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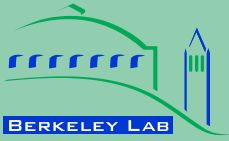
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Environmental Energy Technologies Division

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Revisit of Energy Use and Technologies of High Performance Buildings

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ABSTRACT

Energy consumed by buildings accounts for one third of the world's total primary energy use. Associated with the conscious of energy savings in buildings, High Performance Buildings (HPBs) has surged across the world, with wide promotion and adoption of various performance rating and certification systems. It is valuable to look into the actual energy performance of HPBs and to understand their influencing factors.

To shed some light on this topic, this paper conducted a series of portfolio analysis based on a database of 51 high performance office buildings across the world. Analyses showed that the actual site Energy Use Intensity (EUI) of the 51 buildings varied by a factor of up to 11, indicating a large scale of variation of the actual energy performance of the current HPBs. Further analysis of the correlation between EUI and climate elucidated ubiquitous phenomenon of EUI scatter throughout all climate zones, implying that the weather is not a decisive factor, although important, for the actual energy consumption of an individual building. On the building size via EUI, analysis disclosed that smaller buildings have a tendency to achieving lower energy use. Even so, the correlation is not absolute since some large buildings demonstrated low energy use while some small buildings performed opposite. Concerning the technologies, statistics indicated that the application of some technologies had correlations with some specific building size and climate characteristic. However, it was still hard to pinpoint a set of technologies which was directly correlative with a group of low EUI buildings.

It is concluded that no a single factor essentially determines the actual energy performance of HPBs. To deliver energy-efficient buildings, an integrated design taking account of climate, technology, occupant behavior as well as operation and maintenance should be implemented.

INTRODUCTION

Worldwide concern with non-renewable energy depletion and anthropogenic climate change has accelerated in recent years (USDOE 2013). It is commonly recognized that the building sector is a big contributor to energy consumption and green-house-gas (GHG) emission (New Building Institute, 2012). In light of the awareness of this significance, programs aimed at High Performance Buildings have been widely implemented by energy-conscious architects, engineers as well as governments (Peterman et al 2012). Globally, the number of certified HPBs under various rating systems has increased exponentially in recent years (U.S. Green Building Council 2013). With the confluence of all these driving forces, it is no exaggeration to say that HPBs are now revolutionizing the appearance of the Architecture industry.

In the meantime, with many certified HPBs being occupied for years, researchers are provided with the opportunity to re-evaluate the actual performance rather than the simulated results. New Building Institute (NBI) studied 121 USGBC LEED-NC buildings aiming at better quantifying the actual energy performance levels of green buildings and understanding the relationships of actual performance levels to other benchmarks, including initial modeling and ENERGY STAR ratings (New Building Institute 2008). On behalf of the U.S. General Services Administration, Fowler (2010) also studied 22 federal buildings focusing on evaluation of measuring environmental performance, financial metrics, and occupant satisfaction. These studies mostly concluded that the HPBs outperform the conventional buildings from the perspective of general statistics. On the contrary, it should not be neglected that the performance of every individual building varied greatly in those studies. Regardless of the general performance, some instances in these researches were spotted to cost more than

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those without certification (New Building Institute 2008). Given this, the energy performance of individual building and the underlying driving forces of these various performances appear to be more vital than the holistic statistic, for the sake of further development of HPBs. Keeping this in mind, the primary goal of our study is to provide an insight into the diverse energy performance based on the analysis of the actual energy consumption as well as the influencing factors.

METHODOLOGY

Our study covers 51 office buildings in various regions across the world with high performance ratings, including USGBC LEED Gold & Platinum, Germany DGNB Gold, Japan CASBEE “s”, UK BRREEAM Excellent, and China Three-Star Certification. All the data on the buildings are drawn from public accessible sources, including building databases managed by DOE (USDOE 2013), NBI (NBI 2013), LBNL (LBNL 2013) and also books on HPBs (Yudelson et al 2013). These buildings had at least one complete year of actual operational energy consumption data. The 51 buildings comprised of 21 buildings in the U.S., 11 in Europe, 5 in Australia, 7 in Asia Region and 7 in China.

The major focus of our research is to provide some insight into the actual energy performance of these buildings and to understand the relationship between the energy use and the influencing factors, including location (region), climate, building size, and technologies used. Portfolio analyses were employed to identity and understand the relationship between the energy performance and these factors.

