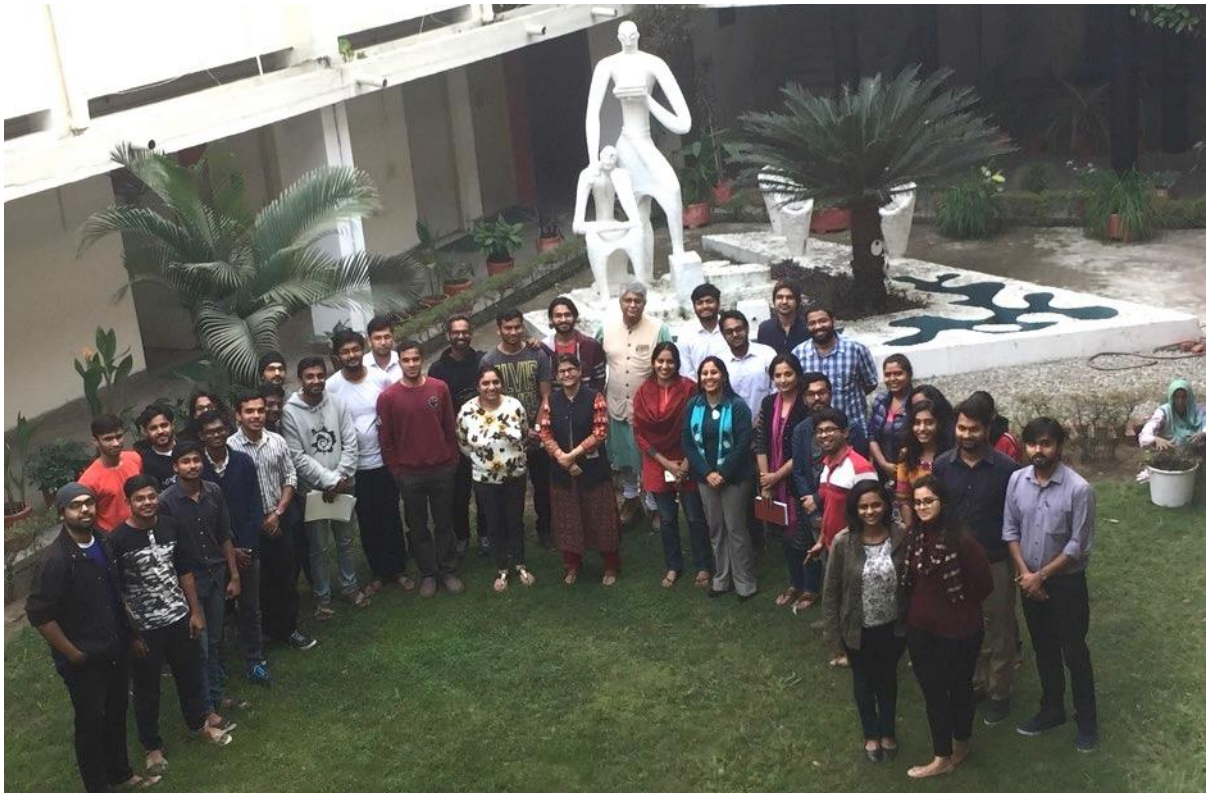

Figure AN4: CBERD's Reshma Singh with students and faculty after the CBERD presentations at Indian Institute of Technology (IIT) Roorkee.

ii. *Visit to India partner institutions and industry campuses, May 2017:*

U.S. team members PI Ashok Gadgil, co-PI Mary Ann Piette, Program Director Reshma Singh, and R&D lead Christian Kohler participated in an extensive two-week long trip around Indian cities in May 2017, and co-presented along with the Indian team at the CBERD Stakeholder Forum. Dr. Rajeev Thayal, head of sponsor Indo-US Science and Technology Forum (IUSSTF) opened the meeting by mentioning that CBERD was a "most successful PACE program, with impeccable coordination between India and U.S. teams." The team also conducted work sessions at CBERD partner institutions and site visits and outreach in five cities: Mumbai, Delhi, Hyderabad, Ahmedabad, and Gurugram. (*Figure AN5*).

iii. Interactive Roundtable on Smart and Energy efficient Buildings in India: Challenges and Solutions, New Delhi Roundtable, May 2017, co-hosted GREHA, India.

