RESEARCH

A STUDY OF THE ENERGY EFFICIENCY RENOVATION ON PUBLIC HOUSING PROJECTS

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ABSTRACT

While the energy efficiency of commercial buildings, schools, and private homes has received increasing attention, the energy performance of public housing has long been neglected. The high energy usage and resulting utility costs associated with such subsidized houses have added great financial burdens to the government and tenants. Therefore, improving public housing's energy performance becomes an important task. This paper presents a comparative study that mainly investigates the effectiveness of energy efficiency measures (EEMs) recently implemented in the Columbus Metropolitan Housing Authority's green renovation projects. Whole building energy simulation results show that due to budget constraints, the limited EEMs put into place would only result in a marginal (7.6%) improvement to the renovated building's energy performance prior to renovation. Another 38.5% reduction would be needed, using the performance requirement of the current building energy code as a reference. Based on these findings, this research offers some insights into more cost-effective energy efficiency upgrades that can help reduce public housing's energy consumption and green renovation costs.

KEYWORDS

public housing, home, energy efficiency, energy simulation, LEED

INTRODUCTION

The U.S. residential sector (including single-family, multifamily and manufactured home building types) alone accounts for about 22% of national energy use and 21% of carbon dioxide emissions (EIA 2010). Reducing home energy consumption is very important in light of the rising energy costs and the continuingly deteriorating environment. Although public housing (accommodating low-income families, seniors, and people with disabilities) makes up only a small portion of homes in the U.S., its high energy use, and the resulting utility expenses cannot be ignored.

It has been noticed that many public housing units are in poor condition, with deteriorating building systems and inferior energy performance. However, their current existence is still very beneficial as places of hope for low-income urban residents in consideration of ongoing

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shortages of affordable housing in many U.S. cities (Vale 2002; Econsult Corporation 2011). High utility costs thus impose great financial burdens on the residents and the government who has been providing subsidies.

According to the U.S. Department of Energy's (DOE's) Buildings Energy Data Book, the federal government provides approximately $4.0-4.4 billion as fuel subsidies for low-income housing on a yearly basis. The U.S. Department of Housing and Urban Development (HUD), one of the two major agencies dispensing fuel subsidies, spends over $1.48 billion to pay all or part of the utility bills (including water and sewage) for 1.2 million low-income households each year (i.e., an average of $1,233 per household per year). Public Housing Authorities (PHAs) usually allocate around 30% of their budgets on utilities (HUD 2006; DOE 2009; Econsult Corporation 2011). Despite this monetary support, some low-income tenants still need to pay part of their utility bills. According to Power (1999), of those living at or below 100% of the federal poverty guidelines, up to 20% of their family income was used to pay energy bills.

The energy efficiency of public housing has faced long-time neglect. Except for some interest during the energy crisis of the 1970s, it was not until recently that this problem received significant attention due to the green building movement. As a result, PHAs became more likely to choose environmentally friendly building products (e.g., high-performance windows, high efficiency furnaces/boilers, energy efficient lighting, and low-flow plumbing fixtures) in routine upgrades or green renovations (Fiedler et al. 2009; Soliman 2009; Hartwell 2011). In addition, the stimulus package signed by President Obama in February 2009 designated $4 billion to repair and modernize public housing, including increasing energy efficiency (One Hundred Eleventh Congress of the United States of America 2009). Around 3,100 housing authorities received capital funds from the stimulus package, which were then used by many PHAs to leverage funding of other sources to strengthen their public housing improvement efforts (Econsult Corporation 2011).

The Columbus Metropolitan Housing Authority (CMHA) in Columbus, Ohio, received $9 million in stimulus funds for public housing renovations and energy efficiency improvements (Soliman 2009). Due to the nature of this fund, CMHA started its green renovation projects within months of receiving stimulus money. By March 2010, a number of changes had already been made to some of the selected housing communities while upgrades in other places were underway. Since no specific standard or guideline was mandated or recommended by HUD to regulate this round of green renovations, the incurred changes were mainly based on initial suggestions from CMHA and architects' recommendations. The effectiveness of these changes in energy efficiency and economic efficiency was not well studied. Therefore, it remains unclear how effectively the money was spent and how much energy was saved after the renovation.

The purpose of this study was to investigate the effectiveness of energy efficiency improvements made by CMHA and offer insights into more cost-effective energy efficiency measures (EEMs) for future public housing green renovation projects. Using the whole building energy simulation method, this paper mainly compares the energy performance of a selected public housing unit under three conditions: before renovation, after renovation, and renovated to the current energy code. After determining the current EEMs' effectiveness, this paper proposes a few more cost-effective energy conservation measures and validates them by using energy simulation and a payback period calculation.

