RESEARCH

EVER GREEN: A POST-OCCUPANCY BUILDING PERFORMANCE ANALYSIS OF LEED CERTIFIED HOMES IN NEW ENGLAND

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ABSTRACT

The purpose of this research was to conduct a pilot study of LEED certified homes in New England one to five years after occupancy to determine whether they continue to perform at the level predicted during the certification process. Four criteria were defined to assess the performance of each home: (1) energy consumption for heating, cooling, lighting, electronics and appliances; (2) building envelope and air infiltration; (3) operations and maintenance; and (4) occupant satisfaction and indoor air quality. Both qualitative and quantitative methods including blower door and duct blaster tests, utility bill analysis, and an occupant satisfaction survey were used to measure the post-occupancy performance of seven LEED certified homes in New England. Discrepancies were found between the original building performance as determined at the time of certification and the current level of building performance. While this is limited, initial research, these findings indicate a need for further post-occupancy research that can provide feedback to green certification programs, allowing them to be modified as necessary to better reflect the actual environmental impacts of certified buildings.

KEYWORDS

post-occupancy, LEED, residential, certified homes, home performance, energy consumption

INTRODUCTION

In the United States, buildings are responsible for almost 48% of greenhouse gas emissions (Architecture2030 2010, US Department of Energy 2010). The building sector also contributes between 15% and 40% of all environmental impacts and is responsible for 12% of water consumption, 65% of total waste, and 71% of all the electricity use in the United States (US Environmental Protection Agency 2002, USGBC 2009). If traditional building practices continue to be the norm, these impacts are likely to increase as the economy recovers and new building construction resumes.

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The current efforts by builders, engineers, and architects are helping to reduce the environmental impact of buildings and address the crisis of climate change and energy security in the United States. However, much progress remains to be made in addressing how effectively these high performance buildings are functioning once they are built. When builders and homeowners build green they typically follow the guidelines of one of these nationally recognized certification programs: the US Environmental Protection Agency's *Energy Star* program, the US Green Building Council's (USGBC) *Leadership in Energy and Environmental Design* rating system (LEED), or the Green Building Initiative's *Green Globes* which works in partnership with local chapters of the National Association of Home Builders. Furthermore, many state and municipal governments encourage or require new buildings to be constructed according to a local green code or to the standards of a national certification program.

In the US, LEED has become the foremost green building certification program. To earn LEED certification a home must be tested by a third party to verify building performance. The tester checks the ducts and building envelope for leaks and verifies the heating and cooling systems are operating correctly, ensuring that the building is performing as well as predicted and meets the certification standards. This is all done during the construction phase and LEED does not currently require or offer a post-occupancy evaluation program to ensure that the home continues to perform to the standards at which it was originally certified.

The most effective way to ensure that the home is performing properly is to conduct a post-occupancy audit after construction is complete and the home has been lived in for at least one year. Collection and evaluation of twelve complete months of utility bills, reevaluation of the building envelope, examination of the current building conditions, and interaction with the building occupants are the most effective methods to assess and understand how much energy is being consumed after the home is occupied. Obtaining data for a minimum of one year of occupancy provides sufficient time for the homeowners to understand how various features of their home are performing and for the mechanical systems to be properly calibrated. It also allows the analysis to account for any seasonal variations in energy consumption and building performance.

Because LEED and other certification programs are relatively new, especially in their current form, few post-occupancy studies have been conducted and post-occupancy research thus far has focused on commercial buildings. In 2008 the New Buildings Institute evaluated the performance of 112 LEED certified commercial buildings and found that approximately half of the buildings met or exceeded the predicted energy performance while the other half failed to meet expectations. A full 25% of the buildings had energy use intensities that were significantly lower than the design projection (Turner and Frankel 2008). In another post-occupancy study of 11 LEED certified buildings one building exceeded its predicted energy use by 300% because of HVAC and lighting systems control issues. While six of the buildings in this study actually exceeded expectations, none were within 20% of the design performance (Turner, Cathy 2006). Both of these studies underscore the need to continue conducting post-occupancy research to ensure that the certification level of a building accurately reflects its energy performance and to expand this research to residential construction.

The primary goal of this research was to assess whether LEED certified homes continue to perform at the level predicted at the time of certification. To do this, we conducted a pilot study of LEED certified homes in New England. By analyzing the performance of the mechanical, electrical, and architectural systems, we were able to quantify the energy efficiency of these homes and identify any discrepancies between post-occupancy and design performance. These results strongly suggest a need for further residential post-occupancy research while allowing us to provide feedback to the builders and designers and make recommendations for improvements that may benefit the homeowner. They also help us to understand how certification programs may need to change to better reflect the post-occupancy performance of the buildings.