ANALYSIS OF ENERGY CONSUMPTION AND THE DRIVING FACTORS

Variations of energy performance

By ordering the site energy use intensity (EUI) from minimum to maximum, **Figure 1** illustrates the profile of energy performance of the 51 buildings. In **Figure 1**, each bar represents the EUI of an individual building in the database. To demonstrate the regional distribution, bars are color-coded according to the location of a building. Apart from the EUI bars, four lines were also drawn representing four EUIs for benchmarking, including (1) average energy consumption of the office buildings in the 2003 CBECS database (U.S. EIA 2013), (2) median value of energy consumption of the office buildings in the 2003 CBECS database, (3) target of energy performance of office buildings in ASHRAE 90.1-2004 (U.S DOE 2011) and (4) target of energy performance of office buildings in ASHRAE 90.1-2010 (U.S DOE 2011).

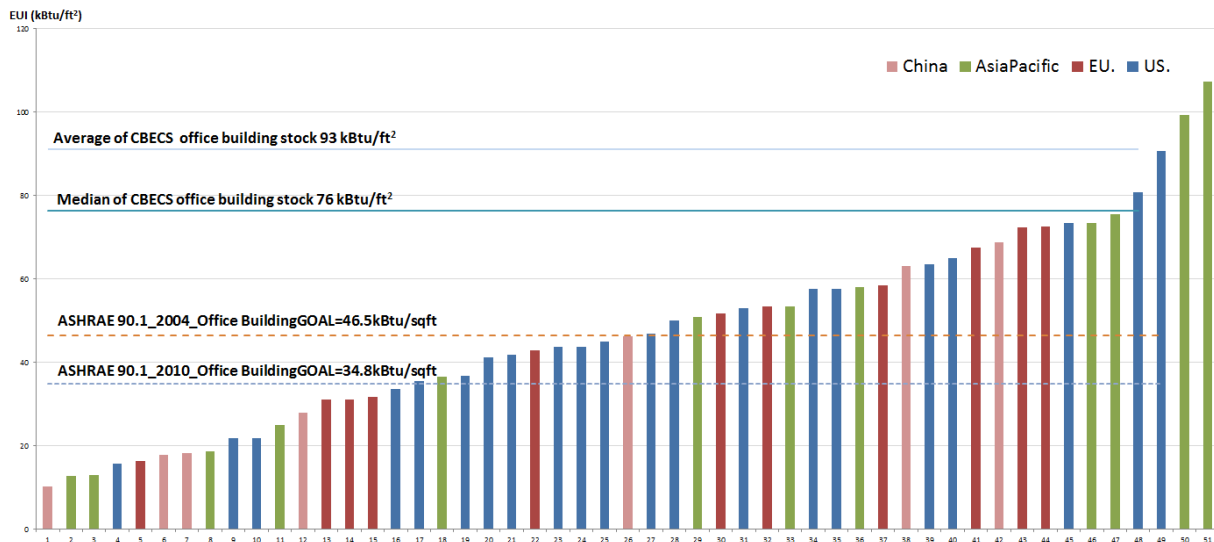


Figure 1. Distribution of Site EUI of the 51 High Performance Buildings

Looking at **Figure 1**, EUIs vary from 10 to 110 kBtu/ft², by a factor of up to 11. This phenomenon of scattering indicates that even with similar certification, energy performance of HPBs varies substantially. In comparison with the

energy use of average office buildings, most HPBs demonstrate better energy performance. However, it should not be neglected that there are still three buildings performed worse than conventional buildings. Therefore the high level of overall performance rating of a building does not directly correlate to low energy use. The median EUI value of this database is 46.2 kBtu/ft², which is barely lower than the ASHRAE 90.1-2004 target of 46.5 kBtu/ft². This means that for our database, only 50% of all the buildings are compliant with a relatively outdated standard, the ASHRAE 90.1-2004, in terms of overall energy performance. When considering the more recent standard, the ASHRAE 90.1-2010, with an EUI target of 34.8 kBtu/ft², the proportion of compliance goes down sharply to 30%. These statistics altogether imply a challenging state that most HPBs do not perform well in actual energy use. Certification of HPBs cannot guarantee the delivery of energy-efficient buildings. Aside from this, for the distribution of EUI within each region, it could be noted that bars with same color spread widely from low to high EUI. Looking at the statistics of variation in **Table 1**, the status quo of HPB's actual performance in every region is similar to each other. In view of the great discrepancy of HPB's actual performance, an exploration on the driving factors of EUIs is valuable to reveal the driven forces behind energy use.