BACKGROUND

Introduction to CMHA's Public Housing Renovation Projects

CMHA was created in 1934 by the Ohio General Assembly. It owns approximately 3,500 public housing units, all funded by HUD. On a yearly basis, $3-5 million is granted by HUD as CMHA's operating and maintenance budget. This figure is based on a formula that considers operating and utility costs and rent collected from residents. According to Mr. Soliman, CMHA's Director of Capital Improvements, funds from HUD are usually not sufficient for maintaining public housing, and therefore CMHA has no plan to add new projects. In fact, due to high maintenance costs, CMHA has already sold some of its high-rise buildings. In addition, demolition of its six oldest and largest public housing projects has also been included in the five-year plan submitted to HUD in 2008 (CMHA 2008; Price 2009; Soliman 2009).

Most Columbus public housing was built during 1940s-1970s when building energy codes did not exist. However, these houses' current energy performance could have been improved to some degree through routine maintenance during which aged housing components or subsystems were replaced with more energy-efficient ones. The 30-year maintenance history of the Poindexter Village housing project (CMHA's oldest public housing apartment complex built in 1940) exemplified what typical maintenance, repairs, and upgrades have been performed by CMHA. As shown in Table 1, it was not until 2007 that CMHA started targeting energy efficiency and environmentally friendly improvements, including changing all boilers to high efficiency ones and replacing existing plumbing fixtures with those having water saving features (Soliman 2009).

According to CMHA's current needs, the $9 million in federal stimulus money was allocated to nine renovation projects including Sawyer Manor, Kenmore Square, Glenview Estates, Thornwood Commons, Indian Meadows, Post Oak, Ohio Townhouses, Eastmoor Square, and Trevitt Heights, 798 units in total (Soliman 2009). To ensure the proper implementation of green features, Leadership in Energy and Environmental Design (LEED) accredited architects were selected. Before the renovation design process began, CMHA provided a

TABLE 1. The Maintenance History of Poindexter Village.

Year	Maintenance, repairs, and upgrades
1980	Window replacement
1982	Roof replacement
1985	Change of hot water or steam boilers
1988	Some roof replacement
1990–91	$15 million overall renovation: new landscape, reconfiguration of floor plan by enlarging bedrooms and kitchens, new baths, doors, drywall and electrical wiring, roof repair, adding parking spaces
1992	Adding new 5-bedroom units
1994	Adding a new community center
2003	Air conditioning added
2004	Floor, beam, and roof soffit replacement
2005	Roof shingle and siding replacement and added canopies
2007–09	$3 million energy efficiency and water conservation improvements

list of required changes to the hired architects. These were typical green applications already in use by CMHA, such as low-flow toilets, insulated doors and windows, etc. The architects were left some flexibility in selecting additional green technologies and products that could meet CMHA's budget requirements. As one important goal of the stimulus package was to create jobs for U.S. workers, these projects were required to use only U.S. made building products, which could potentially increase the renovation costs. More details about the applied EEMs are presented in the "Methods and Procedures" section of this paper.

A History of EEMs Applied in Public Housing

As mentioned earlier, the high utility costs of public housing are mainly covered by government subsidies. During the energy crisis of the 1970s, policymakers realized that the full reimbursement of utilities gave PHAs no incentive for energy efficiency improvements and no funding mechanism existed to help them pay for the up-front costs of energy conservation measures. Therefore, a series of incentives including savings retention, utility rate reduction, frozen base, and additional subsidies were developed (Vermeer 2002). According to Vermeer, by 2001, PHAs had executed 87 incentive plans, resulting in annual savings of $31.9 million in energy and water costs. In addition, due to the growing awareness of green building practices, more and more PHAs started to integrate EEMs and other green technologies into their routine upgrades or major renovations.

In 1999, the Ashville Housing Authority rehabilitated a 100-unit multifamily building using energy efficient windows and doors, heat pumps, efficient lighting, efficient appliances, and water fixtures. These measures reduced the building's energy use by approximately 30%. This level of savings was deemed typical for common cost-effective energy efficiency improvements (EWC 2006). The Boston Housing Authority (BHA) retrofitted a 540-unit property in 2000 by mainly converting the central heating and domestic hot water (DHW) systems (Vermeer 2002). The Seattle Housing Authority (SHA) utilized Washington's Evergreen Sustainable Development Standards criteria to improve energy efficiency and correct enclosure deficiencies in senior housing buildings. The selected low-cost EEMs included a liquid air- and weather-resistive barrier, additional exterior insulation, ENERGY STAR appliances and lighting fixtures, double-glazed insulated windows, and sealing exhaust vents. SHA also considered building external partnerships to perform cost/benefit analyses of renewable energy options such as solar water heating (Hartwell 2011).

