LBNL-6991E

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Integrated Design for High Performance Buildings

Tianzhen Hong[1], Cheng Li[1], Richard Diamond[1]

Da Yan[2], Qi Zhang[2], Xin Zhou[2], Siyue Guo[2], Kaiyu Sun[2], Jingyi Wang[2]

[1]Environmental Energy Technologies Division, LBNL
[2]Department of Building Science and Technology, Tsinghua University, China

July 2014

Please cite this report as follows:
Hong, T., Li, C., Diamond, R., Yan, D. et al. Integrated Design for High Performance Buildings. Lawrence Berkeley National Laboratory, July 2014. LBNL-6991E.

Acknowledgement

This report is a summary of research work conducted by LBNL, and Tsinghua University, China in 2013 under the 5-year research program of the U.S.-China Clean Energy Research Center for Building Energy Efficiency (CERC-BEE).

The LBNL's research was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Tsinghua's research was supported by the Ministry of Housing and Urban-Rural Development and the Ministry of Science and Technology of China, under Contract No. 2010DFA72740-02.

Special thanks to the U.S. and China CERC-BEE management, our industry partners, the Industry Advisory Board, and the Technical Advisory Committee for the strong support on the project.

Table of Contents

1. Introduction

United States and China are the world's top two economics. Together they consumed one-third of the world's primary energy. This creates an unprecedented opportunity and challenge for governments, researchers and industries to join together to address current energy and global climate change issues. Such joint collaborations can have a huge global impact and lead to the creation of new jobs in energy technologies and services.

1.1 CERC – The U.S.-China Clean Energy Research Center

The U.S. – China Clean Energy Research Center Building Energy Efficiency Consortium (CERC-BEE, http://cercbee.lbl.gov/) was established in 2009, formalizing a working relationship between the U.S. Department of Energy and Chinese Ministry of Science and Technology. Historically, under the Science and Technology Cooperation Agreement of 1979 and later reaffirmed in the 1991 amendment, the U.S. and China have cooperated together in a diverse range of scientific fields, including basic research in physics, chemistry, earth and atmospheric sciences, environmental management and a variety of energy related engineering fields. The CERC program builds upon this history, cementing an U.S.-China scientific and technological collaboration.

"The key idea of CERC is to address our joint challenges better, faster and cheaper by finding productive ways to work together and learn from each other." - US CERC Director Robert Marlay, at Stanford IP Conference, Feb. 26, 2013.

CERC facilitates joint R&D for the advancement and implementation of clean energy technologies, bringing together teams of scientists and engineers from the United States and China. This flagship initiative, funded in equal parts, supports collaborative participation from universities, research institutions and industry. CERC operates under the umbrella that U.S. funds support U.S. researchers and that Chinese funds support Chinese researchers.

Currently within CERC program, more than a dozen high visibility R&D projects focused on building energy efficiency (BEE) are being conducted. Research achievements have improved energy efficiency in new and existing buildings by reducing greenhouse gas emissions, increasing indoor comfort, and reducing stress on the electric grid. Moreover, the technologies developed and insights gained through CERC are being adopted and implemented worldwide. CERC-BEE R&D teams are comprised of U.S. national laboratories, U.S. and Chinese universities, research institutes, and industry partners. Currently, Lawrence Berkeley National Laboratory leads the U.S. participation in the program.

CERC has three primary research themes: (1) CERC Building Energy Efficiency (CERC-BEE) focused on the research and development of building technologies, tools, and policy to improve the design and operation of buildings for reducing energy use, (2) CERC Clean Vehicles focused on research and development of new technologies for electric vehicles and alternative fuels to reduce air pollution and carbon emissions from the transportation sector, and (3) CERC Advanced Coal Technology focused on research and development of technologies to improve efficiency and reduce air emissions of coal power plants and new technologies for carbon capture and storage.

The CERC-BEE Consortium conducts R&D on building energy efficiency technologies and practices, in the United States and China. CERC-BEE's vision is "To build a foundation of knowledge, technologies, tools, human capabilities, and relationships that position the United States and China for a future with very low energy buildings resulting in very low CO_2 emissions."

BEE develops innovative technologies and strategies for use in new and existing buildings, to improve efficiency, save energy, reduce greenhouse gas emissions, increase indoor comfort, and reduce the stress on the electric grid. As new construction proceeds around the globe, collaborative BEE research efforts are helping to lock in tremendous potential energy savings for the long term, via more efficient and low carbon infrastructure. Figure 1 shows the six research areas and projects within the CERC-BEE research framework.

Figure 1 CERC-BEE Research Areas and Projects (http://cercbee.lbl.gov/research-commercialization)

1.2 Research Background

In 2010, buildings in the U.S. and China consumed about 40% and 25% of the primary energy, respectively. Worldwide, the building sector is the largest contributor to the greenhouse gas emissions. Having a better understanding and improving the energy performance of buildings is a critical step towards sustainable development and the mitigation of global climate change.

Buildings exhibit varied measured energy use resulting in diverse performance. Figure 2 shows site energy use intensities (EUIs) of 100 LEED-NC certified buildings, from the 2008 New Building Institute Study, *Energy Performance of LEED for New Construction Buildings*. At each LEED certification level (certified, silver, gold-platinum), energy use of green buildings varied by a factor of up to 4, even excluding outliners.

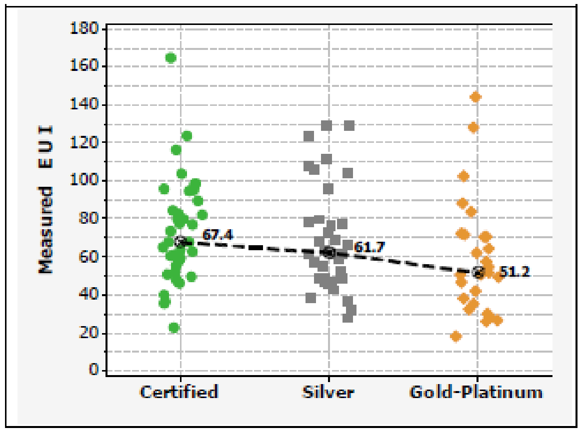


Figure 2 Measured Energy Use Intensities (kBtu/ft²) of LEED-NC Certified Buildings (courtesy New Building Institute)

Measurements conducted by Tsinghua University, China indicated large differences in the energy use of campus buildings located in similar climates, in both the U.S. and China (Figure 3). In fact, the buildings in the US were designed to meet more stringent energy codes than those in China, making the extreme differences surprising.

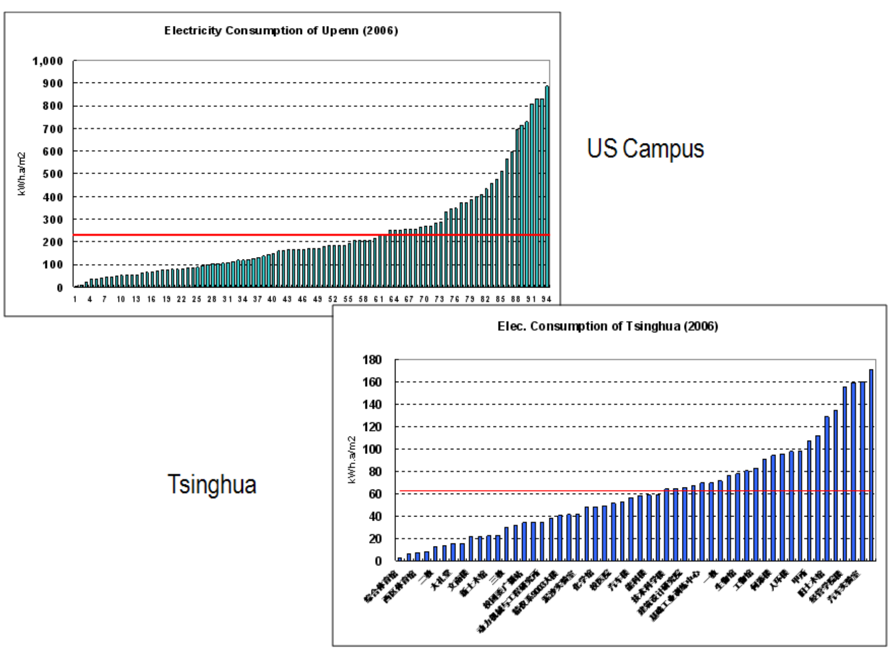


Figure 3 Measured Electricity Use Intensities of Campus Buildings in the U.S. and China (courtesy Tsinghua University, China)

As identified in the IEA ECBCS Annex 53 *Total energy use in buildings: Analysis and Evaluation Methods*, there are six driving factors that determine the energy performance of buildings: (1) climate, (2) building envelope, (3) building equipment (energy and water services systems), (4) operation and maintenance, (5) occupant behavior, and (6) indoor environmental conditions. Unlike the conventional linear design process for traditional buildings, the design process for HPBs calls for a multidisciplinary approach among the architecture, engineering, construction, commissioning and post occupancy operation groups, to guarantee the delivery of expected building performance. This interactive process, termed the "Integrated Design Process or IDP" has been widely adopted as the preferred method in the design and operation of HPBs. Understanding how these six drivers affect energy performance and which drivers have a more significant role under certain conditions, can provide the needed insight into answering why large variations in actual and simulated building energy use, occurs. The insight into narrowing this discrepancy also plays a crucial role in improving the design and operation of buildings, for lower energy use and lower carbon emissions.

2. Research Objectives and Technical Tasks

2.1 Research Objectives

This research project aimed to gain a better understanding of high performance buildings (HPBs) and to promote the implementation of integrated design. Specifically, the research team strived to achieve the following research objectives:

(1) Capture the global status quo of HPBs, with respect to energy consumption, influencing factors and design strategies; Analyze the influencing factors of energy use in HPBs.
(2) Facilitate and exchange performance information throughout the building life cycle by reviewing data models and proposing a performance-based data schema suitable for simulated and actual performance of HPBs.
(3) Develop a simulation framework to evaluate technology performance considering the uncertainties of the main influencing factors in building design, operation and maintenance.
(4) Conduct a design charrette and apply the concept of integrated design into the practical design procedure in order to test the suitability in the real design environment.