CBERD organized a roundtable discussion and working group on R&D solutions for India's buildings challenges with a select group of stakeholders, including practitioners and industry members from verticals such as building energy monitoring (Zenatix), HVAC (Daikin, Bluestar), commercial real estate (MetroValley India, Tishman Speyer), bilateral R&D programs (BEEP), and A&E firms (Incubis, AB Lall Associates, Kalpakrit, Kukreja Associates). The attendees showed great interest in the deployable CBERD tools and technologies. CBERD's Mary Ann Piette, Reshma Singh and Christian Kohler facilitated the working group – that developed a set of future R&D activities based on market-oriented challenges. *(Figure AN5).*

Figure AN5: (Left, top) At Infosys Hyderabad campus with CBERD Indian team members. (Right, top) With a CBERD prototype developed by CBERD partner IIT Bombay.

(Left, bottom) CBERD U.S co-PIs Mary Ann Piette and Dr. Ashok Gadgil meeting with Dr. Sanjay Bajpai (DST) and Dr. Renu Swarup (DBT) in New Delhi. (Right, bottom) Interactive Roundtable with select stakeholders in New Delhi

Figure AN6: Strategic Review of U.S. - India Energy Cooperation co-hosted by CSIS and CBERD. The discussion was rich with participation from the representatives of industry, research, civil society and philanthropy, pictured above with Indian Consul General Ambassador Venkatesan Ashok.

iv. *U.S.-India Strategic Review of US-India Energy Cooperation, Berkeley Sep 2017* (*Figure AN6*). CBERD co-hosted this half-day event with the Center for Strategic and International Studies, a think tank from Washington DC. The event brought together 25 representatives from government, civil society, research institutions, philanthropy and private sector to disseminate information about the bilateral CBERD program, and discuss ways what we may build and leverage energy partnerships between U.S. and India.

v. *CleanTech Week, February 2017, invited by Clean Tech Open*. (*Figure AN7*). CBERD was invited to participate in CleanTech Open's global annual event in San Francisco, The CleanTech Week. CleanTech Open is the world's largest clean tech network and accelerator program. The CBERD teams, including visiting Indian CBERD co-PI Vishal Garg and IIIT-H staff researcher Sam Godithi presented the CBERD program. There was robust interest and follow-up ideas generated, especially from visiting Indian govt. officials, Indian cleantech entrepreneurial teams and the cleantech ecosystem.

Figure AN7: (Left) CBERD at Clean Tech Week, San Francisco Feb 2017. Pictured are: Rajan Kasetty (Los Angeles Cleantech Incubator, LACI), Surendra Tripathi (Govt. of India), Reshma Singh (CBERD), Deepak Gadhia (RenewTech), Sibabrata Das (Atomberg technologies).

(Right) Dr. Ashok Gadgil and Mary Ann Piette in discussion with Dr. Renu Swarup from Govt. of India at the Clean Energy Ministerial Event in San Francisco, June 2016

vi. *Clean Energy Ministerial, 2016* (*Figure AN7).* CBERD was invited to present as part of the Partnership

to Accelerate Clean Energy (PACE) program, where the team had dynamic interactions with high-level international policy and technology experts.

vii. *US India Energy Dialogue, jointly hosted by US DOE and Government of India, September 2015* (*Figure AN8*). The U.S.-India Energy Dialogue is a long and successful strategic partnership in the energy sector, with cooperation between the two countries. CBERD presented its research and development outcomes to the DOE- GOI working groups, led by US Secretary of Energy and Indian Minister of Power, Coal, and New and Renewable Energy.

viii. U.S. and International Conferences, Workshops, and Publications: Apart from these key events detailed above, the CBERD has presented and published at several prestigious international technical conferences and workshops leading to significant outreach benefit to a variety of stakeholders including researchers and academicians, builders, developers, architects, engineering practitioners, vendor and product industry folks, facility managers and operators. Conferences include *ACEEE Summer Study on Energy Efficiency in Buildings, ASHRAE Conferences, USGBC's Greenbuild India* , *Passive Low Energy Architecture (PLEA) Conference*, *Windsor Conference: Making Comfort Relevant, International Conference on Countermeasures to Urban Heat Island, International Building Performance Simulation* Conference (IBPSA). Journals include *ASHRAE Journal: Science and Technology for the Built Environment, Architectural Science Review, Building and Environment, Energy, Energy and Buildings, Energy Policy, Journal of Building Engineering, Journal for Facilities Management, Renewable Energy and others.*

Figure AN8: CBERD at U.S. Energy Dialogue hosted by U.S. Department of Energy with Government of India. (Top) PACE program PIs, including CBERD PIs Rajan Rawal and Dr. Ashok Gadgil and with the former U.S. Secretary of Energy Ernest Moniz and India Minister of Power, Coal, and New and Renewable Energy Piyush Goyal, (Below): Dr. Phylis Yoshida, former Deputy Assistant Secretary U.S. Department of Energy (DOE), Jyoti Arora, Joint Secretary Ministry of Power India, and Reshma Singh (CBERD).