The government's stimulus money has facilitated PHAs nationwide to perform a large number of public housing upgrades, renovations, or begin new development projects within a 3-to-4-year period. The Allegheny County Housing Authority in East Pittsburgh used $4.4 million in stimulus funds to pay for a geothermal water system, which could cut the energy costs of a 94-unit public housing project by 50%. With additional financial support from the county, this renovation project also included insulated roofs, new windows, and ENERGY STAR rated lighting and appliances to further enhance energy efficiency (Sherman 2009). For many PHAs, "going green" was another main focus. Therefore, besides commonly used EEMs, more comprehensive green features were incorporated. For example, the Chicago Housing Authority rehabilitated a vacant apartment building using energy efficient mechanical and lighting systems, storm water management landscape features, natural lighting, air circulation, and a green roof (The City of Chicago 2011).

In a study commissioned by the Council of Large Public Housing Authorities, two PHAs were selected to showcase how they spent the stimulus money and what long-term benefits were created to the public housing properties and residents. Besides the widely reported improvements in ventilation, indoor air quality, moisture control, and mold prevention, annual utility savings in these properties were estimated (Econsult Corporation 2011). For example, The Cambridge Housing Authority spent $36.5 million and $2.8 million on two of its renovation projects and the estimated annual savings were $409,000 and $121,000, respectively (Econsult Corporation 2011). Although the study did not provide a cost/benefit analysis, when the recorded expenditure and estimated savings were made available, long payback periods (89 and 23 years, respectively) were obvious to readers. The long payback years, if acceptable for the stimulus funds, do not make sense from an economic standpoint if the money was raised from other sources. This suggests the need for performing cost/benefit analyses before major EEMs were actually adopted.

EEMs Recommended by Energy Efficient/Green Home Programs

Government agencies and non-government organizations have already started addressing energy efficiency issues in existing homes. The U.S. government launched the Weatherization Assistance Program (WAP) in 1976 to enable low-income families to reduce their energy bills by applying basic weatherization procedures. The income-qualified public housing projects are eligible for such assistance. The major strategies include conducting a home energy assessment, adding insulation for building envelopes, sealing all types of leaks, etc. (WAPTAC 2011a). Primary window replacements were not considered cost effective in weatherization compared to other measures such as weather-stripping and efficient lighting (EWC 2006; WAPTAC 2011a). The program also collaborated with the ENERGY STAR program to make qualified products, such as energy efficient light fixtures, air conditioners, dehumidifiers, and home appliances affordable for low-income applicants (WAPTAC 2011b).

Some organizations have developed building energy codes, green home guidelines, and energy efficiency/green home certification programs. The International Code Council (ICC) has created several codes featuring energy efficient home building requirements such as the International Energy Conservation Code (IECC) and the International Residential Code (IRC) (ICC 2009a). Standard 90.2 titled "Energy Efficient Design for Low-Rise Residential Buildings" was developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in 2001 and fully endorsed by the American National Standards Institute (ANSI) (ASHRAE 2007). These codes address home energy efficiency either through mandates on insulation, fenestration, and building subsystems, or using a performance-based compliance path supported by energy simulation results. Although these codes and standards are only required for new housing projects, they can be used as references for energy retrofits (e.g., providing proper insulation values). It is up to PHAs to decide whether meeting the current energy code is their project goal for renovation and whether the associated costs are under their budgets.

In 2008, the first nationwide guideline for green residential renovations, REGREEN, was created by the American Society of Interior Designers (ASID) and the U.S. Green Building Council (USGBC) (ASID and USGBC 2009). It adopts a systems-thinking approach to integrating the most effective practices in home remodeling. The guideline offers nearly 200 green strategies. The proposed EEMs consist both of more expensive methods (e.g., using high-efficiency HVAC equipment) and less costly measures, such as installing programmable thermostats, insulating water heaters, or making use of trees and landscaping to reduce cooling loads. While this guideline provides a brainstorming checklist for remodeling professionals, it is still up to them to select the appropriate strategies to balance the remodeling costs with energy savings. A computer model for energy efficiency is then recommended to determine the overall efficiency of the home, predict energy bills, and see how energy efficient a home is when compared with the current building energy code.

A few other energy efficiency or green home certification programs also exist, such as ENERGY STAR (EPA 2011a), the National Green Building program (NAHBGreen) (NAHB 2009), the Enterprise Green Communities (Enterprise Community Partners 2011), and the LEED for Homes (USGBC 2008). All these programs offer comprehensive approaches to improving energy efficiency or making a home green. For example, NAHBGreen covers six green building categories, ranging from lot development, to energy and water conservation, and to indoor environmental quality. The proposed EEMs focus on properly sized, high efficiency HVAC systems with sealed ducts, adequately insulated and sealed building envelopes, passive solar design (including exterior shading and solar reflective roofing), energy efficient lighting, water heating and home appliances, and renewable energy applications. The LEED for Homes program covers almost the same green categories as NAHBGreen does.