2.2 Technical Tasks

This project included four technical tasks:

(1) Case studies of HPBs

The research team selected and studied HPBs in the U.S., China, Europe and Asia Pacific regions. The focus was to identify key strategies of integrated design, operation and maintenance that would help achieve the energy target of the selected buildings. Major contents of the study include:

- Benchmark the actual energy performance of the HPBs and discuss findings with the building owners, design teams, building operators and facility managers.
- Research the correlation between the energy performance and the influencing factors, including: climate, building size, technologies, occupant behavior, and building operation and maintenance.
- Identify and analyze the critical gaps and challenges in the integrated design process, and propose potential solutions.
- Compile a report on the status quo of the HPBs with guidance to achieve integrated design and operations.

(2) Methods and tools to better exchange and share information across multidisciplinary fields during the building life cycle

In light of the extensive applications of building information modeling (BIM), there is motivation to expand the information system to include the whole building life cycle. The primary work of this task was to review the existing data models and propose a new schema to host the performance information generated by simulation. The research team reviewed related studies to gain a clearer picture of the current status of BIMs. One primary focus was to study methods and tools to enhance the interoperability of the performance data (simulated or measured) within the context of integrated design. Valuable references included the COMNET compliance report schema, the BEDES and the EnergyPlus result schema for LEED in XML.

(3) A protocol to evaluate energy conservation measures

High performance buildings rely on passive energy service systems and technologies that are more climate responsive and human oriented, such as: (i) free cooling (air-side or water side), (ii) Variable Refrigerant Flow, (iii) Ground Source Heat Pump (GSHP), (iv) Solar Domestic Hot Water (DHW), (v) daylighting, (vi) hybrid ventilation, (vii) adaptive comfort and, (viii) local conditioning by personal devices (fan, heater, etc.). Adaptability and the energy savings potential of these measures requires robustness. A protocol was proposed to evaluate the energy conservation measures (ECMs) based on climate characteristics (multi-decade weather data), different practices of operation and maintenance, and various types of occupant behavior.

(4) "Design charrette" for the demonstration buildings in China

At the early design stage, energy features have the lowest cost of implementation and the most potential impact. Within a multidisciplinary design circumstance, a "design charrette" involving all the related stakeholders can help clarify many crucial strategies needed to maximize the potential energy savings. Therefore, a "design charrette," organized at the design phase of the new demonstration buildings, will enable the owner, design team (architects and engineers), and contractor to present, discuss, and coordinate energy design features as part of the integrated design process. Moreover, a list of energy features will be identified and discussed. The in-depth discussions will hopefully generate a manual with technical advice and strategies for each building.

3. Research Findings

This section summarizes the key research findings. Detailed descriptions of the research work, technical approaches, and results were included in the Appendices.

3.1 Summary

- **Research of HPBs and integrated design**

The portfolio analysis and case studies of 51 selected HPBs revealed that nearly half of the buildings fell short of the ASHRAE Standard 90.1-2004 energy target. Furthermore, the actual energy use of the certified high performance office buildings varied by a factor of as much as 11. Thus, looking at the average performance marks, a large number of HPBs fall short of their expected energy savings potential. The results indicate that the certification of a HPB does not necessarily correspond with the actual energy performance. This raises questions about the current practice of using simulated rather than the actual performance matrix, as the basis for certification. The fact that no specific region demonstrated exceptional or consistent energy performance, suggests that achieving the actual energy savings of HPBs, is a global challenge.

Our analysis of the influence of climate, building size, efficient technologies, occupant behavior, and O&M in HPBs, indicated that no single factor dictated the building's actual energy performance. In fact, increasing the number of efficient technologies did not necessarily improve energy performance. However, results suggest occupant behavior and O&M could have a significant positive role in realizing wanted building energy savings.

Because no single factor determined building energy performance, strategies for saving energy should take into account all elements that affect actual energy use. For example, (1) the climate may affect cooling and heating loads, the use of daylighting, and design and operation of natural ventilation, (2) the arrangement of the building's functions and the behavior of the occupants influences the building's operational schedule and thus the energy use, (3) the presence of high efficiency equipment and the employment of good O&M practices will directly reduce energy use. An integrated design approach that takes into account all of the above factors, offers the greatest potential for producing a building with the expected actual energy performance. The findings from this study should help architects, engineers, operators, and policy makers to improve the design and operation of HPBs, as well as the degree to which HPB rating systems accurately reflect actual building performance.

The CERC-BEE Chinese research team investigated high performance technologies in residential buildings. Currently, China has started to adopt high performance technologies in some new residential projects. An evaluation of the energy consumption of a residential prototype using a high performance envelope, was conducted. Different climates and resident habits were considered in a series of comparison studies. The results revealed that the high performance envelope, which was highly rated in Europe, did not perform as efficiently as expected in all regions in China. The envelope was effective in Northern China, where the energy consumption for space heating made up a significant portion of the energy profile. Oppositely, the application of the high-tech envelope in Southern China provided a negligible contribution. Concurrently, the Chinese research team investigated some key parameters of the building envelope and the associated influence on the energy consumption for space heating in Shanghai, China. The results indicated that the improved envelope saved energy used for heating, but that performance relied heavily on the habits of window opening and occupant operation pattern of the heating system.

Aside from the envelope, there is a tendency to employ high efficiency centralized air conditioning systems in apartment buildings in China. The Chinese research team conducted three projects investigating AC efficiency and revealed that the actual energy use intensity was 2 to 5 times more than the peer buildings using split systems. Detailed analysis revealed that the load features of non-synchronized cooling demand and low load rate on the user side, consumed more energy than expected. These result proved once again that high-efficiency systems must be matched with occupants' use patterns, to maximize performance.

Another study conducted by the Chinese team was to analyze and quantify the discrepancies in the cooling energy consumption which existed between two high-grade office buildings in Beijing and Hong Kong. The cooing energy consumption of the latter was more than four times that of the former. In order to discern the causes of this huge energy gap, the following steps were executed: (1) a field investigation of the envelopes, internal loads and operating schedules, etc., (2) the development of energy models of the two office buildings using DeST (Designer's Simulation Toolkit) and based on survey results, (3) the calibration and validation of energy models, comparing simulated and measured cooling energy consumption and, (4) analysis to discern energy consumption discrepancies and potential energy savings. The results suggest the following main factors drive the discrepancies in cooling energy consumption: (1) window performance, (2) operating schedules, (3) thermostat settings, and (4) internal loads. This study used a simulation-based approach to understand the impacts of the influencing factors on energy consumption of office buildings. This technique can be valuable in designing new energy efficient buildings as well as guiding efficiency retrofit projects.

- **A protocol to evaluate energy conservation measures**

  Current simulation-based evaluation of building technologies assumes a single set of building data. This method leads to technologies which do not achieve the actual energy savings. The reason for the poor energy performance is due to the lack of data and methods needed to consider the complexity and uncertainty in the evaluation process. To address this issue, a new simulation framework was formulated, to evaluate the energy performance of technologies and to consider a more realistic variation of the driving factors. The driving factors of interest included building operation and maintenance (O&M), weather, and occupant behavior. The framework defined a matrix of scenarios in which technologies were evaluated creating a range of expected performance. This methodology can provide the information necessary to conduct risk assessment during energy efficiency decision making. The framework included: (1) O&M categorized into good, average, and poor practices, (2) weather data categorized into TMY and AMY and, (3) occupant behavior categorized into three styles: energy savings, norm, and energy wasteful. The framework compiles data for new and existing commercial and residential buildings in the U.S.

  Indoor heat gains, from occupants, lighting and office equipment, are important components of the air-conditioning cooling load in office buildings. An investigation revealed that occupant and electrical power density are different in zones with the same function, meaning the heat gain intensity from occupants and electric equipment/appliances varies randomly. Therefore, it is difficult to discern the indoor heat gain density in the design stage. Designers often over-estimate indoor heat gains when calculating peak cooling loads and sizing air-conditioning equipment capacity. This often leads to the selection of oversized chillers and pumps which waste energy during operation.

  The research team proposed a model describing the spatial distribution of the internal heat gains and introduced a "parameter of distribution." The proposed model and associated parameter draws upon the on-site investigation. Using this model, designers can calculate chiller capacity that is much closer to the actual demand.

- **The new data schema for building performance information in integrated design process**

  We reviewed the integrated design process from the perspective of the building life cycle and listed the critical information at every stage. From this review, a comprehensive, efficient and standardized information exchange, especially for the exchange of building performance data, appeared to be vital for integrated design, especially in multidisciplinary circumstances. Part of this review came from the EnergyPlus Results Schema project funded by the U.S. DOE and included the contributions of Rob Hitchcock and Kevin Settlemyre.

The research team pointed out four vital features of the building performance schema, needed for a seamless information exchange and integrated design process. These four features are as follows: (1) engine neutral & interoperability, (2) linked to input (building and system characteristics), (3) extensibility and, (4) synchronization with mainstream codes.

Additionally, a review of the data schema in the prominent software or programs in the fields of simulation, code compliance and integrated design, was conducted. Our review indicated that all the present data schemas fell short of the required data schema, with interoperability and seamless information exchange being the biggest challenges.

Seeing this circumstance, we proposed a new data schema for the information exchange in building IDP. The new schema hosts the data in a hierarchical structure, with multiple major categories covering the data fields as much as possible. By applying the popular format of XML, the new schema guarantees the delivery of interoperability and seamless integration.

