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ScienceDirect

Procedia Engineering 145 (2016) 766 – 773

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

An Empirical Study on the Energy Consumption in Residential Buildings after Adopting Green Building Standards

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Abstract

In the past decades, a tremendous effort has been put into research and development of improved building systems and technologies to reduce the building energy consumption and advance energy efficiency. However, there is little to no published quantifiable evidence that assesses the energy consumption and efficiency for residential buildings with a context of green building standards. To fill this gap of information, this paper reports an empirical study that investigates the green home energy efficiency and its interaction with resident behaviors. This work uses an integrated approach of energy simulation and multivariate regression modeling. The data are from a sample of more than 300 residential units which meet the green building standards. Findings identify 43% of the annual reduction in energy usage and energy expenditures for a typical American home. Findings also identify four energy-consumption-related resident behaviors depending on which the actual energy efficiency performance of green building technology may differ.

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Peer-review under responsibility of the organizing committee of ICSDEC 2016

Keywords: Energy efficiency; resident behavior; green buildings; sustainability; built environment.

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Peer-review under responsibility of the organizing committee of ICSDEC 2016
doi:10.1016/j.proeng.2016.04.100

1. Introduction

In 2014, buildings accounted for 41% (38.5 Quadrillion Units of BTUs, or Quads) of the primary energy consumption in the United States, greater than that attributable to either industry (33%) or transportation (27%). Building energy consumption represents a cost of approximately $416 billion in 2012 dollars. In an effort to reduce building energy consumption, the nation has established the long- term goal of 30% reduction in energy use intensity by 2020.

In the past decades, a tremendous effort has been put into research and development of improved building systems and technologies with a goal of reducing energy consumption and advancing energy efficiency. In the residential building market, more than 32,000 homes have been constructed using energy-efficiency building technologies within last four years [1]. However, there is little to no published quantifiable evidence that assesses the energy consumption and efficiency for residential buildings with the context of green building standards. In absence of such evidence, a subjective evaluation of the green building technologies and their contributions to the energy use reduction will remain unlikely.

In order to fill this gap of technology, the researchers have conducted an empirical study which provides quantifiable information on the green home energy efficiency and its interaction with resident behaviors. The objectives of the presented work are to (1) identify the effects of green building technologies to home energy consumption; and (2) explore possible non-technological factors that impact the actual home energy consumption, e.g., resident behaviors.

2. Background

2.1. Importance of energy efficient homes

The US Department of Energy (DOE) 's Energy Outlook released in 2006 indicates that United States homes consumed 356 Billion kWh of electricity solely for the purpose of satisfying heating and conditioning needs [2]. This consumption equates to over 30% of total annual household electricity consumption being dedicated to space conditioning. This does not account for the many US households using sources other than electricity to meet heating needs; often natural gas.

The DOE estimates that the typical household spends approximately 8-14% of their income on energy expenditures. Of this, a third typically is consumed by energy demands for heating and cooling needs (DOE 2005). This indicates that for the typical America household, heating and cooling cost consume approximate 3-5% of their gross annual income. This percentage is not insignificant when considering the rising housing cost burden. Today, more than one-in-three American homeowners and one-in-two renters are considered to be cost burdened. It is estimated that 12 million renters and homeowners dedicate more than half of their annual incomes to housing expenses [3].

In a study examining the housing cost burden of the Housing Choice Voucher program recipients [4], housing cost burdens averaged 36%. This study further indicated that for more than a third of these households their housing cost burden exceeded 40% of their income. Structural and climate differences were attributed to contributing burden factors. The correlation between housing typology and conditioning costs has long been recognized as a factor affecting affordability.

When evaluating one's ability to financially cover housing expenditures, the common measures of affordability presented in the preceding section consider total housing expenditures inclusive of all utility expenses. However, the cost burden of these utilities is often not given adequate consideration during the construction of a home. Lee and Chin [5] noted the cost of energy bills is influenced so strongly by decisions made during design and construction that it necessitates taking a life-cycle perspective when evaluating housing. They further stated, "Investment in energy-efficiency measures may increase purchase price, yet decrease future energy bills."

2.2. Home energy consumption influences

A variety of influences, either directly or indirectly, impact household energy use. These influences are important considerations for energy-use assessments and models [6]. According to DOE [7], the important contributors to residential energy consumption include the domains of space heating, space cooling, water heating, lighting, electronics, and appliances.

Durak [8] has reviewed building science fundamentals, energy assessment tools, and commonly accepted business practices, and identified a comprehensive list of energy consumption influence parameters that drive the demand and expenditure of energy consumption domains in the residential setting. Interrelationships between the energy consumption domains and identified household energy consumption influence parameters were investigated to aid in the future development of more accurate energy models. As a result of the investigation, a condensed set of minimum influence parameters was derived from the comprehensive list to represent those needed to achieve a credible level of accuracy and confidence in energy assessments and the produced results.