It is worth mentioning that the guideline and certification programs reviewed above are all applicable to single-family and multifamily affordable housing renovation projects, and therefore they can be good references to green renovation project teams. For example, the Ithaca Housing Authority has incorporated ENERGY STAR into the housing units it manages by requiring all contractors to use only ENERGY STAR qualified products and adopting significant energy conservation measures in its 341 multifamily public housing units (EPA 2011b). BHA has also aimed to obtain LEED for Homes certification for its green renovation projects. The ultimate goal is to build a cost-effective, replicable, sustainable rehabilitation model for public housing (The City of Boston 2009). It should be noted that some programs, such as ENERGY STAR and the LEED for Homes, are not applicable to high-rise residential buildings at the current stage. However, this may be changed in the future.

Despite some success in home energy conservation, the existing codes, guidelines, and certification programs may not have adequately addressed cost concerns related to energy efficiency improvements. It has been noted that replacing windows, installing a new roof, or retrofitting the HVAC system can be expensive. Obtaining green home certification might also be costly. Field practitioners are, therefore, seeking out more economical EEMs. Hoffman (2011) performed a cost-benefit analysis on a series of energy conservation measures. Table 2

TABLE 2. Cost-effective EEMs (Adapted from Hoffman 2011).

Energy Efficiency Measures	Cost ($)	Payback period	Return of investment (tax free)
Low flow shower heads	$118	2.6 months	453%
Heater wrap	$20	6 months	189%
Energy efficient lighting	$16	1.14 years	87.5%
Smart strips	$20	1.26 years	78.8%
Domestic re-circulation	$167	3.24 years	30.8%
ENERGY STAR Refrigerator	$800	4.76 years	21%
Solar DWH system	$6,250	5 years	20%
Solar photovoltaic system	$30,000	5.72 years	17.45%
Spray foam insulation	$7,000	13.6 years	7.3%

lists those relevant to public housing renovation and displays their payback periods and return of investment in descending order from the shortest payback time to the longest. Apparently, adding insulation is not a good option compared to using low-flow showerheads or adding heater wraps due to the former's longer payback period of 13.6 years. The cost-effectiveness of solar applications (especially for the solar photovoltaic system) is not clear without a clarification on whether the federal and state incentives were excluded in the calculation.

METHODS AND PROCEDURES

This research mainly aims to investigate the effectiveness of energy efficiency improvements made by CMHA in its green renovation projects, and to provide insights on more cost-effective EEMs for future green renovations. Four research questions were presented:

- How much energy could be saved in a renovated house?
- Are these adopted energy efficiency measures (EEMs) cost-effective options?
- How energy efficient is a renovated house compared to the current building energy code?
- If continual improvement needs to be conducted, what might be some other cost-effective EEMs that can be applied to public housing?

In the following, detailed research methods and procedures are explained.

Data Collection

Collecting detailed information related to the existing conditions and renovation design of the selected public housing project is an important research task. In the early stage of this study, information about public housing renovation was collected through face-to-face interviews with CMHA officers: Mr. Soliman (Director of Capital Improvements) and Mr. Nesbit (Director of Public Housing). They had good knowledge of the development of Columbus public housing and were closely involving in the green renovation process. A list of questions was prepared to guide the interviews. The information obtained includes the maintenance history of Columbus public housing, EEMs applied by CMHA in the past, the projects selected for green renovations, the design teams hired, and CMHA's budget and specific requirements for these projects.

After meeting CMHA officers, the authors contacted the four architectural firms that CMHA hired for green renovations and selected one with whom to collaborate. This was due to the integrated architectural design and engineering services the firm offered to CMHA and its willingness to participate in the study. To obtain technical information for energy simulation, a three-page detailed questionnaire was developed and used during the first face-to-face meeting with Mr. Vedaie, the architect assigned to work on the firm's CMHA projects. A few additional visits to Mr. Vedaie were also conducted on an as-needed basis (e.g., picking up project drawings and collecting supplemental project information).

The selected firm was responsible for three of CMHA's renovation projects: Trevitt Heights, Eastmoor Square, and Ohio Townhouses. Based on the information provided by the architect, a housing unit in Trevitt Heights was selected for energy simulation. It was selected because, among the three renovation projects, Trevitt Heights had the lowest number of building plan types (only three). Therefore, energy simulation performed for one building could represent the energy performance of a large portion of renovated buildings in the community. To enhance the understanding of the selected house, site visits were conducted to observe the house's exterior conditions and environment.