METHODOLOGY

We utilized a range of qualitative and quantitative methods to evaluate seven LEED certified homes in New England according to the following five criteria: 1) energy used for heating, cooling, appliances, and electronics; 2) water consumption; 3) insulation and air infiltration; 4) maintenance and repair requirements; and 5) indoor air quality and occupant comfort. Homes were selected using the USGBCs list of LEED certified homes in the US (USGBC 2009). We initially contacted the homebuilders via email who then introduced us to the homeowners.

To determine energy consumption we used accessible data from utility bills that were provided by the homeowners. We collected a minimum of 12 months worth of utility records from the homeowners and more when available. From these records we calculated the energy use intensity (EUI) of each home in kBTU/ft^2/year (kWh/m^2/year) and compared it to the predicted or as-designed EUI. The predicted EUI was calculated based on the annual end-use consumption by fuel type as reported in the original certification documents. The original certification documents were obtained from the builder or original tester. For three of our participating homes we had access to multiple years of utility records. In these cases we calculated the EUI for each year and then compared the average EUI for all of the years to the predicted value. Both calculations reflect only purchased energy and exclude onsite, renewable energy production.

A thermal imaging camera was used to document leaks in the building envelope caused by improper insulation or air sealing. We also conducted blower door and duct blaster tests to diagnose any air leakage and estimate energy efficiency losses. While conducting these tests we attempted to replicate the original testing conditions as closely as possible but found this to be difficult as we were unable to obtain any testing protocol documents from the certifying organizations. During the blower door test, we used a large fan to depressurize the house relative to outside and simultaneously measured air flow through the fan. The volume of air flowing through the fan is equivalent to that penetrating the building envelope as a result of the pressure difference. The standard means of reporting air flow is in cubic feet per minute or liters per second at a house pressure of 50 Pascals (Pa) (CFM_{50} or L/s_{50}). Only one of our seven homes had duct systems, which we evaluated by conducting duct blaster tests. The duct blaster is very similar to the blower door: a fan depressurizes the duct system and measures air leakage. We used the duct blaster in conjunction with the blower door to measure total air leakage to outside of the conditioned space at a pressure of 25 Pa (CFM_{25} or L/s_{25}). The results of these tests were then compared to the original testing data, upon which certification was based. This allowed us to determine whether any changes in the performance of the building envelope had occurred over time.

Through interviews with occupants and the occupants' records of service requests and costs we evaluated the operations requirements of each home as well as the perceived performance and comfort of the homeowners. A modified version of the occupant survey created by the Center for the Built Environment (CBE) at the University of California, Berkeley (CBE 2009) was mailed or emailed to the homeowners before each testing visit to ensure they had sufficient time to read and understand the questions and formulate their answers. During each testing visit we sat down with the homeowners to review their survey responses and discuss any other concerns they may have. The survey focused on occupant behavior such as number of occupants and amount of time spent doing various activities in the home and asked homeowners to rate their satisfaction with interior and exterior design features such as temperature differences, noise, and photovoltaic performance.

RESULTS

Quantitative Results

Figure 1 shows the relationship between predicted and measured EUI for our seven homes. While all of the homes performed better than the national average (46 kBTU/ft^2/year or 145 kWh/m^2/yr) (Solar Oregon 2010), only two performed approximately as predicted and the other five homes actually performed better than predicted with a standard deviation of 11.61.

As can be seen in Table 1, two homes had differences in air infiltration of less than 50 CFM_{50} (24 L/s_{50}); in the other five homes we found differences ranging from 100 to 650 CFM_{50} (47-246 L/s_{50}) and these can be attributed to variations in building performance between now and when the homes were originally tested for certification. When we tested the one home with ductwork we found no measurable air leakage from the heating system to the outside while the original tester measured leakage of 1 CFM_{25} (0.5 L/s_{25}).