Most literature pointed that the influence of home energy consumption is related to total square footage [9]. Total square footage impacts heating and cooling requirements as well as the lighting energy consumed by a household. The bigger the square footage, the more energy required to meet these needs. Total square footage of a house does not only impact energy consumption items, but can additionally affect other influence parameters such as footprint area, number of rooms, and volume. Changes to the total square footage can, in turn, alter the affected influence parameters and thus impact the energy consumption items they influence.

3. Materials

3.1. Data collection

The initial sample in this study was 312 residential units across the State of Virginia. The units included both new constructed and renovated residential buildings. New construction project units are located in the counties or cities of Arlington, Hampton, King George, Lynchburg, Petersburg and Wytheville. Renovated project units are located in the counties or cities of Abingdon, Arlington, Chesapeake, Christiansburg, Orange, Richmond, Scottsville and Virginia Beach. Table 1 summarizes all the sample units and records collected for this research. It is noted that the number of complete records is less than the sample size due to missing data or data unavailability.

Table 1. Summary of sample home units

Location	Project type	Technical records	Utility records	Behavior records	Complete records
Chesapeake City	Family	33	31	33	31
Richmond City	Senior	22	23	23	22
Richmond City	Family	30	29	36	28
Orange Town	Family	20	18	21	17
Wytheville Town	Family	24	12	14	12
Lynchburg City	Senior/ Disability	15	13	16	13
Virginia Beach City	Family	23	21	24	21
Hampton City	Family	7	9	12	7
Arlington City	Family	0	3	6	0
Pulaski Town	Senior	18	17	18	16
King George County	Senior/ Disability	24	14	15	14
Arlington County	Family	5	5	3	3
Petersburg City	Senior	25	25	20	20
Christiansburg Town	Family	14	20	9	4
Scottsville Town	Senior	13	19	8	7
Total		273	259	258	215

The sample selection was based on the building's geographical location, application of Energy-Efficiency (EE) retrofit technologies, and the sustainable construction practices. The selected units are all built or renovated after 2009, which ensures the availability of the state-of-art energy-efficiency technologies for all the units during construction. Another criterion for selection is that the units were required to meet the green building standard of Home Energy Rating Systems (HERS).

HERS presents the energy rating of a home's energy efficiency. The HERS Index is a nationally recognized scoring system for measuring a home's energy performance. Based on the results of field testing and energy modeling, an energy rated home receives a HERS Index Score. A score relates the home to the average standard American home. A score of 100 is equal to the standard home. Lower scores indicate a home performing better than the standard American home. A zero on the HERS index is given to a home demonstrating a net energy demand of zero. The HERS Index Score can be described as a sort of mile per gallon rating for houses. It provides prospective buyers and homeowners insight into how the home ranks in terms of energy efficiency [10].

In this research, two particular sets of data were collected from the participated units. One data set is pertaining to building technologies (termed as "technical records"); while the other is pertaining to resident behaviors (termed as "behavior records"). The technical record includes a home's mechanical system for heating/ cooling, mechanical system for water heating, insulation in the building shell, and lighting and appliance features. The behavior record includes temperature settings, ventilation settings, use of washer/dryers, comfort settings, etc.

3.2. Technical records

The key technical records are described as follows.

- Conditioned area
- Conditioned volume
- House type
- Air-source heat pump
- Water heating.
- Ventilation system
- Programmable thermostat
- R-value
- Windows
- Infiltration rate
- Lighting and appliances

3.3. Behavior Records

The researchers conducted a survey to collect the resident behavior data. Surveying such big amount of units in person was a difficult task. Therefore, when the research team reached out for consent for utility bill information, we also planned to collect responses for the resident behavior survey. To ensure privacy and confidentiality of data collected on resident behavior, researchers implemented a three-part approach in the research. First, we contacted with property managers to make them aware of the process and instructed them not to collect resident data themselves. Second, we created a survey handout of the survey instrument with a Spanish translation. Lastly, we coordinated with property managers to 1) hold meetings of residents for collecting survey data in person, or 2) email the link to the survey. The research team was on site to answer any questions regarding the survey and to ensure residents that their information would not be used for anything outside of the study's parameters. The research team also tried to attract residents' attention by organizing pizza parties, however many residents did not show up for the party where data were meant to be collected. Thus, the survey team also went into the developments and knocked on doors, asking people randomly to answer the survey and sign releases. As an alternate plan for on-site data collection, the team asked property managers to anonymously collect surveys left for residents.