- **Design charrette**

The integrated design process (IDP) aims to coordinate the design features across multiple disciplines, in order to achieve the maximum performance. A Design charrette facilitates the IDP considering the interactions and integration of various energy systems during operation and maintenance with in the building. This charrette was constructed to support the integrated design and commissioning of the five demonstration buildings in China, by engaging building owners, the design team, developers, and other stakeholders.

The one-day charrette was hold in Wuhan on October 29, 2013 before the two-day CERC-BEE conference. Thirty-eight participants, including researchers and management staff from both countries and the four developer teams, were grouped into 6 tables with one developer team per table. The charrette kicked off with Richard Diamond's greetings and Richard Karney's opening speech, followed by the goals of the charrette, and presentations on the concepts, processes, and tools of integrated design and commissioning. Discussions were conducted by groups focusing on 3 to 5 design goals, strategies, technologies, and commissioning of individual demonstration buildings. The charrette ended with Richard Diamond's conclusions and a summary of action items.

3.2 Research of high performance buildings and integrated design

The research team selected 51 HPBs throughout the world to conducted analysis on the energy use intensities (EUIs) and other pertinent driving factors, such as technologies, climate and behavior patterns. The four criteria used for the building selection included:

(1) Newly constructed and occupied office buildings,
(2) Buildings located in the U.S., Europe, China, or the Asia - Pacific region,

(3) Buildings with at least one complete year of site energy use records and information on the total floor area (to enable calculation of actual EUI),
(4) High-level of performance certification, such as LEED Platinum or Gold, CASBEE "S," or China Three-Star.

Figure 4 shows the general locations of the fifty-one buildings selected.

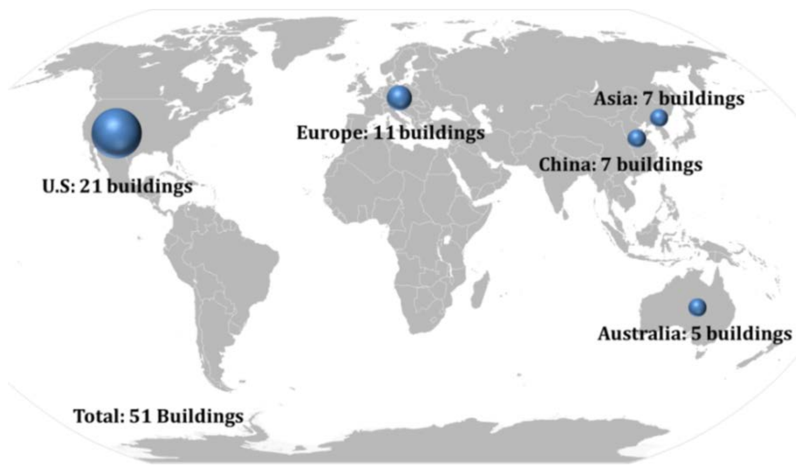


Figure 4. Distribution of the high-performance buildings selected for this study

Figure 5 shows the EUIs of all of the selected buildings. The color coded bars are ordered from minimum to maximum and vary from 30 to 330 kWh/m^2, a factor of as much as 11. Nearly half of the instances do not reach the ASHRAE 90.1 2004 standard and the compliance rate drops to 30% when compared with the ASHRAE 90.1 2010 standard. The global status of the inconsistencies in HPBs' energy performance poses a real challenge for building certification programs. Currently, "high performance" does not necessarily lead to actual low energy use. Therefore, improvement in the design and operation of HPBs becomes imperative.

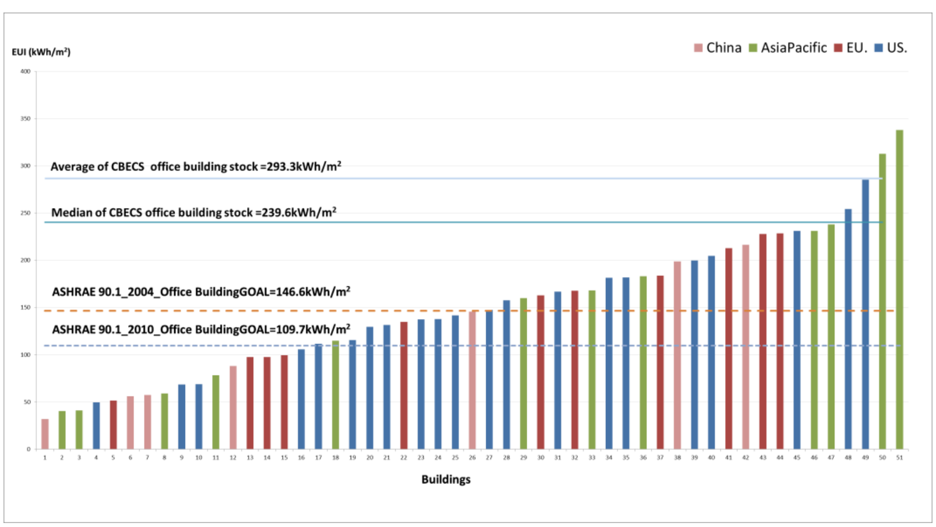
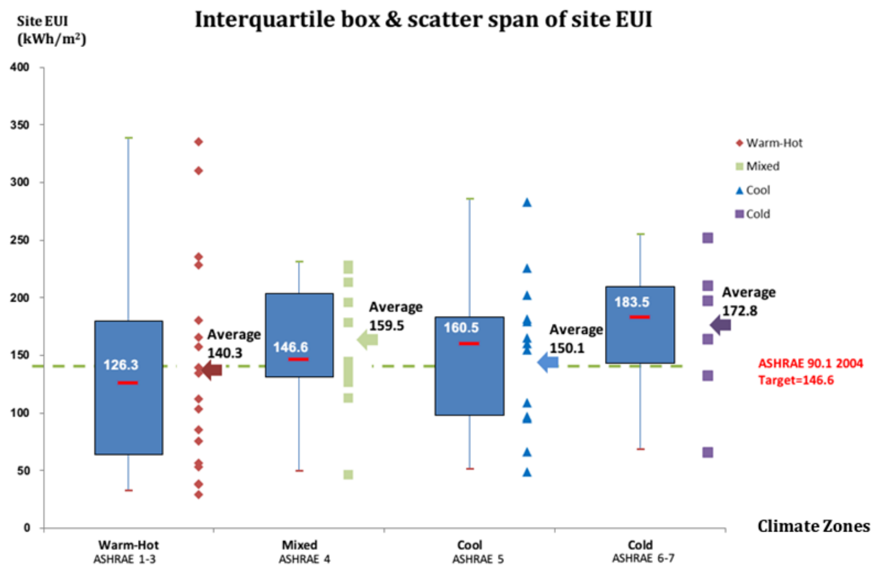


Figure 5. Distribution of site EUIs of the 51 office buildings, compared to benchmarks

Analyses were conducted to identify the correlations between EUI and climate, building size, technologies, human behavior, as well as maintenance. Figure 6 shows the distribution of EUIs in four climate zones. The EUIs were widely scattered in all climate zones, indicating that although climate impacts energy consumption, it is not the primary decisive factor.



	Warm-Hot	Mixed	Cool	Cold
Minimum of Floor area (10^3 m^2)	1.9	3.9	2.6	3.2
Maximum of Floor area (10^3 m^2)	106.0	39.7	82.4	30.0

Figure 6. Distribution of site EUIs of the 51 buildings among four climate zones

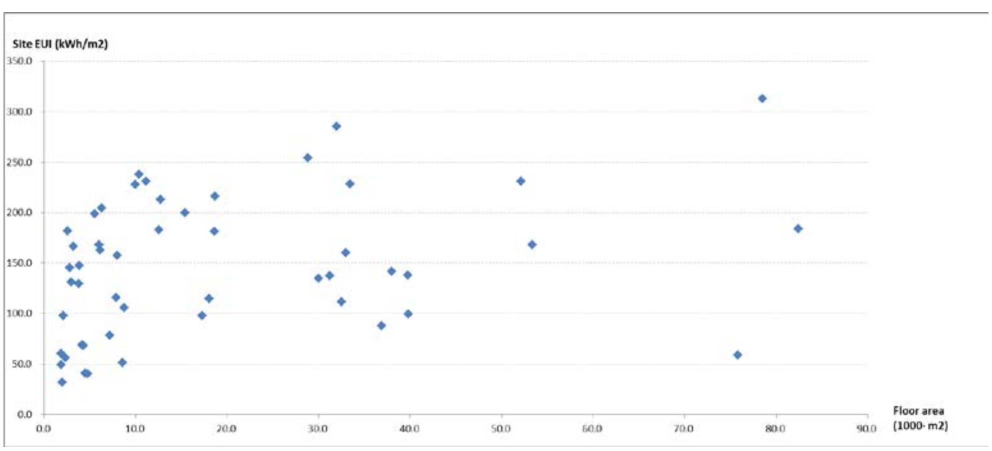


Figure 7. Correlation between floor area and EUI

Figure 7 shows the correlation between the building size and EUI. The results demonstrated a slight trend towards lower energy use in smaller buildings, however the correlation was not absolute. Some small HPBs exhibited high energy use, while some large HPBs exhibited low energy use. This implies that the buildings size and function may implicitly affect the energy use in buildings, but do not individually dictate overall performance.

Table 1 shows the pertinent energy technologies from every building, with the corresponding EUI, ordered from minimum to maximum. Statistics of the application ratio in relation to building size are listed in Table 2. Daylighting, envelope improvements, and efficient HVAC equipment were the most commonly considered measures. Besides these three technologies, high-efficiency lighting, lighting controls, natural ventilation and renewable energy technologies were extensively applied in practice. The scatter in the data of the application status, highlighted in Table 1, suggests that no single set of efficient technologies correlated directly to low EUIs.