Table 1. Statistics of EUI Distribution by Regions

	Scale of Variation (Highest/ Lowest)	Average EUI (kBtu/ft ²)	Median EUI (kBtu/ft ²)
U.S.	6	48.5	45.0
EU	4	48.0	51.7
Asia & China	11	46.1	46.1

Impact of Climate

It is a consensus that climate has a significant impact on the energy consumption of a building. Hence the influence of climate should be explored to uncover the related effect. Typically, climate is treated as an independent parameter in the regression of energy performance in the form of heating degree days (HDDs) and cooling degree days (CDDs) (Hong et al 2013). The prerequisite of treating climate quantitatively is the abundant weather data. Due to the lack of weather data for the 51 buildings, we simply considered the impact of climate by categorizing the EUI data according to buildings' ASHRAE climate zones. This method is also the one employed in the NBI report (New Building Institute 2008). Similar to the NBI report, the climates of the 51 buildings are grouped into four types. The interquartile box and the scattering span of the EUI based on that classification is presented in **Figure 2**. X-Axis represents four climate types. The corresponding ASHRAE climate code is listed below the name of every zone on X-Axis. Red bar of every interquartile box denotes the median value while the color arrow points out the corresponding average value of every data stock. The ASHRAE 90.1-2004 target (EUI of 46.5kBtu/ft²) is indicated in horizontal green dash line as a benchmark.

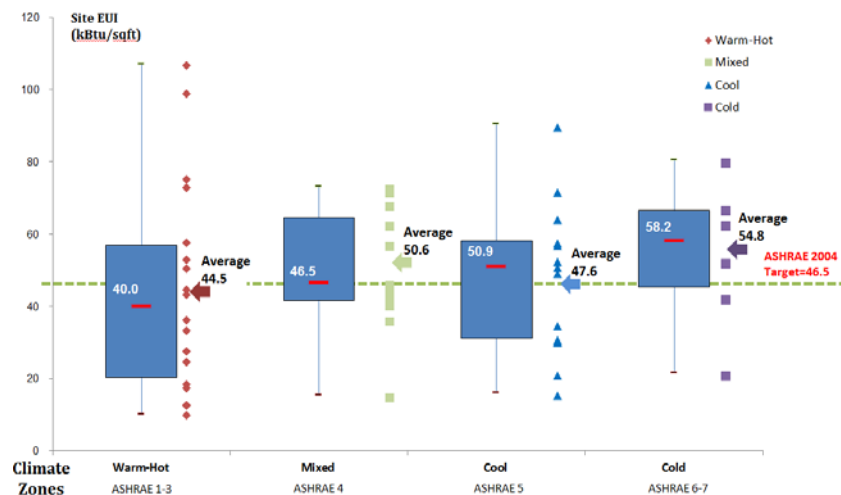


Figure 2. Distribution of Site EUI in four climate zones

From the viewpoint of holistic performance, namely, the median and average value, HPBs' performance in warm-hot zone goes beyond the other zones as well as the line of ASHRAE 90.1-2004 target. The reason of this is perceived to be the absence of space heating and the widely application of natural ventilation in this climate. Although the general statistic is satisfactory, it should not neglect the fact of the wide scattering of EUIs in this zone. For the warm-hot zone, EUI spans from 15 to 110 kBtu/ft², which presents the greatest scale of spread among the four climate zones. Despite the fact that this zone has the most energy-efficient buildings, buildings with higher EUI than ASHRAE 90.1-2004 target still account for half of the stock in this zone. In confluence of both the good and bad building performance, average EUI is barely better than the AHSRAE target. In fact, moving to the other situations, we discovered the ubiquitous scatter of EUI throughout all the climate zones. From mixed zone to cold zone, no more than 50% of the buildings performed better than the ASHRAE 90.1-2004 target. In the meantime, EUIs of those poorly performing buildings turn to raise the average value. In confluence of the two factors, the overall energy performance in the mixed, cool and cold zones are depressing, as shown in **Figure 2**.

Given the substantial scale of EUI spread in every climate zone, it can be concluded that even sharing same climate background, buildings present remarkably different energy performance, which might be due to some other factors.