The key behavior records are described as follows.

- Temperature setting during summer
- Temperature setting during winter
- The season when opening windows
- Use of a space heater
- Use of a fan
- Humidity setting
- Length of showers
- Use of dishwashers
- Use of washer and dryer
- Comfort setting during winter
- Comfort setting during summer
- Knowledge or education on building systems

4. Methods

To obtain the research objective #1 of identifying the green building technology's effects to home energy consumption, the researchers employed post hoc analysis through comparing the estimated home energy consumption, observed home energy consumption, and the location-based average home energy consumption. The estimated energy consumption is the simulated energy usage with the inputs of building technical data. The observed energy consumption is the actual energy usage which reflects on the residents' utility bills. The location-based average energy consumption is the public data that can be retrieved from existing publications or online database.

Specifically, the researchers used industry-standard energy models to estimate the intended design and construction on energy efficiency for each occupant household. Model estimates of utility costs are per unit for EE designs and provide a nominally estimated design effect based on the commonly. The residential energy analysis and simulation was performed in the REM/Rate software.

To obtain the research objective #2 of identifying non-technical factors' impact to home energy consumption, the researchers conducted the interaction regression modeling which combines the behavior data and energy usage. In the regression, the observed energy consumption is the dependent variable, and the estimated energy consumption and behavior variables are the regressors. The regression model is described in Equation 1 as follows.

$$E_{obs} = \beta_e E_{est} + \sum_{i=1} \beta_i B_i + \sum_{j=1} \beta_j E_{est} B_j + \varepsilon \quad (1)$$

where E_{obs} is the observed energy consumption; E_{est} is the estimated energy consumption; B_i or B_j is the ith or jth behavior predictor variable; β is the beta coefficient, and ε is a constant.

The researchers used the stepwise regression to select the best model. Stepwise regression is an automatic analytic technique in model building [11] that allows identifying a useful subset of predictors. The technique requires two significance levels: one for adding variables and one for removing variables. In other words, it combines the forward and backward selection techniques. The process systematically adds the most significant variable or removes the least significant variable during each step. Stepwise regression is modified from forward selection that it checks all candidate variables in the model to compute if the significance is reduced below the designated tolerance level in very step. As a result, all nonsignificant variables can be removed from the model one after another. The cutoff probability for adding variables should be less than the cutoff probability for removing variables so that the procedure does not get into an infinite loop.

5. Results

Table 2 summarizes the annual reduction in terms of energy and cost as a result of the incorporation of building energy efficient technologies. Results indicate that per-unit energy reduction is 5,384.3 kWh per year, which is 28.1% greater than estimated. Combining the average utility rate of $116.7 per 1000 kWh for Virginia [12], such savings equal $628.4 per year. Findings suggest that the per-unit reduction is estimated to be 34.1% yet are observed at an even larger amount of 43.7%.

Table 2. Annual reduction in energy consumption and financial expenditures

	Reduction per unit			Reduction per sq. ft.		
	Energy (kWh)	Savings ($)	Pct. (%)	Energy (kWh)	Savings ($)	Pct. (%)
Estimated	4,203.9	$490.6	34.1	5.3	$0.60	34.1
Observed	5,384.3	$628.4	43.7	6.8	$0.80	43.4

The researchers also calculated the savings by conditioned area (in square footage), considering that the per-unit data might not necessarily provide a complete picture of energy usage. Analysis indicates that the actual energy savings are 6.8 kWh per square foot, which equals to $0.80 per sq. ft. These resulting savings were then compared with national energy usage data [7]. Results in Table 2 show that area-based savings are as much as 43.4% of new standard construction for the sampled homes.

Table3 summarizes the results of comparison between the estimated and observed annual energy consumption. The estimated energy consumption is simulated based on each unit's specific building system. The authors expected units to be energy efficient after adopting green building technologies. Results from energy simulation show an overall energy consumption of 8,000.1 kWh per unit per year, lower than the statewide average of 12,204 kWh. Moreover, the estimated energy consumption for divisions by construction type and occupant type are less than the state average: new units 7,439.6 kWh, renovated units 8,424.1 kWh, units for senior residents 7,245.4 kWh, and the units for non-senior residents 8,409.1 kWh. Results from variance analysis indicate that new developments and non-senior units contain higher variability in energy usage.

