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An insight into actual energy use and its drivers in high-performance buildings

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HIGHLIGHTS

- Fifty one high performance buildings across the world were studied.
- The actual energy performance of the 51 buildings varied by a factor of up to 11.
- Climate, building size, or technologies alone is not a decisive factor of energy use.
- Occupant behavior, operation and maintenance have significant influence.
- Integrated design encompassing all key factors is key to high performance buildings.

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ABSTRACT

Using portfolio analysis and individual detailed case studies, we studied the energy performance and drivers of energy use in 51 high-performance office buildings in the U.S., Europe, China, and other parts of Asia. Portfolio analyses revealed that actual site energy use intensity (EUI) of the study buildings varied by a factor of as much as 11, indicating significant variation in real energy use in HPBs worldwide. Nearly half of the buildings did not meet the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 90.1-2004 energy target, raising questions about whether a building's certification as high performing accurately indicates that a building is energy efficient and suggesting that improvement in the design and operation of HPBs is needed to realize their energy-saving potential. We studied the influence of climate, building size, and building technologies on building energy performance and found that although all are important, none are decisive factors in building energy use. EUIs were widely scattered in all climate zones. There was a trend toward low energy use in small buildings, but the correlation was not absolute; some small HPBs exhibited high energy use, and some large HPBs exhibited low energy use. We were unable to identify a set of efficient technologies that correlated directly to low EUIs. In two case studies, we investigated the influence of occupant behavior as well as operation and maintenance on energy performance and found that both play significant roles in realizing energy savings. We conclude that no single factor determines the actual energy performance of HPBs, and adding multiple efficient technologies does not necessarily improve building energy performance; therefore, an integrated design approach that takes account of climate, technology, occupant behavior, and operations and maintenance practices should be implemented to maximize energy savings in HPBs. These findings are intended to help architects, engineers, operators, and policy makers improve the design and operation of HPBs.

1. Introduction

Worldwide concern about depletion of non-renewable energy sources and anthropogenic climate change has accelerated in recent years [1,2]. Energy use in buildings accounts for one-third of the world's total primary energy consumption and contributes significantly to greenhouse gas (GHG) emissions [3–5]. With growing consciousness of the need to save energy in buildings, high-performance buildings (HPBs) (a.k.a. green, sustainable, or low-energy/low-carbon buildings) have emerged around the world as an important component of efforts to reduce energy use and global GHG emissions [4,5].

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As HPB initiatives have been extensively implemented by energy-conscious architects, engineers, and governments [6–9], a variety of rating systems have been developed to certify the performance of these buildings. These rating systems, such as the U.S. Green Building Council's (USGBC's) Leadership in Energy and Environmental Design (LEED) system [11] and the Three Star rating system in China, assign credits for various indicators [10] and thus directly influence the design of HBPs. These rating systems have also had a stimulating effect on the HPB market. Fig. 1(a), which is based on data from the USGBC [12], shows that more than 1000 LEED-certified buildings are constructed worldwide per year. Fig. 1(b) shows that, in China, the largest construction market in the world, HPBs are enjoying exponential growth. These data indicate the major impact of HPBs on the building industry.

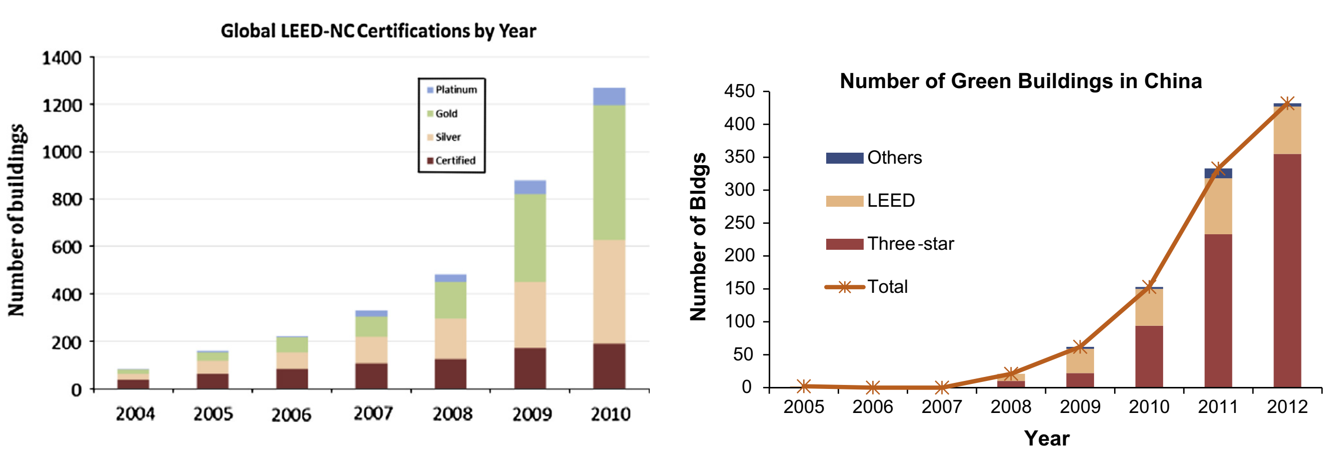
Many certified HPBs have already been occupied for a number of years, offering researchers the opportunity to evaluate the buildings' actual performance rather than the simulated results on which ratings and certifications are based [10,13–19]. In 2008, the U.S. General Services Administration (GSA) conducted a post-occupancy evaluation to determine the actual performance of their green buildings. Actual energy use, CO_2 emissions, water use, and occupant satisfaction were studied in 12 representative GSA green buildings [20,21]. Results showed that these buildings generally outperformed their conventional peers in these areas.