It should be noted that the median EUIs seem to increase for buildings located from hot to cool to cold climate. This is mainly due to the use of site energy as the performance metric, which simply adds energy consumption from various sources including electricity, natural gas and other fuels used for space or water heating. If primary or source energy is used as the performance metric, electricity usually carries a much higher (around 3) source factor for the calculation of source energy. This will result in a reverse of the trend that EUI in hot climate demonstrate the higher EUI.

Impact of Building Size

There is a common perception that large buildings inherently consume more energy than their small peers on per unit of floor area. To look at the relationship between EUI and building size, the original dataset was split into 5 sub-sets according to the floor area, and the proportion of EUI of 4 levels within every sub-set was calculated in **Table 2**.

Table 2. Proportion of Site EUI by floor area

Floor Area (1000 ft ²)	Site EUI (kBtu/ft ²)			
	0~30	30~50	50~70	>70
<50	50.0%	35.7%	14.3%	0.0%
50~100	30.0%	30.0%	40.0%	0.0%
100~200	0.0%	25.0%	37.5%	37.5%
200~500	7.7%	46.2%	23.1%	23.1%
>500	16.7%	0.0%	33.3%	50.0%

Looking at **Table 2**, for buildings no larger than 50000 ft², 50% of them have the Site EUI less than 30 kBTU/ft². Expanding the range up to 50 kBtu/ft², we can still readily spotted 35.7% of the buildings lying in the range. Although there is yet 14.3% with EUI higher than 50 kBtu/ft², buildings smaller than 50000 ft² seem to have a higher possibility to achieving an energy-efficient building. Moving down to the level of 10000 ft², the proportion of EUI lying in the first two categories (lower than 30 kBtu/ft² and 30~50 kBtu/ft²) goes down comparing to that in the previous level. Meanwhile, proportion located in the range of 50 to 70 kBtu/ft² significantly rises by nearly 30%. This shows a trend of more energy use with the increase of the floor area. Furthermore, for buildings larger than 500000 ft², EUIs higher than 70 kBtu/ft² begin to dominate with proportion of 50%. In the latter three levels, although the percentage of three categories lower than 70 kBtu/ft² is not consistent with the patterns of buildings smaller than 10000 ft², it is evident that low EUI is much harder

to achieve for large buildings. The general trend revealed by these statistics shows that small buildings have higher possibility to reaching a low EUI while general EUI in large building ends up being higher than the smaller peers. Usually, small buildings are simple in the respect of function and operation. Buildings are usually dominated by spaces like offices or meeting rooms. Working schedules in these buildings are also as regular as 8 hours and 5 days a week, which turns off the energy use equipment at night. On the contrary, large buildings are usually designed as headquarters or multi-functional complexities in metropolises. Some large buildings may have large data center which operates continuously and consume lots of energy. To fit these diverse functions, operating hours are usually extended with most of the fundamental equipment operating simultaneously, which inherently increases the energy consumption of large buildings. Therefore, it seems reasonable to assume that large building may have higher EUI than smaller ones.

However, the pattern of the correlation of each individual building demonstrates a different view. **Figure 3** plots the correlation between EUI and floor area for every building. The correlation demonstrated in **Figure 3** is fairly weak. Drawn from **Figure 3**, the Pearson correlation coefficient between EUI and floor area is 0.32, which indicates that there is no clear and strong evidence that small buildings will have lower EUI. Despite the statistics, it can be found that some large buildings have EUI lower than 30 kBtu/ft². In the meantime, some small buildings also have EUI higher than 60 kBtu/ft². All of these suggest that building size may have some effects on EUI, but it is still highly possible to realize an energy-saving building with deliberate design and operations.