Selection of the Energy Simulation Tool

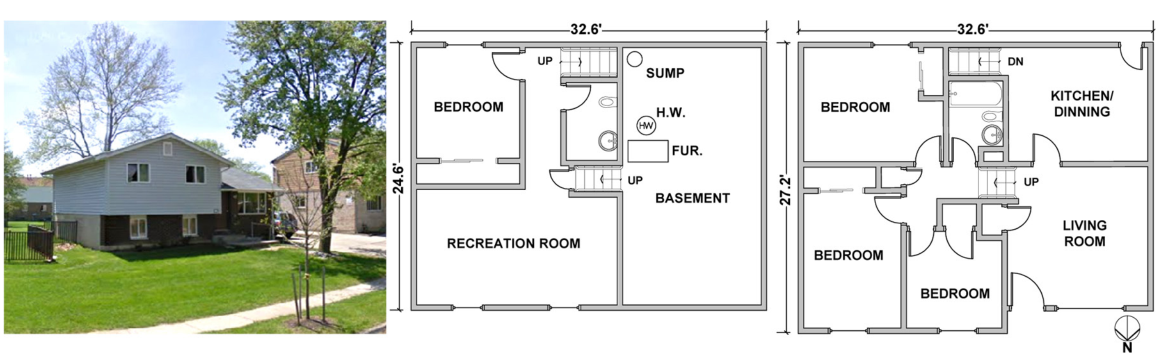
Due to timing and data accessibility issues (i.e., a portion of the green renovations is still ongoing and the yearly energy consumption data for the renovated houses is not available and would be difficult to obtain in the future), the whole building energy simulation method was selected to predict the energy performance of a renovated house. A technical review of existing energy simulation tools was conducted based on the Building Energy Software Tools Directory on the DOE website (DOE 2010a). The search was narrowed down to three widely acknowledged whole building energy simulation tools: EnergyPlus (DOE 2010b), EnergyGauge USA (Florida Solar Energy Center 2010) and eQUEST (the Quick Energy Simulation Tool) (James J. Hirsch and Associates 2009). Although they are all based on the powerful "DOE" simulation engine, eQUEST was selected for this study due to several reasons, including its user-friendly interface, accurate and professional results, easily understandable graphical reports, and capability for side-by-side EEM comparison (with up to five design alternatives).

The Creation of eQUEST Modeling Runs

This study used the Design Development (DD) Wizard in eQUEST to build three modeling runs: Run 1 (the baseline model for existing housing conditions), EEM Run 2 (after the renovation), and EEM Run 3 (current code). By comparing their predicted monthly and annual energy performance, this study was able to determine the effectiveness of the green renovations. The Type C housing unit in Trevitt Heights was selected for energy simulation and analysis. Figure 1 shows the house's external appearance and floor plans.

The Type C housing unit is a split-level, four-bedroom, single-family house with the main entrance facing north. The total floor area is 1,654 sq ft: an upper level of 852 sq ft and a lower, partially below grade level of 802 sq ft, including one basement utility room. The house has a floor height of 9.0 ft and floor-to-ceiling height of 8.0 ft. The roof pitch is about 20 degrees. There are two established trees on the site: one in front of the house and the other in the backyard. No shrubs or trellises shade the exterior walls and no blinds were installed for the windows. The detailed information used to create the three modeling runs for this house is described below.

FIGURE 1. Site environment and floor plans of a Type C housing unit.



a. Site environment   b. The lower floor plan   c. The upper floor plan

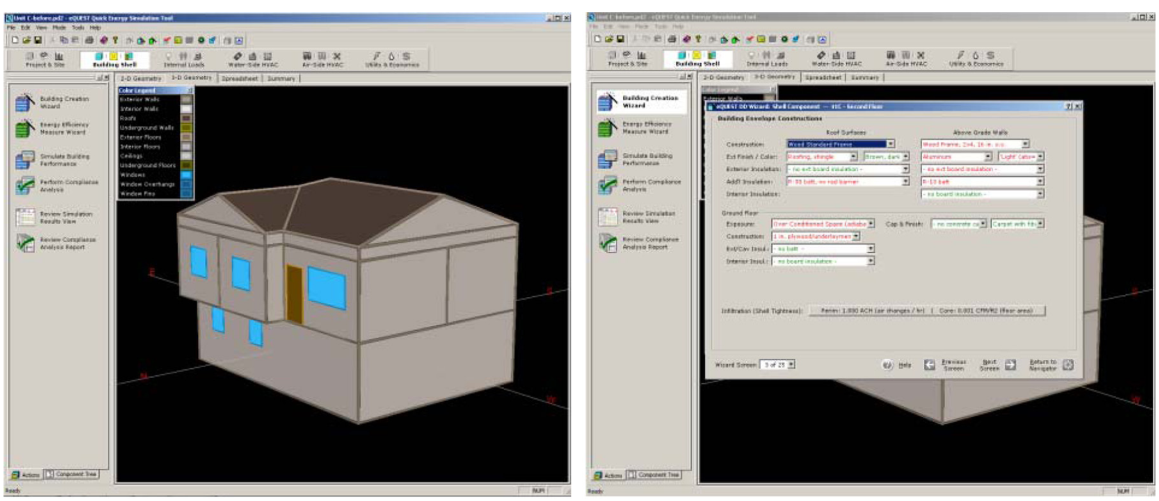
Run 1 (The Baseline Model for Existing Housing Conditions)

To maintain the simplicity of the eQUEST model, the four-level split home was modeled as a two-level home with the same floor layouts shown in Figures 1b and 1c. The lower level was set 4.5 ft below grade. The building type selected was "multifamily, low-rise (exterior entries)" since the software does not provide a single-family building type. However, this alternative would not affect the simulation results because it is also applicable to the modeling of single-family houses. The eQUEST location was set as Columbus, Ohio for retrieving hourly weather data. The utility rates were defined as 12 cents per kWh for electricity (using the average rate from American Electric Power Ohio) and 65.3 cents per therm, plus a monthly customer charge of $21.46 for natural gas based on the rate from Columbia Gas of Ohio (PUCO 2011). Table 3 lists major housing parameter values used in the baseline model.