Although actual energy use is the most reliable indicator of the success of HPBs, all current rating systems for newly constructed HPBs base certification on predicted energy savings that are calculated by simulation tools based on a building's proposed design compared to a baseline design that meets minimum code requirements. However, multiple studies report gaps between designed and actual energy consumption in HPBs, including a 2004 report by the National Renewable Energy Laboratory [17], 2006 research by Diamond [18], and 2012 research by the University of California, Santa Barbara [22]. These prior studies indicate that actual energy consumption is the most meaningful metric for evaluating the performance of HPBs.

Turner's 2006 analysis collected information on 11 LEED buildings in the northwestern United States (the cities of Seattle and Portland) and compared their actual energy use, designed energy targets, and baseline energy use [16]. The actual energy use deviates from the simulated performance by more than 20% for all the buildings; and the actual energy use in 40% of the buildings was greater than designed or simulated. The extent of the discrepancy between predicted and actual energy use in these buildings was as high as 2. Likewise, Diamond reviewed actual and simulated energy performance of 21 LEED-certified buildings [18]. Actual energy use of the buildings was, on average, only 1% lower than simulated performance, but large variability (standard deviation of 46%) in the sample set highlighted a remarkable disparity in performance among buildings. This research suggests that there can be a significant inconsistency in performance among HPBs that have the same level of certification.

In 2008, the New Buildings Institute (NBI) analyzed utility billing data for 121 LEED-certified commercial buildings. This study concluded that LEED buildings in the U.S. generally saved 25–30% compared to energy usage in conventional buildings [19]. However, this study has been heavily criticized for its methodology and conclusions. Critics argued that the study's data collection methods were likely to result in biased sampling and that the study's analysis approach resulted in misunderstanding regarding sources of energy consumption and carbon emissions [23,24]. The study was also criticized for drawing conclusions based on simple comparison of the median EUI of LEED buildings to the mean EUI of all U.S. commercial buildings without any statistical tests. Newsham et al. argued that the average trends in the NBI study might be spurious [25].

Despite the controversy regarding approach and metrics used in the NBI study, there is no question about the value of that analyzing HPB energy performance and it is clear that the large variability among EUIs in HBPs worldwide needs to be studied. And even though the NBI study concluded that LEED-certified buildings are generally saving energy, the NBI analysis results (Fig. 2) do not support the conclusion that LEED buildings *consistently* deliver expected energy savings. Fig. 2 shows that EUIs of NBI study buildings at every certification level are scattered by a factor of up to 4, and buildings with EUIs greater than those of conventional buildings are found throughout all three LEED certification levels (The Gold and Platinum levels are combined in Fig. 2). Although the average energy consumption of the buildings at each of the three LEED certification levels is lower than the average of commercial buildings in the 2003 Commercial Buildings Energy Consumption Survey (CBECS) database, a significant number of buildings nonetheless consume more site energy than the average for commercial buildings in the CBECS database. In tandem with these results, media reports of buildings that do not live up to their green labels threaten the credibility of HPBs [26–28]. In sum, although the general or average performance of HPBs might be acceptable, the evidence does not support the conclusion that all high-performance-certified



(a) Worldwide Number of LEED-New Construction (NC) certified buildings

(b) Growth of green buildings in China [13]

Fig. 1. Growth in green buildings, globally and in China.