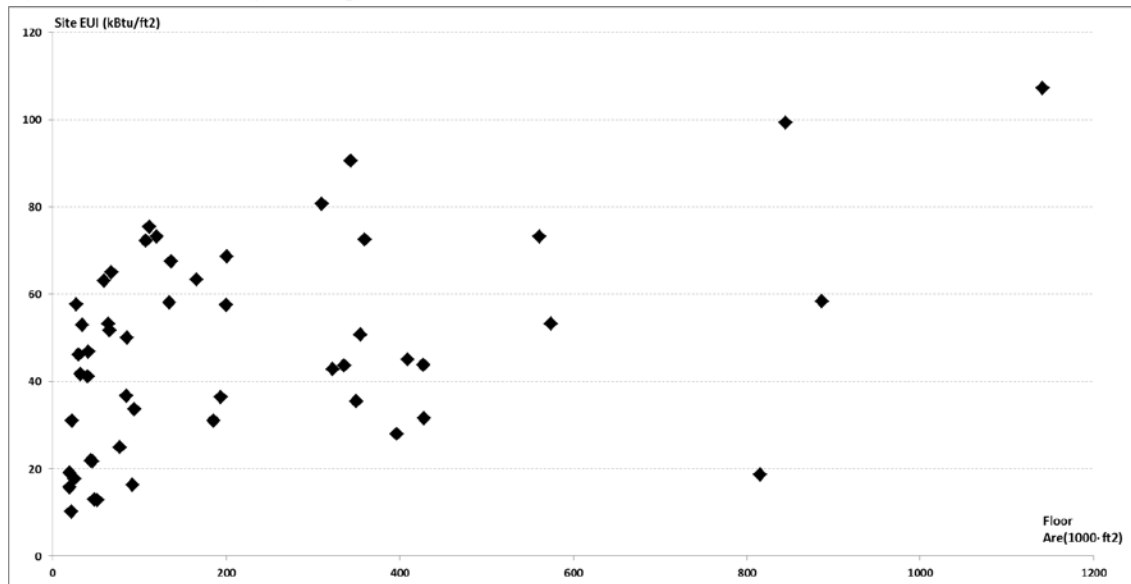


Figure 3. Correlation between the building floor area and EUI

Impact of Building Technologies

In the practical design of high performance buildings, much attention is usually put on the so-called “high performance technologies”. Accordingly, there has been a prevailing sense that these so-call technologies are the crucial factors determining the energy performance of buildings. Advocates stated that energy consumption in building is induced by the usage of all equipment. Therefore the essence of energy saving rests upon the improvement of equipment performance. From this viewpoint, advocates naturally perceive these technologies as the determinant of energy savings.

The theory mentioned above is arguable since it may overvalue the importance of building technologies whereas ignore other key factors of building performance. Therefore, it is imperative to verify that statement based on the buildings technology information along with real energy performance of buildings. **Figure 4** illustrates the application of all the technologies along with the corresponding EUI of every building. For a clear and easy analysis, buildings are ordered by their EUI, from low to high. All information related to technologies is classified into three major categories, including:

- 1) Lighting related technologies: use of daylight, high efficiency lighting systems, lighting control strategies (e.g. occupancy control, dimming control);
- 2) Envelope technologies: insulation improvement, glazing improvement and shading devices;
- 3) HVAC technologies related to space cooling and heating: natural ventilation, night purge, underfloor air distribution (UFAD), chilled beam, high efficient equipment and ground source heat pump.

Onsite renewable energy technologies are also listed to reveal their status quo of application. For the purpose of parallel comparison, the listed information is simply the presence of one specific technology. The bottom line in **Figure 4** lists the overall application ratio of each individual technology in our stock.

EUI (kWh/m ²)	Lighting			Envelope improvement (Insulation/shading/glazing improvement)	HVAC System						Renewable Energy		
	Maximum Utilization of daylighting	High efficient lighting system (low power density)	Lighting control (Occupancy or dimming controlling)		Daytime Natural Ventilation (System control)	Night Purge (Thermal mass)	Chilled Beam	UnderFloor Air Distribution	High efficiency & 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	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						
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	Y		Y		
111.6	Y			Y	Y	Y		Y	Y				
115.1	Y			Y			Y		Y				
115.7		Y		Y				Y	Y				
129.6	Y		Y		Y						Y	Y	
131.5			Y							Y			
134.9	Y			Y	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	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	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						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%

Figure 4. Status of application of building technologies

As shown in **Figure 4**, the top three popular technologies used in the HPBs are daylighting utilization (76.5%), high efficient HVAC systems (64.7%) and the improved envelope (62.7%). They spanned from the low EUI buildings to the high EUI buildings. These high application ratios and their wide distributions indicate their broad range of applicability and suitability. However, the widespread employment of the three technologies also implies an undelightful issue that the three technologies have no direct relationship to the energy savings in buildings. Reckoning that they have become the fundamental strategies in a newly constructed building, it should be emphasized that more deliberate design and operations is a key to delivery of an energy efficient building.