Qualitative Results

From our occupant survey we found that none of our participating homeowners felt that their green home required any extra maintenance. Two of the homeowners had lived in their home for 1–2 years and five had lived there for 3–5 years. During this time, only two homeowners had spent more than $200 on maintenance. Following the completion of construction or before purchasing their homes, all of the homeowners were led on a walk-through of the home by the builder and were given a homeowner's manual detailing the features of their

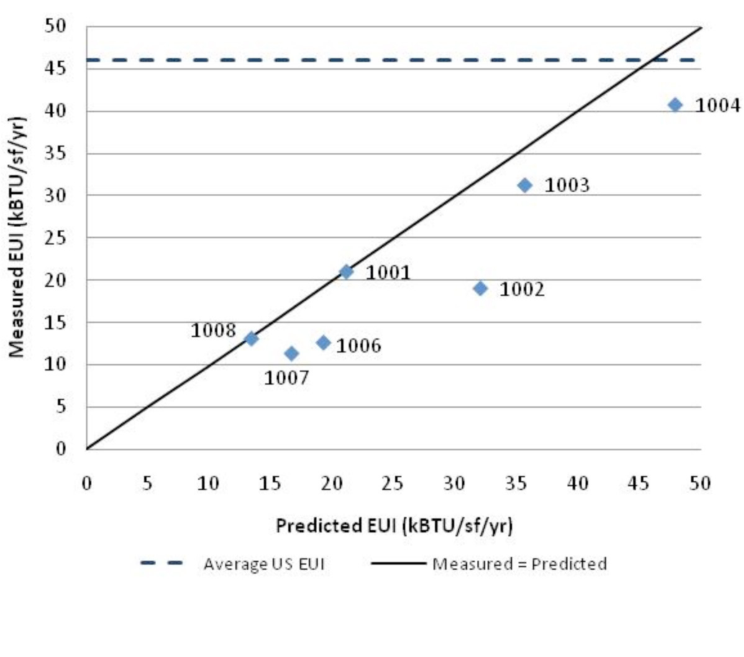

FIGURE 1. Measured vs. predicted energy use intensity.

TABLE 1. Comparison of post-occupancy air infiltration to original infiltration.

Home ID	Conditioned Area		LEED Certification Level	Original Infiltration		Post-Occupancy Infiltration		Absolute Difference		% Difference
	sq ft	sq m		CFM_{50}	L/s_{50}	CFM_{50}	L/s_{50}	CFM_{50}	L/s_{50}	
1001	4585	426	Platinum	1070	505	1570	741	500	236	46.7%
1002	3593	334	Silver	850	401	750	354	100	47	11.8%
1003	2424	225	Gold	790	373	990	467	200	94	25.3%
1004	1536	143	Certified	402	190	666	314	264	125	65.7%
1006	1352	126	Gold	380	179	354	167	26	12	6.8%
1007	4983	463	Gold	1701	803	1677	791	24	11	1.4%
1008	5173	481	Silver	1224	578	1875	885	651	307	53.2%

TABLE 2. Level of homeowner satisfaction.

Home ID		1001	1002	1003	1004	1006	1007	1008
LEED Certification Level		Platinum	Silver	Gold	Certified	Gold	Gold	Silver
Overall Satisfaction	Very Satisfied		X			X	X	X
	Satisfied			X	X			
	Moderately Satisfied	X						
	Dissatisfied							
	Very Dissatisfied							
Satisfaction with Energy Efficiency	Very Satisfied					X	X	
	Satisfied		X		X			X
	Moderately Satisfied	X		X				
	Dissatisfied							
	Very Dissatisfied							

homes as well as the maintenance and operations requirements of the mechanical systems. All of the homeowners reported that they refer to their manual at least once a year and three consult it four or more times each year. Only one homeowner felt that the level of education provided by the builder was inadequate.

Table 2 shows each homeowner's level of satisfaction with their home overall and with the energy performance of their home. It is interesting to note that the homeowner who reported feeling inadequately educated is also only moderately satisfied with their home and with its energy performance.

DISCUSSION

According to our energy use intensity analysis (Figure 1) homes 1001 and 1008, are performing almost exactly as predicted. However, the occupants of home 1001, which is certified LEED platinum, reported that the master bedroom is too cold during the winter months so they turn down the heat, close the door, and relocate to another bedroom. This lowers their energy use for several months of the year and as a result the numbers indicate that the home is performing as predicted. Obviously that is not the case as this should not be necessary in a home with the highest level of green certification. If this were not done, the home would require more energy for heating and have a higher EUI. While the energy consumption of home 1008 matches the consumption predicted at the time of certification numerous air infiltration issues, which will be discussed later, were identified in this home.