Table 1. Building technologies in relation to site EUI

	Lighting				HVAC System						Renewable Energy		
EUI (kWh/m2)	Maximum utilization of daylighting	High-efficiency lighting system (low power density)	Lighting control (occupancy or dimming controlling)	Envelope improvement (insulation/shading/ glazing improvement)	Daytime natural ventilation (system control)	Night purge (thermal mass)	Chilled beam	Under-floor air distribution	High-effeciency & energy-saving equipments (chiller/fans/pump / air economizer / heat recovery)	Ground-source heat pump	PV	Solar thermal	Wind turbine
32.1	Y			Y	Y		Y				Y	Y	Y
40.4				Y	Y				Y		Y		Y
41.0	Y		Y	Y	Y						Y		
49.5	Y	Y	Y	Y					Y	Y			
51.4	Y			Y		Y			Y	Y	Y	Y	
56.0	Y	Y		Y	Y				Y			Y	
59.0	Y	Y	Y	Y	Y				Y				Y
60.2	Y	Y			Y		Y				Y	Y	Y
68.4	Y		Y	Y	Y	Y	Y		Y	Y	Y	Y	Y
68.7	Y	Y	Y	Y	Y				Y	Y	Y		
78.5	Y						Y						
88.0	Y				Y				Y			Y	
97.7					Y				Y	Y	Y		
97.7	Y				Y	Y			Y	Y	Y		
99.7						Y			Y	Y	Y	Y	
105.9	Y			Y				Y					
111.6	Y			Y	Y	Y		Y	Y		Y		
115.1	Y			Y			Y		Y				
115.7	Y	Y		Y				Y	Y				
129.6	Y		Y		Y								
131.5	Y		Y	Y						Y	Y	Y	
134.9	Y			Y	Y				Y				
137.5		Y	Y	Y					Y		Y		
137.9				Y	Y	Y	Y	Y			Y	Y	Y
141.9		Y	Y					Y		Y			
145.6	Y	Y	Y	Y	Y				Y		Y	Y	
147.6									Y		Y	Y	
157.7													
160.2	Y	Y					Y						
163.0	Y					Y	Y		Y				
166.8	Y		Y	Y					Y				
168.0	Y		Y		Y	Y			Y				
168.1	Y		Y	Y	Y				Y	Y	Y	Y	
181.6	Y		Y	Y					Y				
181.9		Y	Y										
183.2	Y	Y	Y	Y		Y		Y	Y		Y	Y	
184.0	Y			Y	Y			Y	Y			Y	
199.0		Y		Y					Y				
199.9	Y		Y					Y		Y			
204.9													
213.0				Y	Y		Y		Y				
216.5	Y		Y	Y	Y		Y		Y				
228.0	Y		Y				Y						
228.6	Y			Y							Y		
231.1	Y			Y	Y	Y			Y				
231.1	Y								Y		Y		
238.1	Y	Y		Y	Y		Y		Y				
254.4	Y	Y							Y	Y	Y	Y	
285.7	Y			Y	Y	Y					Y		
313.1	Y			Y	Y								
338.0	Y			Y	Y			Y	Y		Y		
Ratio	76.5%	29.4%	37.3%	62.7%	51.0%	21.6%	23.5%	17.6%	64.7%	23.5%	45.1%	29.4%	11.8%

Table 2. Technology application ratio in relation to building size

Building Size (m2)	Maximum utilization of daylighting	High-efficiency lighting system (low power density)	Lighting control (occupancy or dimming controlling)	Envelope improvement (Insulation/shading/ glazing improvement)	Daytime natural ventilation (system control)	Night Purge (thermal mass)	Chilled beam	Under-floor Air distribution	High-effeciency & energy-saving equipments (chiller/fans/pump /air economizer /heat recovery)	Ground-source heat pump	PV	Solar thermal	Wind turbine
＜5,000	73.3%	40.0%	60.0%	66.7%	66.7%	6.7%	20.0%	0.0%	60.0%	33.3%	66.7%	46.7%	26.7%
5,000 - 10,000	66.7%	22.2%	11.1%	44.4%	11.1%	33.3%	22.2%	22.2%	55.6%	11.1%	11.1%	11.1%	0.0%
10,000 - 20,000	90.0%	20.0%	50.0%	60.0%	40.0%	20.0%	50.0%	20.0%	80.0%	20.0%	30.0%	10.0%	0.0%
20,000 - 50,000	63.6%	36.4%	18.2%	54.5%	45.5%	36.4%	18.2%	27.3%	54.5%	27.3%	63.6%	36.4%	9.1%
＞50,000	100.0%	16.7%	33.3%	100.0%	100.0%	16.7%	0.0%	33.3%	83.3%	16.7%	33.3%	33.3%	16.7%

Given the above analysis, the climate, size of the building and the application of specific technologies, failed to exclusively control the energy performance of HPBs. Therefore, additional potential drivers, such as human behavior and building operation and maintenance, can have a large impact on HPB performance. Therefore, we investigated the influence of occupant behavior as well as operation and maintenance on energy performance in two detailed case studies.

The IBR headquarters, a medium size office building in Shenzhen, Southern China, took into account occupant behavior and local habits, integrated these drivers actively into the design. The people in Shenzhen place a high value on fresh air and have a relatively broader indoor thermal threshold, relative to the typical thermal comfort range. Therefore, the designers left all control of the IBR building's windows to the discretion of occupants.

In addition, high-inertia thermal mass and solar shading systems were designed to shield the building from solar heat and to capture the night cooling. The floor plan allowed for adequate natural ventilation during regular office hours. The space cooling included a hybrid system consisting mechanical air conditioning (AC) and natural ventilation (NV), with operation sensitive to season variations. From April 22 to October 21, the AC only operated from 8 am to 6 pm on weekdays and when the forecast daily maximum temperature was higher than 27℃. The remaining portion of the year, occupants relied solely on NV, with the only AC use going toward the information technology portion of the building and for some special functioning rooms. During the period from November, 2011 to October, 2012, the mechanical cooling operated for a total of 108 days, whereas in the typical office buildings in Shenzhen during the same period, mechanical cooling operated for 140 days. Quantitatively, the annual site EUI of the AC in the IBR building was 15.5 kWh/m^2 compared to 21.9 kWh/m^2 in a peer building, indicating that the use of NV in the IBR building helped reduce space cooling energy use significantly.

Another case study, used benchmarking to compare a CalSTRS building (The Headquarters of the California State Teachers' Retirement System) with the average California commercial building performance, taken from the CEUS database. The CalSTRS building, an 18-story, Class A office building in Sacramento, California, with a high-quality integrated design. Highlights of the energy-saving technologies and design strategies included: maximum daylighting, dimmable artificial lighting control system, UFAD with occupant-adjustable diffusers, water-source heat pump for cooling and heating of the public areas, and two chillers with variable-speed compressors for the office tower. Notably, the building does not have an exorbitant amount of technologies deployed, nor does the building's configuration stand out from that of other buildings. However, the highly integrated design, which was partly a resultant of being owner occupied, set the CalSTRS building apart from other buildings and helped to account for the building's stellar energy performance.

Coordinated by a sustainable consulting firm, the design team included all major project stakeholders, namely the owner/developer, architect, engineer, landscape architect, contractor, and operations team. The design team valued occupant behavior, post-occupancy operations, and maintenance as important elements of their sustainable design. From the very beginning, the occupants' preferences and the building operator's advice were extensively considered and incorporated into the design process. Input from the occupants and building operator gave the design team the opportunity to resolve many accessibility and functionality issues that could have hindered O&M. Moreover, the sustainable consulting firm assumed the role of commissioning agent for the building and a thorough commissioning was completed in early 2011. The building's computer-based maintenance and management system was provided by Facility 360. Preventive and scheduled maintenance ensured reliable operation of the building systems. Other recent initiatives to increase the energy savings included:

- Automating the west shaft supply air damper to direct the main air supply to load areas
- Resetting the main air-handling unit pressure set point
- Resetting the chilled water supply temperature
- Resetting the under-floor air damper set points
- Adjusting fan terminal unit airflow set points to match local load conditions
- Modifying cooling tower operation on cooler days to minimize fan power

CalSTRS ended up winning the LEED-NC Gold certification, LEED-EBOM Platinum certification, and received high scores of 94 (in 2011) and 92 (in 2012) in the EnergyStar rating system, for its excellent post-occupancy performance. Figure 8 presents the benchmarking results between CalSTRS and the average performance in the CEUS database with California commercial buildings.

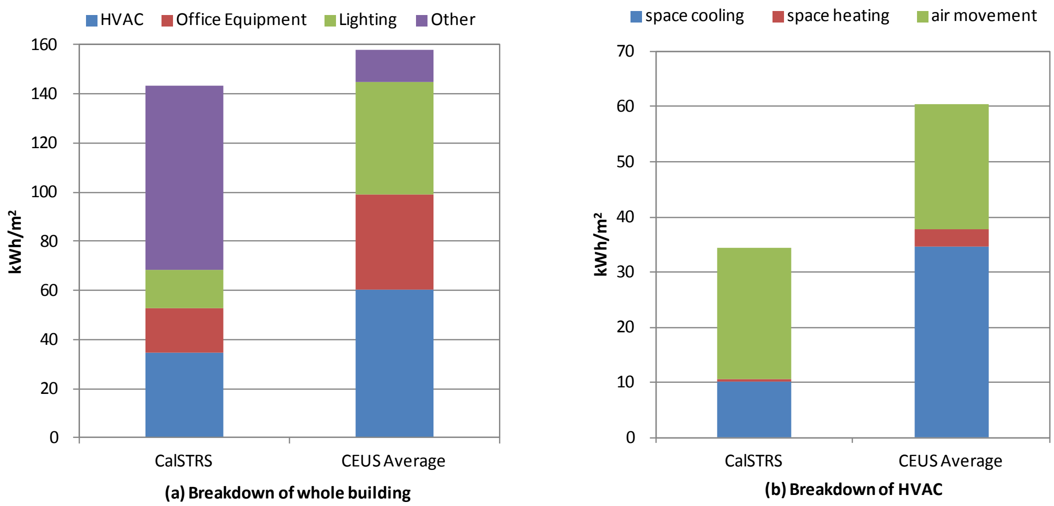


Figure 8 Benchmarking CalSTRS headquarters energy use

3.3 A protocol to evaluate energy conservation measures

Building technologies are usually evaluated using energy modeling tools under a single set of assumptions in the design and retrofit process. This process of evaluation is one of the key issues leading to the underperformance of actual energy savings in new and existing buildings. This problem is mainly due to the lack of data and methods available and therefore results in a lack of consideration of the associated complexity and uncertainty in the technology evaluation process. This research presents a new simulation framework that can be used to evaluate the real energy performance of building technologies, considering the realistic variations of the driving factors. The framework defines a matrix of scenarios for technology evaluation, to fully understand and quantify the variations in energy savings. This enables risk assessment in energy efficiency decision making. The framework includes building O&M, weather and occupant behavior, where (1) O&M will be categorized into good, average, and poor practices, (2) the weather data will be categorized into TMY (Typical Meteorological Year) and AMY (Actual Meteorological Year) and (3) the occupant behavior will be categorized into three styles: energy savings, norm, and energy wasteful.