It is known that the completeness of modeling information is important for performing accurate simulations. However, it is hard to obtain all building parameter values for such an old house and to know every detail about its usage and maintenance. Therefore, when some building parameters' real world values were not available, their default values predefined in the software (e.g., design ventilation rates and interior lighting loads) were used for simulation. Since the real building usage profiles for individual households living in Type C units could be very different, the default building operation schedule and occupancy profile were adopted to standardize these variables. For non-HVAC (Heating, Ventilation, and Air Conditioning) end-uses, including DHW, interior lighting, cooking equipment, and others, their default hourly profiles were directly used or slightly altered to reflect typical uses of low-income families. Figure 2 displays two screenshots that show eQUEST modeling interface examples.

After all of the building information for the baseline model was input into eQUEST, monthly and annual energy consumption was simulated, with both detailed and summarized reports generated. Since the modeled housing unit was built in 1971, in addition to regular

FIGURE 2. Screenshots of eQUEST modeling interfaces.



a. 3D geometry of the modeled house

b. Input interface example

TABLE 3. Building Parameter Values for Type C Housing Unit.

Housing parameter	Value used in simulation	Housing parameter	Value used in simulation
Lower level building envelope construction			
Floor construction	6″ concrete (earth contact)	Interior finish	Carpet w/ fiber pad
Ext./cav. insulation	No perimeter insulation	Wall construction	12″ CMU grouted 24″ o.c.
Ext. finish/color	Brick/red	Exterior insulation	None
Higher level (above grade) building envelope construction			
Wall construction	Wood frame, 2×4, 16″ o.c.	Ext. insulation	No ext. board insulation
Ext. finish/color	Aluminum/light (abs=0.4)*	Add'l. insulation	R-13 batt
Roof surfaces			
Roof construction	Wood standard frame	Ext. insulation	No ext. board insulation
Ext. finish/color	Roofing, shingle/brown, dark	Add'l. insulation	R-30 batt, no radiant barrier
Building interior construction			
Ceilings	Wood, standard framing w/ drywall finish, no insulation	Vertical walls	Frame w/o insulation
Exterior (shell)			
Shell tightness (infiltration)	1 ACH (air changes per hour)**	Window frame	Reinf'd vinyl, oper, ins spacer, 2.78″ width
Window glass type	Double clear 1/8″, 1/4″ air	Window overhangs	None
Window fins	None	Window blinds/drapes	None
Roof skylights	None	Door type	Steel hollow core w/o break
Heating, ventilation & air conditioning (split system single zone DX coil w/ gas furnace, residential)			
Heating equip. size	82.0 kBtuh	Return air path	Ducted
Crankcase heating	Allowed	Efficiency	0.806
Heating thermostat set point (occupied)	72°F	Heating thermostat set point (unoccupied)	72°F+
Cooling equip. size	3.0 tons	Condenser type	Air-cooled
Cooling thermostat set point (occupied)	75°F	Cooling thermostat set point (unoccupied)	75°F
Min. design air flow	1.09 CFM/ft^2	Efficiency	SEER 10.00
Supply fans power	0.30 BHP	Fan flow & OSA	Auto-size flow w/ 1.15 safety factor
Fan type	Variable speed drive	Fan "on" mode	Intermittent
Domestic Water Heating (DHW)			
Water heater fuel	Natural gas	Water heater type	Storage
Hot water use	20.00 gal/person/day++	Input rating	37.5 kBtuh
Storage tank capacity	40 gal.	Thermal efficiency	0.750 fraction
Storage tank insulation	7h–ft2–°F/Btu	Standby loss	5.00%/hr
Supply water temp.	130°F	Recirculation	0%

* Vinyl siding is not an option in eQUEST for exterior finish. Light color aluminum was selected as an alternative.
**Older homes can have measured ACH up to 2-3. Homes with an ACH above "1" are generally considered to be leaky (Kamon Company 2008). The borderline value "1" was selected by this research for the baseline model.
+eQUEST default setting does not alter the thermostat temperature set point when the house is not occupied. A survey of public housing residents (N=42) performed by this research showed that 76% of these residents kept a constant temperature on their thermostats all the time regardless of being at homes or away.
++National average hot water use rate (Hoffman 2011).