The other five homes (1002, 1003, 1004, 1006, and 1007) have lower than predicted EUIs. For home 1002, which has an EUI that is 41% lower than predicted, the original certification report did not account for the electricity production of the photovoltaic array. Therefore, the predicted EUI does not accurately reflect the expected performance of this home. The homeowners also added a solar thermal system in February of 2009 that reduced their energy demand. Home 1003 has an EUI that is 12% lower than predicted. This house is kept at a constant temperature of 63°F (17 °C); despite this energy-saving measure, it has used 8% more propane than expected. There is an even more significant difference in electricity consumption, which has been 60% lower than predicted for the three years that the home has been occupied. Homes 1004 and 1007 are both used part-time, which may have complicated the predicted energy consumption calculations as the homes may not actually be used as often as expected. For home 1007 the original certification report also failed to account for energy savings from the solar thermal system. It is likely that these two factors are responsible for the 32% difference between the predicted and measured EUIs. Regardless of the reasons for the discrepancies, it is clear that the predictions used as the basis for certification do not reflect the actual energy performance of these five homes.

We were able to identify some differences in building performance with the blower door test. Home 1001 showed an infiltration rate almost 50% higher than when originally tested. This home had been vacant for two years after construction was completed in 2006 so we were not surprised to find differences, although we did not expect the performance to have changed so much. With the help of the thermal imaging camera we located wall cavities where the blown-in cellulose insulation had settled considerably or was missing entirely, especially in the master bedroom. While cellulose insulation is not a new material and has annual sales of $115 to $125 million, it is not used as frequently as fiberglass insulation which has annual sales of $4 to $6 billion (Carter 2007). With cellulose having a significantly smaller market share, there are fewer contractors that have experience working with it. Because of this, it is likely that many certified green homes have experienced the same loss of insulative value over time as was seen in home 1001.

Although we were unable to locate similar insulation settling in home 1003, it had an infiltration rate that was 25% higher than when originally tested. The homeowners reported that they had installed a woodstove and added passive ventilation since the time of certification. These changes certainly affected the air-tightness of the building envelope, reducing the energy efficiency of the home. Currently, green building certification programs have no way to account for changes such as this that may have a significant impact on building performance.

Homes 1004 and 1008 both had considerably higher infiltration rates with differences of 66% and 53%, respectively and also had similar sources of this increased infiltration. In both homes we identified insulation settling like that seen in home 1001 and also found infiltration around the joints between the wall sole plates and the sub floor. Improper air sealing also played a critical role as there were infiltration issues around doors, electrical outlets, recessed lights, ventilation fans, and the attic hatch that contributed to the decreased building performance.

Homes 1006 and 1007 tested within 26 and 24 CFM_{50} (12 and 11 L/s_{50}), respectively, of their original values. These differences are not large enough to attribute to changes in building performance and are within an acceptable margin of error due to operator error and wind effects. Although we measured an infiltration rate of 100 CFM_{50} (47 L/s_{50}) less than expected for home 1002 it is not likely that this home is actually performing better after being lived in for several years than when it was originally tested in its best possible condition. The discrepancy may be a result of differences in testing equipment calibration, testing protocols and conditions, or a combination of these factors. Although a better than expected performance might be considered a positive thing, it is crucial that the level of certification accurately reflect the environmental impacts of the building for the certification program to be meaningful and effective.

While the occupant survey helped us understand how the homeowners felt about their green home and identify any problems they might have, we found that it may have been misunderstood by respondents as to whether they should report their own activities and preferences or those of all members of the household. There are also additional questions such as the typical thermostat set point, use of air conditioners or fans, and satisfaction with the passive and active ventilation systems that could provide more insight into the relationship between occupant behavior and the measured energy performance of the building. With further refinements and pre-testing of the survey instrument, the responses could be used to conduct a more rigorous and informative quantitative analysis of occupant satisfaction and behavior and the relationships between variables such as the level of satisfaction with the home and the homeowner's level of involvement during design and construction. This would also allow us to account for self-selecting and reporting biases that may influence the responses as homeowners voluntarily participated in this study.

CONCLUSIONS

Despite the limited scope of inference of this pilot study, our findings, although preliminary, are not insignificant. They strongly indicate a need to continue post-occupancy research and collect more data about the long-term performance of certified green homes. Further study would benefit from a larger sample size, an improved occupant satisfaction survey, and a regression analysis of multiple-point blower door readings to more accurately determine the rate of infiltration. These modifications to the research methodology would allow us to better understand how building performance might change over time and how to account for these changes in the building certification programs to ensure that they accurately reflect the long-term energy efficiency of these homes.

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