Using this framework, a technology will be evaluated through building simulation using various scenarios to capture the potential range of energy savings and to support better assessment and investment decision making of energy efficiency technologies. The following scenarios have been identified as particularly important in the technology evaluation process:

(1) Scenario A – the Best Scenario with a combination of good building O&M practice and energy savings occupant behavior. This scenario captures how technologies perform in the best case buildings.

(2) Scenario B – the Worst Scenario with a combination of poor building O&M practice and energy wasteful occupant behavior. This scenario captures how technologies perform in the worst case buildings.
(3) Scenario C – the Average Scenario with a combination of average building O&M practice and norm occupant behavior. This scenario captures how technologies perform in the business-as-usual buildings. This is used in current building simulation.
(4) Scenario D – a combination of good building O&M practice and energy wasteful occupant behavior. This scenario captures how technologies perform in well operated and maintained buildings but with occupants wasting energy.
(5) Scenario E – a combination of poor building O&M practice and energy savings occupant behavior. This scenario captures how technologies perform in poor operated and maintained buildings but with occupants trying to save energy.

Multidecade historical weather data should be used in simulations to account for variations in energy savings, considering long-term time periods and to understand the risk of savings due to yearly weather variation. The framework recommends the following three aspects to reflect different scenarios in reality:

Building operations and maintenance

Building operations and maintenance are critical in guaranteeing good energy and environmental performance. Lin and Hong (2013) and Wang L. and Hong T. (2012) demonstrated the significant impact building O&M problems have on energy use. The current simulation process assumes buildings are operated and maintained perfectly without any problems, leading to an overestimate of energy savings in buildings. In reality, most buildings have certain degree of faulty operational problems resulting in increased energy consumption. This framework will define good, average, and poor practices of building O&M, from sources such as the ASHRAE Standard 180 Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems, the FEMP O&M Best Practices, IFMA, BOMA, and commissioning case studies.

Weather data

Weather plays an important role in building energy consumption. Current building simulation uses standardize TMY weather data to evaluate the energy performance of technologies. The assumption is made that energy savings is not sensitive to the weather data as long as the same weather data is used in both the proposed and the baseline building simulations. Hong et al. (2013) demonstrated that weather data has a significant impact on the energy savings of building technologies. This framework recommends using historical 30-year AMYs (Actual Meteorological Year) weather data (which are now available for all U.S. cities) when evaluating technologies, to fully consider the impact of yearly weather variations on building performance.

Occupant behavior

Researchers have concluded that occupant behavior has a significant impact on energy use in residential and commercial buildings. For example natural ventilation systems may rely upon the occupant opening windows under favorable cooling conditions and closing windows during other times, to achieve expected design intent. This operation strategy cannot be met if occupants act randomly or oppositely. Current building simulation ignores or over-simplifies occupant behavior with deterministic schedules of occupancy, comfort temperature setpoints, and interactions with lighting and HVAC systems. Hong and Lin (2012) demonstrated that the occupant's energy style can change energy use by a factor of three, in private offices. This framework defines three occupant energy behaviors: energy savers, norm, and energy wasters, in residential and commercial buildings.

The framework changes how building technologies are evaluated, and has the potential of being applied to many related activities, for example: (1) the proposed ASHRAE Standard 209 Energy, focusing on simulation aided design for buildings (excluding low-rise residential buildings), (2) DOE's Prioritization Tool, which deals with building energy code and standards development, building performance scoring and rating tools, (3) the ASHRAE series of Advanced Energy Design Guides and Advanced Energy Retrofit Guides, (4) COMNET, and (5) the NREL Uniform Methods Project.

This framework captures the dynamic complexity of actual building O&M, weather variation, and occupant behavior, which are important driving factors of the energy performance of buildings. When an individual and a package of building technologies are evaluated using this framework, a range rather than a single value of energy savings, is generated. This range is associated with various scenarios of building conditions and will provided users the ability to perform risk assessment and make more rational investment decisions. Technologies that have consistent attractive energy savings, regardless of the building conditions, should be the primary choice. Technologies with a wide range of energy savings should be considered secondary choices or not appropriate for deployment. This new process of evaluation and decision making allows users to consider a technology's potential impact on building performance, by assessing various scenarios of how a building might be operated and maintained, considering year-to-year weather patterns and variations in occupant behavior. This new approach becomes even more important in the design of low energy buildings, where passive systems (radiant systems, natural ventilation) and controls (opening/closing windows, switching/dimming lights, operating shades) are frequently used to achieve energy performance.

3.4 The new data schema for building performance information in integrated design

- **The role of information exchange in the integrated design**

  High performance buildings (HPBs) are widely perceived as an important contributor to the realization of sustainable communities. They call for multidisciplinary collaborations involving architects, engineers, construction workers, commissioners and post occupancy operators to guarantee the delivery of the proposed performance over the building's life-cycle. Therefore, an interactive process, termed the "Integrated Design Process" or IDP, has been widely adopted as the method for high performance building design. IDP extensively relies on the massive information flow among team members for the evaluation of strategies and decision makings. Table 3 sums up some of the key information inputs and outputs in an IDP.

Standardization of the data exchange is key for the productivity of interactions in an IDP. Information needs to be transferred clearly, consistently, and effectively to all specialists during the entire design process. Therefore, a communication mechanism facilitating the standardization of data flow is cornerstone for the effectiveness of IDP. Although Building Information Modeling, or BIM is one competent option for this demand, the level of standardization and integration in BIM requires further improvement. In fact, the majority of BIM activity has been on the user input side, with limited attention given to the details of building performance. In light of this, the amalgamation of building information should go beyond the simple integration of the descriptive data of buildings, to include both descriptive and performance data.

Table 3. Information flow in integrated design process

	Decision making	Code compliance	Certification	Operation &Maintenance	Energy Audit & Retrofit	Benchmarking & Ratings
Stage of IDP	Pre-design/ Schematic design/ design development	Schematic design/ design development	Design development	Building operation /post occupancy	Post occupancy	Post occupancy
Type of data	Design strategy/ scenarios/ parameters Simulation output	Design parameters/ Simulation output	Simulation output	On time Simulation Operation record	On time Simulation/Operation record	Measured energy consumption / Operation record
Way of application/ Output	Parametric comparison/ energy analysis report	Specific comparison/ energy performance analysis/ code compliance report	Comparison of baseline vs. proposed	Supervision / operation strategy/ FDD	Comparison of Simulation vs. operation/ Audit or retrofit report	Energy retrofit opportunities/ audit retrofit report

- **Key features of the performance data schema in integrated design**

Engine neutral & interoperability

For IDP, the most important feature is the intensive multidiscipline interaction. No doubt that almost all the IDP stakeholders and participants need particular tools, more or less, to undertake some analysis. Work in one specific area may use outputs from another areas inputs. Moreover, within one specific discipline there are various analysis approaches and modeling tools for users to choose. Modeling tools are capable of generating an overwhelming variety and volume of data, from the simulation of an input building model. The simulation complexity increases as the number of simulations increase and as variations from the original baseline occur. Adding to this complexity, there is the continual increase in measured performance data due to the increasing installation of sensors in buildings. Currently there is no standardized method to organize the data, with each modeling tool generating a uniquely defined output. The lack of standardized data can be highly confusing to users who want to easily and consistently conduct an evaluation from a specific performance perspective such as building energy use or rating, code compliance, or indoor environmental quality. For highly effective data exchange, a non-proprietary, engine neutral data schema turns out to be the keystone. This data schema should serve as a central data dictionary and a widely accepted industrial standard for a range of tools to map to. The data schema only aims at information sharing, rather than software applications. It provides a framework for the development of interoperable software in order to exchange data on building objects and processes, and to create a language that can be shared among the building disciplines.

Linked to Input

All the data, measured or simulated, are logically linked to an input object that generated the data. Accordingly, we could naturally require all the performance data to have a globally unique identification link corresponding to the input side element. This linkage between the performance data and the corresponding input object is the second primary feature of the data schema. This feature would be of particular importance for output instance documents containing data from multiple input models. Also, in the case of multiple simulation runs of the same input model under different conditions (e.g., different simulation options, different weather, and different orientations) there would also need to be a differentiating identification for each simulation run. Given input object and performance identification, the link from output to input could be documented either at the input object hierarchy node or within each report/variable element as an attribute.

Extensibility

With the rapid pace of development in the area of IDP and building modeling, it is critical to keep the data schema open and with the capability to host more data and applications in the future. Flexibility in the schema is an important feature for a mature data schema. The ability to modify and extend the initial schema is therefore a primary design strategy. The approach of using generalized complex type definitions as the building blocks for the specific output elements is central in addressing this issue.