Table 3. Comparison between the estimated and observed energy consumption

Division	Est. (kWh)	Obs. (kWh)	Diff. (kWh)	*N*	Std Err	*t*	*p*	Upper 95%	Lower 95%
Overall	8,000.1	6,819.7	-1,180.4	202	233.0	-5.07	$<0.001^{**}$	-720.9	-1,639.9
New	7,439.6	7,428.4	-11.2	87	362.9	-0.03	0.9755	710.2	-732.6
Renovated	8,424.1	6,359.1	-2,065.0	115	277.7	-7.44	$<0.001^{**}$	-1,514.9	-2,615.0

Note: Est = Estimated; Obs = Observed; Diff = Difference; Round-off errors may apply; ** = Significant at 99%.

While Table 3 lists the paired differences of estimated and observed energy consumption, Fig. 1 plots these data. In the plot, a coordinate with positive value (above 0) on the y-axis denotes a unit with higher observed energy consumption while a coordinate with negative value (below 0) denotes a unit with lower observed energy consumption. Results show that the mean difference is negative, which confirms reduced energy consumption in a real world setting of observed usage. Fig. 1 also illustrates the variability of energy performance across units. While the maximum variance is substantial, either positive or negative, for both new and renovated units, these outliers seem unlikely to be associated with building conditions, design, and construction. Rather, the authors posit that the variance is a result of differing resident behaviors [13].

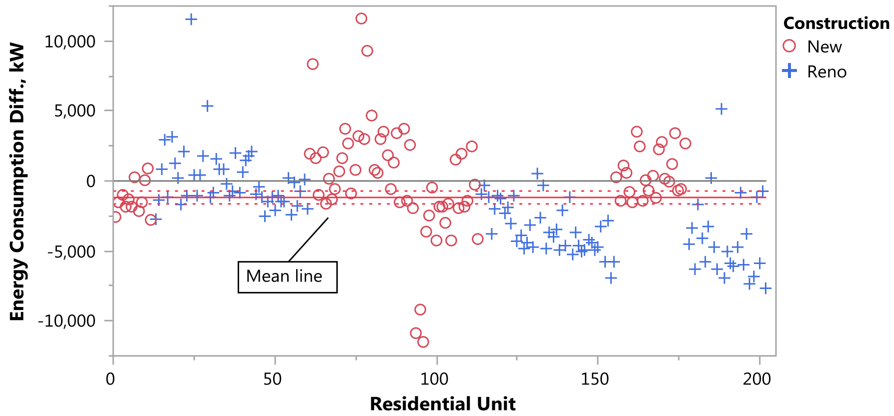

Fig. 1. Variance between the estimated and observed annual energy consumption.

The result of stepwise regression analysis identified the best model which is described as below.

$$E_{obs} \sim E_{est} + B_1 + B_2 + B_5 + B_7 + B_8 + B_{11} + E_{est}B_1 + E_{est}B_2 + E_{est}B_5 + E_{est}B_{11} + \varepsilon$$

This model shows very good of fitness and representativeness based on its following features:

- AIC = 529.01
- *R*-squared = 0.37
- *RMSE* = 0.83
- *SSE* = 130.39

The model indicates four behavior variables that have significant interaction effects with building technologies (i.e., the estimated energy use) and the combination of which results in the actual energy consumption. These behavior variables and their beta coefficients are listed in Table 4. The findings suggest that the actual energy efficiency performance of green building technology may differ depending on the identified behaviors which include the summer thermostat setting, the winter thermostat setting, the humidity setting, and the education of building systems. For example, the behaviors from a resident who possesses building knowledge will significantly leverage the green building system's performance and ultimately reduce the home's overall energy consumption (β = -0.210, p = 0.003).

Table 4. Summary of the identified significant interaction effects

Interaction	β	Std. Err	t	p	Description
B1	-0.145	0.064	-2.28	0.037*	Temperature during summer
B2	-0.417	0.130	-3.21	0.002**	Temperature during winter
B5	0.287	0.083	3.46	0.001**	Humidity setting
B11	-0.210	0.070	-2.99	0.003**	Education on building systems

Note: *= Significant at 95%; ** = Significant at 99%.

6. Conclusions

This paper reports an empirical study that investigates the energy efficiency and resident behaviors in residential buildings after adopting energy-efficiency technologies. This work innovatively integrates the energy simulation approach into multivariate regression modeling. The data are from a sample of more than 300 residential units which meet the green building standards. Findings identify 43% of the annual reduction in terms of energy consumption and energy expenditures for a typical American home with green building technologies. Findings also identify four energy-consumption-related resident behaviors depending on which the actual energy efficiency performance of green building technology may differ.

This work contributes to the body of knowledge by emphasizing the human-environment interactions in pursuing energy efficiency. It suggests that building scientists and mechanical engineers consider residents' routine behaviors during the early-stage design stages to maximize the technology's effectiveness and outcome. On the other hand, our work suggests homeowners regulate their energy-consumption-related habits to mitigate negative influences to technical systems' ideal performance.

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