maintenance and repairs, aged building components or subsystems (e.g., windows, roof, furnace, air conditioning, and siding) were already replaced. So the "existing conditions" used in the baseline model actually represent the house's original conditions with all of these changes applied. This should lead to better energy performance compared to 30 years ago. However, building parameter values shown in Table 3 (e.g., insulation values for exterior walls, air change rate of the building shell, and efficiencies of heating and cooling systems) still could not meet the current code requirements (discussed in EEM Run 3 later), negatively impacting the home's energy efficiency. While the house's energy performance prior to renovation was predicted in the simulation results of the baseline model, its level of energy efficiency was actually determined through comparisons with the predicted energy performance of the same house renovated to the current building energy code. The result is presented in the "Findings and Discussions" section.

EEM Run 2 (After Renovation)

This run was created by adding energy efficiency improvements made by the project architect to the baseline model. The goal was to predict the house's energy performance after these renovations. The incurred value changes in housing parameters are shown in Table 4. The rationales for such changes are explained below.

Replacing windows and doors would improve the thermal efficiency of the housing envelope. Specifically, the new double-glazed low-E argon windows can reflect radiant energy (heat) back to its source with the aid of a thin-layer coating of low-emissivity (low-E) material, e.g., aluminum foil. This reduces solar heat gain during the summer and heat loss in the winter. The argon gas fill has a lower thermal conductivity than air, further improving the windows' insulating performance. The new steel polyurethane core doors have enhanced insulating performance. For example, a steel door with a 1 3/4″ polyurethane core offers an insulating value of R-13. In addition, the new windows have a lower air leakage rating (0.2cfm/ft^2) than the older ones. Replacing the windows and doors and sealing properly, could reduce the house's air infiltration rate after renovation.

In this renovation, existing plumbing fixtures were replaced with those having water-saving features. By using low-flow showerheads (e.g., 1.8 gallon/minute instead of 2.5 gallon/minute)

TABLE 4. Changes in Housing Features due to the Green Renovation.

Housing parameter	Value before the renovation	Value after the renovation
Window glass type	Double clear 1/8″, 1/4″ air	Double low-E, clear 1/4″, 1/2″ argon
Shell tightness (infiltration)	1 ACH	0.7 ACH*
Door type	Steel hollow core w/o thermal break	Steel, polyurethane core w/o thermal break
Hot water use	20.00 gal/person/day	17.30 gal/person/day
Input rating	37.5 kBtuh	25.3 kBtuh
Water heater thermal efficiency	0.750 fraction	0.900 fraction
Hot water storage tank insulation	7.0h–ft2–°F/Btu	12.0h–ft2–°F/Btu
Standby loss	5.00%/hr	1.00%/hr
Supply water temp.	130°F	110°F

*Air exchange rates of 0.35-1.0 are considered to be moderate to a home (not too leaky and not too tight) (Kamon Company 2008). The 0.7 ACH was selected for EEM Run 2 based on the assumption that the renovated house's shell tightness is better than the house before renovation but poorer than a typical new house.

and faucets, hot water use in the renovated house could be reduced. By replacing the existing DHW system with a high efficiency one, the system's thermal efficiency was improved from 0.750 to 0.900. The insulation value of the storage tank was raised from 7.0h–ft2–°F/Btu to 12.0h–ft2–°F/Btu, leading to a reduced standby loss of 1.00%/hr. The supply water temperature was also lowered to 110 °F. All of these changes would help cut water heating energy use.

EEM Run 3 (Current Code)

This run was used to simulate the house's energy performance if it were renovated to meet 2009 IECC requirements (ICC 2009b). Table 5 shows the major changes that need to be made to EEM Run 2. It can be seen that 2009 IECC mandates higher insulation values for housing envelope components and also requires tighter shell construction. To become code compliant, the HVAC system (including both the heating and cooling equipment) needs to be downsized with increased efficiency. Also, the programmable thermostat is required to control the HVAC system on a daily schedule in order to maintain different temperature set points based on the occupancy. The initial temperature set points are 70°F for heating and 78°F for cooling. The code also requires a minimum of 50% of permanently installed lighting fixtures to have energy efficient lamps (e.g., compact fluorescent lamps) that use about 75% less energy than standard incandescent bulbs according to the DOE's ENERGY STAR program (EPA 2011c). This results in a 37.5% reduction of total interior lighting loads.

EEM Run 4 (Proposed)

This study proposed several simple, economical EEMs that were selected from the best green home remodeling practices reviewed in the literature to further enhance the house's energy performance beyond the current renovation. These measures were added into EEM Run 2 to create EEM Run 4 (proposed).

The first proposed measure aims to improve the shell tightness of the house, which can not only reduce the energy lost by air leakage but also make it possible to downsize the HVAC system when it needs to be replaced. For this purpose, bypasses around pipes, ducts, recessed

TABLE 5. Code-compliant Changes in EEM Run 3.