Syncing with codes and standards

One consumer of the developed schema is the codes and standards conformity assessment. Keeping in sync with the latest codes and standards is vital for the information exchange and the IDP. Therefore, the ability to easily modify and extend the schema is a key design strategy. The approach of using generalized complex type definitions as the building blocks for specific output elements is central to addressing this issue.

- **Review of the current data schema**

A preliminary review of existing data models was conducted with the intention to identify aspects of relevance for the development of the new schema. Table 4 provides a summary of the review.

Table 4. Summary of review on the data schema

Name of schema	Field on building performance	Simulation / Measurement	Table of report	Data structure	Input reference	Code compliance	Interoperability / Flexibility of transformation	Extensibiity
gbXML	Generic "result" for energy consumption and all other performance data	Potentially support "simulation" and "measurement"	Do not support report	XML schema	Support	Not specified	Interoperable with other schemas like IFC	Do not support, fixed schema
IFC	Having multiple fields to host the energy performance, and support time series data	Potentially support "simulation" and "measurement"	Do not support report	XML schema	Support	Not specified	Interoperable with other schemas like gbXML	Do not support, fixed schema
Simergy	Predefined reports on energy consumption	Support simulation, not specified on "measurement"	Predefined report element	No schema, only fixed structure	Not specified	Not specified	Accept E+ outputs, Interoperable with some data visualization software	Do not support, fixed data structure
COMNET MGP (Modeling Guidelines & Procedures)	Standardized report element on energy consumption for code compliance	Support simulation, do not support "measurement"	Predefined report element for code compliance	A structural schema , multiple categorization by report type	Having elements on input contents	Specifically proposed for code compliance	Closed structure, do not support any interoperability and data transformation	Fixed, without any extensibility
DOE cBEAST	Predefined output report on energy consumption	Support "simulation"	Predefined report	Web oriented structure, possibly SQL or MySQLlite	Accommodating input and output information	Not specified	Do not have any extensibility and interoperability	Do not have any extensibility and interoperability
Name	Field on building performance	Simulation / Measurement	Table of report	Data structure	Input reference	Code compliance	Interoperability / Flexibility of transformation	Extensibility

BEDES	Energy use, Time series energy use,	Support simulation, do not support "measurement	Support report element, but not specific defined	A dictionary of terms and definitions	Specific category	Not specified	Support interoperability with DOE software or programs	Support
EnergySTAR	Energy use and utility coast	Measured	Not specified	Flat structure	Not support	Not support	- Not Support	Not support
LEED NC	Annual simulated Energy use	Simulation	Predefined report	Not specified	Support	Support	Not support	Not support

- **Outline of the new data schema for information exchange in integrated design**

For the development of the new data schema, the team investigated interoperability, considering input and extensibility features. Efforts were directed towards finalizing the new schema with the incorporation of all requirements.

Data vs. report

Users generally rely on various reports for different applications in the process of IDP. These reports are generated from atomic data, where the virtual interface is between buildings and humans. With major application fields in code compliance, performance rating and benchmarking programs, this process yields a predefined format, encompassing raw data from multiples sources and an aggregated summary, for the holistic performance. Naturally, this structure is desired to be straightforward, offering the consumer a clear feeling of where to locate data. This hierarchical structure, with properly defined categories and terminologies, nicely accommodate these reports.

Reports, compiled from data, are usually utilized by various software tools, from the simulation post processing to the data visualization software. Consumed by software rather than human, performance data need a relatively flat model to reduce the load of query and extraction.

Given the distinct target audience and the requested features, different structures and attributes in the new schema, are accommodated. With regards to engine neutral, we choose XML as the receptacles for the schema, due to its extensibility and the interoperability among the predominant selections.

Structure of report

Based on the predominant fields of application, we defined 13 categories at the highest level of the structure. These range from annual energy performance to comfort and sizing reporting (Figure 9). Moreover, a category for custom defined reports included fourteen classes where several sub reports were defined and hosted the specific contents of building performance. This structure followed the output reports schema created for EnergyPlus. Details of each report were reorganized within every category, based upon the reports of EnergyPlus outputs. Figure 9 illustrates the overall architecture.