One may assume that some other technologies or innovative breakthroughs in high performance buildings may have

some direct links to energy performance. To verify that, the database was split into four sub-sets according to the EUI. The controlling levels are set to those in previous section, namely 30, 50 and 70 kBtu/ft². The application ratio of each technology in every sub-set is calculated separately and listed in **Table 3**.

Table 3. Application ratio of building technologies under four EUI ranges

EUI Range (kBtu/sqft)	Maximum Utilization of daylighting	High efficient 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	UnderFloor Air Distribution	High efficiency& energy saving equipments	Ground Source Heat pump	PV	Solar thermal	Wind turbine
10~30	91.7%	41.7%	41.7%	75.0%	75.0%	16.7%	33.3%	0.0%	66.7%	33.3%	58.3%	50.0%	41.7%
30~50	60.0%	26.7%	33.3%	60.0%	46.7%	26.7%	13.3%	33.3%	66.7%	33.3%	60.0%	33.3%	6.7%
50~70	66.7%	26.7%	53.3%	53.3%	33.3%	20.0%	26.7%	20.0%	66.7%	13.3%	13.3%	20.0%	0.0%
>70	100.0%	22.2%	11.1%	66.7%	55.6%	22.2%	22.2%	11.1%	55.6%	11.1%	55.6%	11.1%	0.0%

As highlighted in red in **Table 3**, some technologies are spotted to have a somewhat positive correlation to the low EUI. They are high efficient lighting system, lighting controls and ground source heat pump. There is a match-up of low EUI and high application ratio for these three technologies. This tendency may possibly lead to an agreeable statement that those are the measures that should be pursued to deliver a low energy building. However, recall the corresponding columns of these three technologies in **Figure 4**, some buildings with these three technologies turn out to use more energy than those without. Overall, the applications of building technologies demonstrate a large scale of scatter. It is challenging to pick out a specific group of technologies which only appeared in buildings with low EUI. This wide scatter presents a totally opposite fact to the statistical conclusion made before. Therefore the proportion ratio is only a general indicator representing the statistical relationship between the building technologies and high energy performance. The higher application ratio only implies that those technologies are widely considered in the pursuit of high performance buildings.

The appearance of scatter, as well as those discrepancies of EUIs sharing the similar technology configurations, suggesting that the stacking or simply adding more technologies do not necessarily lead to low energy use in buildings. Integrated design and operation is the key to integrate all the technologies to achieve optimal energy performance in buildings.

CONCLUSIONS

To better understand energy performance of high performance buildings, a portfolio analysis was conducted on the actual energy use of 51 HPBs across four regions in the world. The pattern of actual EUI distribution presents a significant variation with a scale of up to 11. Only half of the instances in the building stock reach the energy saving target proposed by ASHRAE Standard 90.1-2004. This implies that the certification of HPB cannot guarantee the delivery of real energy-efficient buildings. Group comparisons were undertaken to look at the influences of climate, building size and technologies on energy performance. Although being widely perceived as an important factor influencing building energy use, the great scatter of EUI within the same climate zone indicates that the weather is not a decisive factor of the performance of an individual building. Situation on building size is similar. A tendency that small buildings are more possible to achieve a low EUI was spotted via the statistical analysis on building size via energy use. The correlation analysis on every individual building, however, indicates that the connection between them is relatively weak. Small buildings with high EUI and large building with low EUI were both spotted in the analysis. Hence the building size cannot determine the energy use of a building by itself alone. On the concern of technologies, study on the state of application demonstrates a loose connection between the building technologies and EUI. The energy-efficient building cannot be guaranteed by simply stacking a specific set of technologies.

Seeing that no a single factor can determine the building energy performance, the underlying factor which essentially drives the energy use is still obscured. In the operation of a building, energy is actually consumed to fulfill a set of particular function demands, such as need for space cooling and heating or lighting. The essence of energy savings within a building thus rests upon every aspect in the fulfillments of these demands. And the strategies for energy savings should integrate all the possible fields that might have actual impacts. Climate may affect the cooling and heating loads, the use of daylighting

as well as the design and operation of natural ventilation; the arrangement of the building functions and the occupant behavior may influence the operation schedule of the building and thus reduce the energy use; the high-efficient equipment and the good operation and maintenance of them will directly reduce the energy use for regular operations. In summary, the delivery of energy-efficient buildings should encompass all the related fields and implement an integrated design and operations strategy to fully exploit all the energy saving possibilities.

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