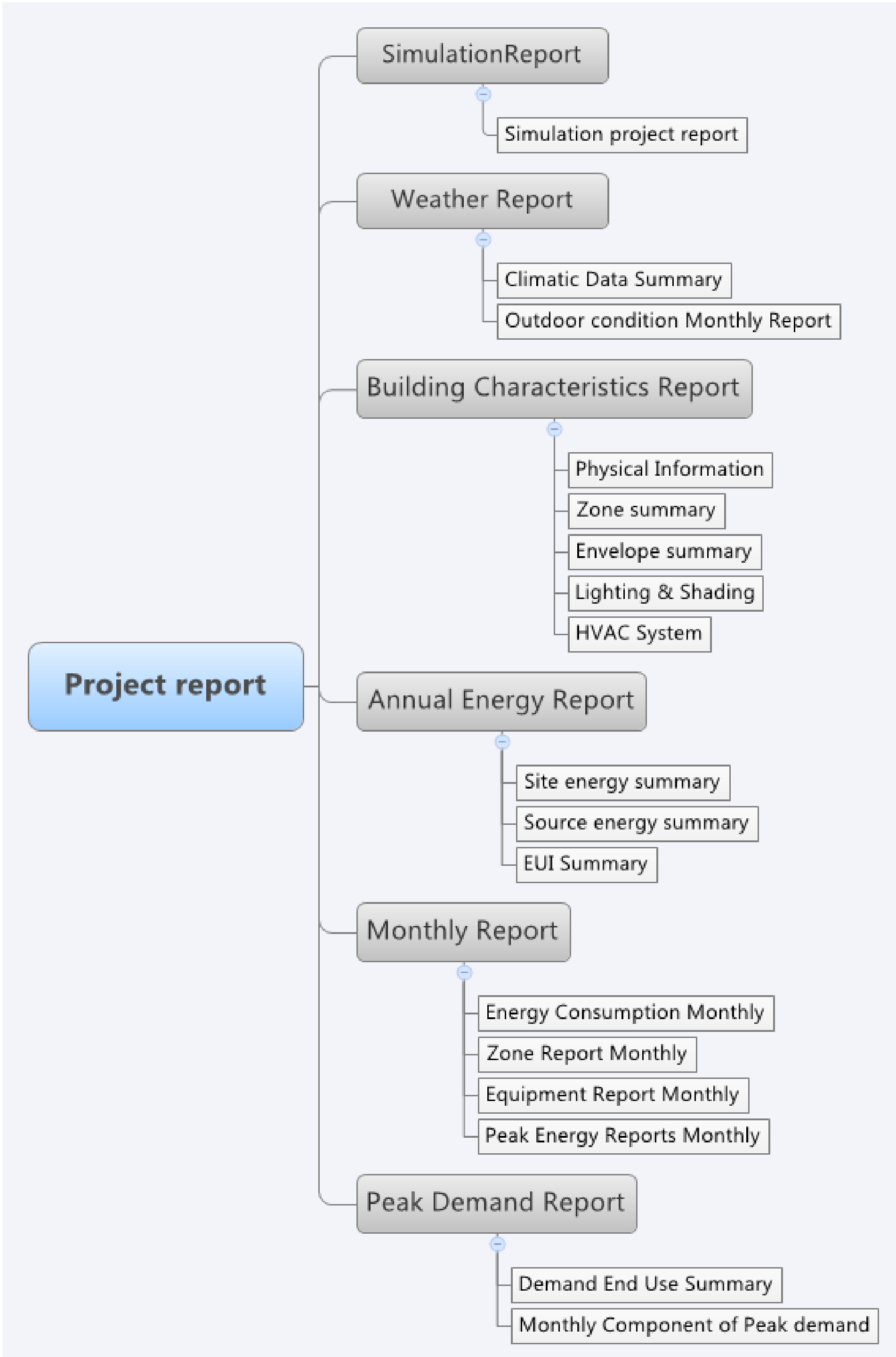


Figure 9 Structure of the new information schema

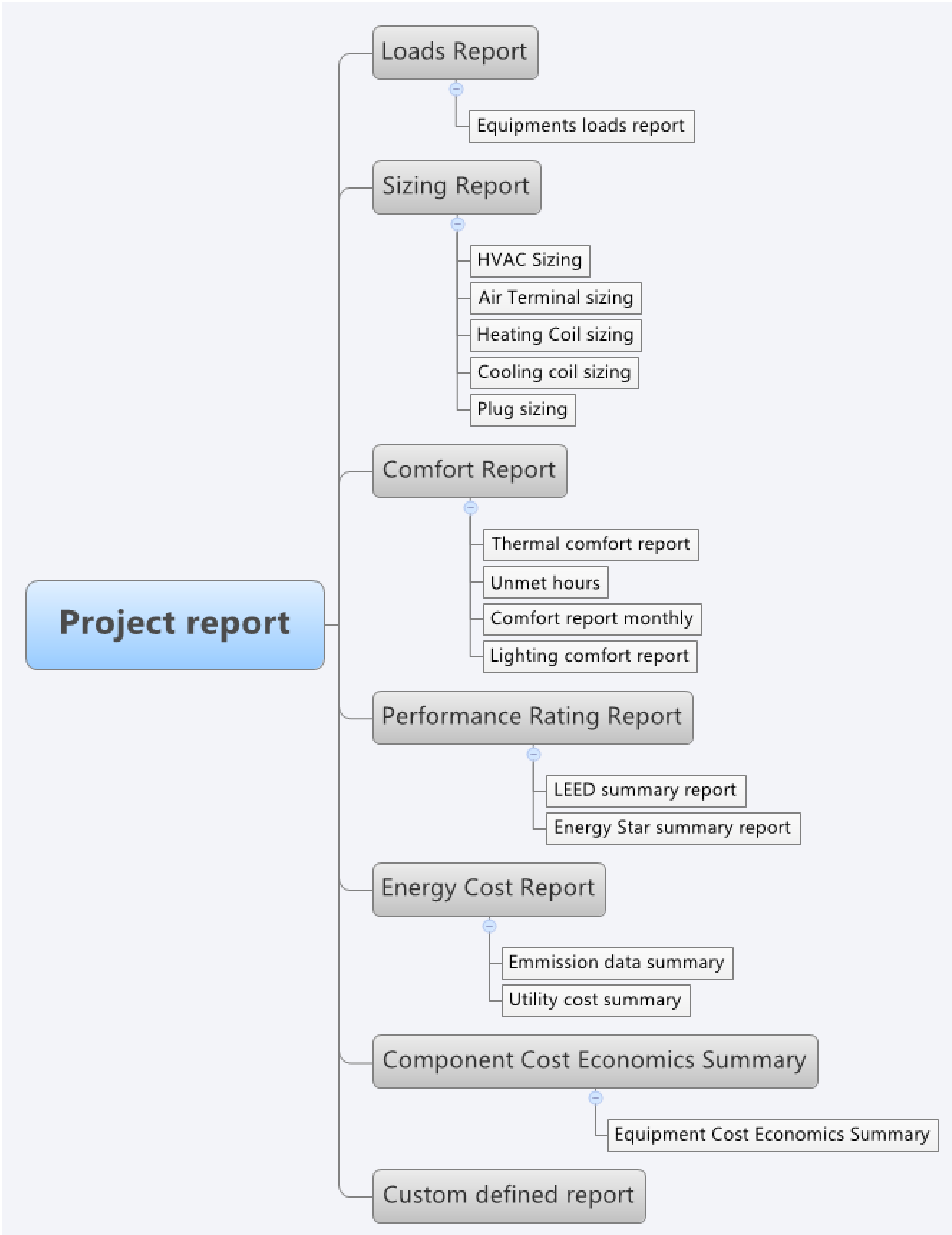


Figure 9. Structure of the new information schema (cont'd)

Data Model

A flat model approach was identified to accommodate the atomic data at a detail level. The flat organization employed child elements of each output result type to categorize each information data. That is, a set of enumerated properties would be used to categorize the data rather than organizing the results into a pre-defined hierarchy. This approach provides: (1) flexibility in defining categories, (2) easy in revising and extending categories, and (3) easy navigation of a hierarchical structure.

XML is still the container of the data schema. A set of three categorization dimensions have been identified to be attached to every data. The first dimension is Performance type with enumerated values of: Energy, Load, Heat Gain, Sizing, Comfort, Building Characteristic, Climate, Economics, Simulation, Performance Rating, User Defined, and Null. The second dimension is spatial type with enumerated values of: Project (multiple buildings), Building, Zone, End Use, Equipment, User Defined, and Null. The third dimension is temporal type with enumerated values of: Annual, Monthly, Daily, Hourly, Time Step, Irregular, and Null. With all three dimensions, software can easily locate the data of interest by navigation. Aggregation on a specific dimension can thereby generate the summary report stored in the report structure.

3.5 Design Charrette on the integrated design of demonstration buildings

Design decisions made during the early phases of the design process have a crucial influence on energy performance of buildings. The integrated building design (IBD) approach aims to better coordinate design features across multiple disciplines to achieve maximum performance. IBD considers the interactions and integration of various energy systems in buildings during operation and maintenance. A Design Charrette was formulated to facilitate the IBD process. It was designed to support the integrated design and commissioning of the five demonstration buildings in China by engaging building owners, design team, developers, and other stakeholders.

The one-day Charrette was hold in Wuhan, China on October 29, 2013 before the two-day CERC-BEE conference. Thirty-eight participants, including researchers and management staff from both countries and four developer teams, were grouped into 6 tables (one developer team per table). The Charrette began with Richard Diamond's greetings and Richard Karney's open speech, followed by the goals of the Charrette, and presentations on the concepts, processes, and tools of the integrated design and commissioning. Discussions were conducted by the groups, focusing on 3 to 5 design goals, strategies, technologies, and the commissioning of individual demonstration buildings. This section provides a summary of the Design Charrette. Additionally, a separate report was written detailing the Design Charrette in more detail.

- **Executive summary of Design Charrette**

The Charrette brought together a group of diverse players with diverse languages, needs, perspectives, etc., and facilitated the exchange of information in a fun and engaging manner. The object was to enhance the communication of ideas.

Participants, with diverse backgrounds, provided both analytical detail and big picture context, in an effort to improve integrated design. Notably, participants introduced themselves by giving their favorite energy-consuming device: computer, a/c, cellphone, espresso maker, lighting, radio, etc., as a reminder that we care about the services energy provides, not energy itself.

Values offered by the teams for their buildings:

Team 1 (Zhuhai): "Chartreuse Tiger"

- Connected with nature
- Comfortable
- Productive
- Happy

Team 2 (Jilin) "White Tiger"

- Warmth—physical and psychological
- Visible
- Walkable
- Practical

Team 3 (Wuhan) "Blue Dog"

- Aesthetics
- Thermal Comfort
- Indoor air quality
- Replicable

Team 4(CABR) "Green Bear"

- Healthy environment
- Zero energy
- Natural materials, recycled content
- Gray water recycling system

Team 5 (Zhuhai) "Red Sun Bird"

- Provide an example for others to learn from
- Low energy, e.g., 50 kWh/m2-y, plus solar renewables
- Cost effective: low cost/high efficiency
- Comfortable for occupants whenever they use the building

Team 6 (CABR) "Green Dragon"

- Healthy
- Smart
- Comfortable

Baseline & Target Energy Use Distribution and Level

The teams estimated the baseline energy usage of a comparable neighbor building built to the design specification of local energy codes. They then estimated the target energy usage of their building with integrated energy features. The results from the 6 groups are presented in Figures 10 to 15.

Table 5. Baseline vs. Target for the Zhuhai Building (Group A)

Zhuhai-A	Baseline (%)	Target (%)
Cooling	40	30
Lighting	30	25
Heating	8	5
Ventilation	10	10
Plug loads	12	30
Total	100	100
Consumption (kWh/m2-yr)	150	50

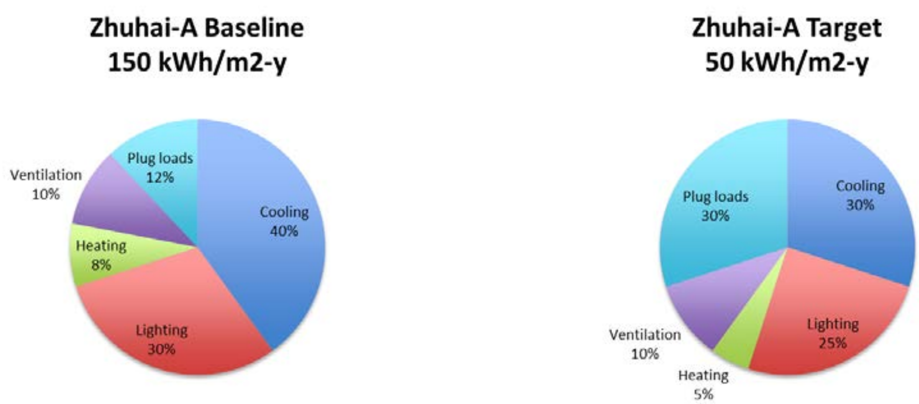


Figure 10. Baseline vs. Target for the Zhuhai Building (Group A)

Table 6. Baseline vs. Target for the Zhuhai Building (Group B)

Zhuhai-B	Baseline (%)	Target (%)
Cooling	35	26
Lighting	28	27
Heating	4	5
Plug loads	33	42
Total	100	100
Consumption (kWh/m2-yr)	92	57

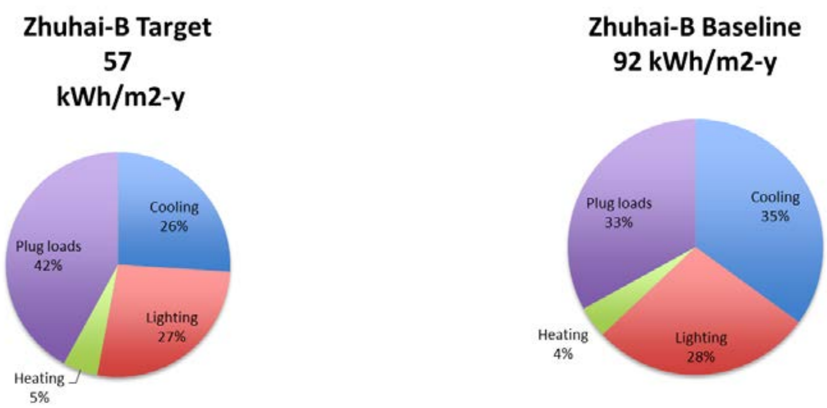


Figure 11. Baseline vs. Target for the Zhuhai Building (Group B)

Table 7. Baseline vs. Target for the Jilin Building

Jilin	Baseline (%)	Target (%)
Cooling	2	0
Lighting	20	12%
Heating	50	29%
Ventilation	13	24%
Plug loads	15	36%
Total	100	100%
Consumption (kWh/m2-yr)	100	42

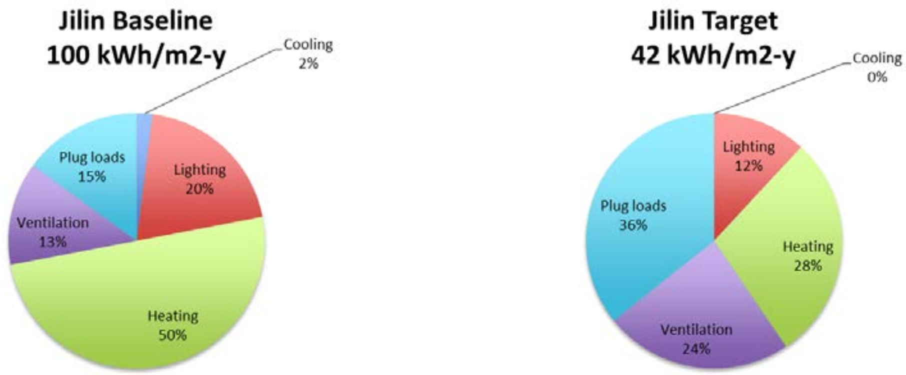


Figure 12 Baseline vs. Target for the Jilin Building

Table 8. Baseline vs. Target for the Wuhan Building

Wuhan	Baseline (%)	Target (%)
Cooling	40	30
Lighting	15	20
Heating	20	20
DHW & cooking	10	10
Plug loads	15	20
Total	100	100
Consumption (kWh/m2-yr)	100	42

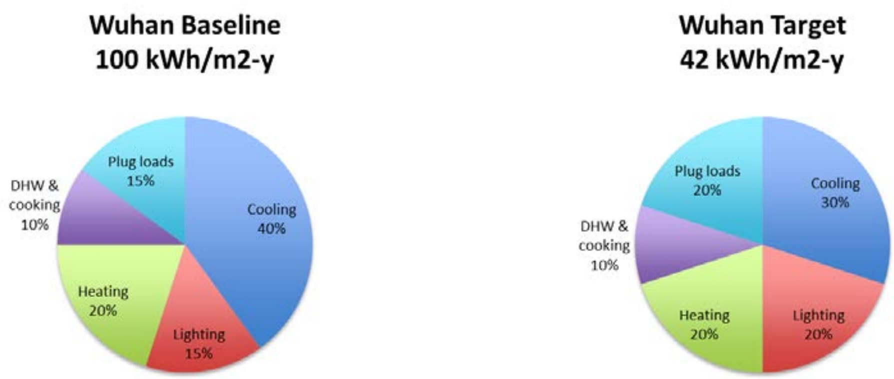
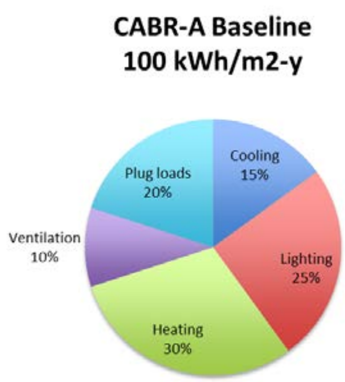


Figure 13. Baseline vs. Target for the Wuhan Building

Table 9. Baseline vs. Target for the CABR Building (Group A)

CABR-A	Baseline (%)	Target (%)
Cooling	15	10
Lighting	25	25
Heating	30	18
Ventilation	10	5
Plug loads	20	42
Total	100	100
Consumption (kWh/m2-yr)	100	49



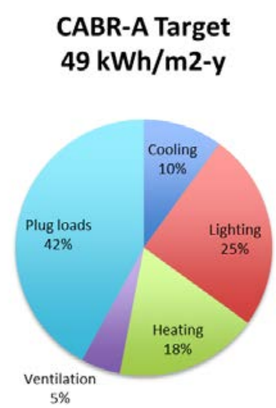


Figure 14. Baseline vs. Target for the CABR Building (Group A)

Table 10. Baseline vs. Target for the CABR Building (Group B)

CABR-B	Baseline (%)	Target (%)
Cooling & Ventilation	35	33
Lighting	20	14
Heating	30	20
DHW	5	0
Plug loads	10	33
Total	100	100
Consumption (kWh/m2-yr)	100	49

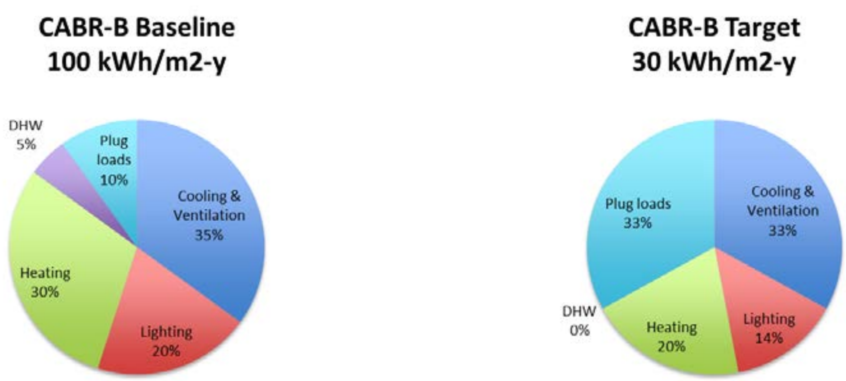


Figure 15. Baseline vs. Target for the CABR Building (Group B)

Design

- Presentation on design tools
- Discussion on energy strategies
- Design integration is more than an assemblage of different technologies, but is a planned and carefully considered collection of interdependent technologies

Construction and Commissioning

- Presentation on Commissioning
- Discussion on commissioning

Performance and Evaluation

Need to collect information on:

1. Energy use, water use, environmental conditions
2. Occupant satisfaction
3. Owner satisfaction
4. Cost data

4. Conclusions

Four technical tasks were conducted to explore some key questions about integrated design for high performance buildings.

The portfolio analysis of 51 selected high performance buildings from around the world indicated that actual energy use varied dramatically, by a factor of up to 11, almost as staggering was the fact that nearly half of the 51 buildings fell short of the ASHRAE Standard 90.1-2004 energy target. Our analysis of the influence of climate, building size, energy efficiency technologies, occupant behavior, and O&M in HPBs indicated that no single driving factor dictated the building's actual energy performance. An integrated design approach, taking into account all drivers, offered the greatest potential for producing a building with actual low energy consumption.

Current simulation-based evaluation of building technologies, does not sufficiently consider the associated complexity and uncertainty, to provide an accurate evaluation process. To address this issue, ta new simulation framework to evaluate energy performance of technologies, considering the realistic variations of the driving factors was proposed. Along with the evaluation framework, existing data schemas were reviewed and recommendations were proposed to accommodate the exchange of building performance data into the whole process of integrated design.

A data schema was proposed to better facilitate the information exchange and to focus on the results and performance data generated from EnergyPlus simulations, during the building integrated design process. The schema should be engine/application neutral, linked to input (building and systems characteristics), extensible, and have a flat structure to ease the transformation of data into different formats.

Lastly, a design charrette was held in Wuhan, China to introduce the concept of integrated design into China's demonstration buildings teams. Thirty-eight participants, including U.S. and Chinese researchers and management staff were grouped into 6 tables with one developer team per table. Communication between the participants cast some light on some key issues in the integrated design process. The verdict of this charrette was summarized into a memo report to facilitate the design of five demo buildings under the CERC-BEE program.

Main outcomes from this project can be summarized as follows:

1. Integrated design, operations and occupant behavior during the building life cycle is the key to high performance and low energy buildings. Technologies alone do not guarantee low energy buildings. Best practice of operations and energy friendly occupant behavior play a significant role in energy performance of buildings. The integrated design workshop and case studies directly support the design and operations of five demonstration buildings in China.
2. The simulation framework improves the way we evaluate technologies and building performance by considering various uncertainties and investment risks. It can be adopted in the building code and standards development, code compliance calculations, and performance ratings. It provides a clear pathway to understand and assess the gap between expected performance during design and actual performance during operations.
3. Data and information exchange across various disciplines of building design and operations are crucial to improve knowledge sharing and timely decision making. The preliminary research of the information exchange feeds into the development of results schema of EnergyPlus, a separate project funded by U.S. Department of Energy.

5. Future Research

The research findings from the project directly feed into the upcoming CERC-BEE Projects, titled "Human Behavior and Standards to Improve Design and Operation of Very Low Energy Buildings," which aims to further understanding of driving forces of building performance, integrated building design and occupant energy-related behavior, in order to create new standards and guidelines for building designers, engineers, researchers and policy makers. This work will go towards improving the design and operation of high performance buildings.

6. Acknowledgement

This work was sponsored by the U.S. Department of Energy (Contract No. DE-AC02-05CH11231), under the U.S.-China Clean Energy Research Center for Building Energy Efficiency, and the China Ministry of Housing and Urban-Rural Development and the Ministry of Science & Technology (Grant No. 2010DFA72740-02). Special thanks to the U.S. and China CERC-BEE management, our industry partners, the Industry Advisory Board, and the Technical Advisory Committee for the strong support on the project.

7. References

Lin H-W., Hong T. (2013) On variations of space-heating energy use in office buildings, Applied Energy, 111, 515-528 (http://dx.doi.org/10.1016/j.apenergy.2013.05.040).

Hong T. Chang W-K., Lin H-W. (2013) A fresh look at weather impact on peak electricity demand and energy use of buildings using 30-year actual weather data, 111, 333-350 (http://dx.doi.org/10.1016/j.apenergy.2013.05.019).

Hong T. and Lin H-W. (2012) Occupant Behavior: Impact on Energy Use of Private Offices, IBPSA Conference Proceedings, 50 (http://www.ibpsa.org/proceedings/asim2012/0050.pdf)

Wang L. and Hong T. (2012) Modeling and simulation of HVAC faculty operations and performance degradation due to maintenance issues, IBPSA Conference Proceedings, 56 (http://www.ibpsa.org/proceedings/asim2012/0056.pdf).

Zhang Q. Yan D. Zhu D-D (2014) The impact analysis of indoor heat gain spatial diverse characteristics on air-conditioning system design and capacity in office building, Heating Ventilating & Air Conditioning,2014(10) (in Chinese)

Zhou X. Yan D. Deng G-W. Zhang X-L. Zhang Y. Jiang Y-W. Jiang Y (2014) Comparison and research about centralized and distributed air conditioning systems in residential buildings, Heating Ventilating & Air Conditioning, 2014(7) (in Chinese)