Housing parameter	Value used in EEM Run 3
Roof insulation	R-38
Exterior wall insulation (wood frame)	R-13 cavity insulation plus 1″ polyurethane (R-6)
Mass wall/basement wall (lower level)	R-11 wood furred insulation
Shell tightness (infiltration)	0.35 ACH*
HVAC-cooling overall size	2 tons**
HVAC-cooling efficiency	SEER 13
HVAC-heating typical unit size	50 kBtuh
HVAC-heating efficiency	92%
HVAC-airflows minimum design flow	0.5 CFM/ft^2
Heating thermostat set point	70°F (occupied) and 55°F (unoccupied)
Cooling thermostat set point	78°F (occupied) and 85°F (unoccupied)
Interior lighting	Interior lighting loads reduced by 37.5%

*New energy efficient homes can be considered tight construction with ACH ranging from 0.2 to 0.3 (Kamon Company 2008). A minimum ACH at 0.35 is allowed for residential buildings without mechanical ventilation (ASHRAE 2001).
**The size of the HVAC system was provided by a leading residential HVAC contractor's design engineer.

light fixtures and electrical wiring as well as cracks and gaps in framing need to be sealed with low VOC (volatile organic compound) polyurethane caulk, which would not adversely impact indoor air quality. The improved infiltration rate is intended to be 0.35 ACH, so additional mechanical ventilation would not be required. This application may need around 15 tubes of caulk at $5.74 each (online price listed on Home Depot's website, as of August 10th, 2011), with a total material cost of approximately $86, without tax. Polyurethane caulk is a very durable product, especially for outdoor applications and can last for 20 years on average.

The second measure is to retrofit the current thermostat with a programmable model. A programmable thermostat can save heating and cooling energy use by regulating the house's temperature in both summer and winter under different operation modes: at home, asleep, or away. In this study, the thermostat would be initially programmed to have a heating temperature set point of 68°F and a cooling temperature set point of 78°F when the house is occupied. The heating and cooling temperature set points under the unoccupied mode would be 55°F and 85°F, respectively. A seven-day programmable thermostat costs around $69 (online price listed on Home Depot's website, as of August 10th, 2011) with a life span of 5–10 years.

The third measure is to replace all the light bulbs in the house with compact fluorescent lamps. Accordingly, the interior lighting power densities in different activity areas (W/ft^2) can consistently be lowered by 75%. This would not only reduce electricity use, but also cut the cooling costs by minimizing extra heat produced by the bulbs. Based on the house's floor plans and the default lighting power densities in eQUEST, this application would require 2, 10, and 3 compact fluorescent bulbs at 100W (equivalent power), 60W, and 40W, respectively. The total cost would be $35 (online price listed on Home Depot's website, as of August 10th, 2011). Each bulb has 10,000 life hours (a six-year life span at 4–5 hours per day). Some other EEMs, such as adding external and internal shading, using landscape features for passive solar design, and replacing roof shingles, were also considered, but not selected. The reasons are presented in the section of "Findings and Discussions."

Payback Period Calculation

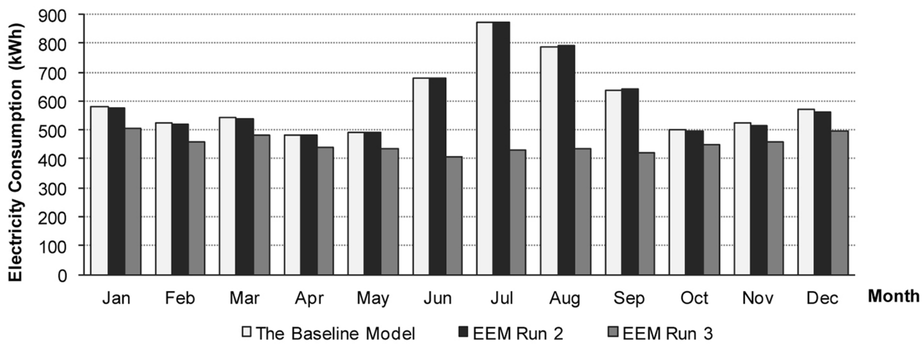
This study performed a simple payback period analysis to evaluate the cost effectiveness of the proposed EEMs. This type of analysis usually does not consider taxes, depreciation, salvage costs, maintenance costs, interests, etc. The number of payback years is computed by dividing the cost of improvement by yearly savings. In this study, it was assumed that material cost accounts for 50% of the total construction costs, excluding changing bulbs, which can be done by maintenance staff or residents for free. Based on these assumptions, the renovation costs for the proposed measures were determined. On the other hand, the yearly energy cost savings were provided by the energy simulation. The energy simulation and economic analysis results would validate whether the proposed EEMs are truly cost-effective and should be among the very first choices for energy retrofit of public housing.

FINDINGS AND DISCUSSIONS

Analysis and Comparison of Energy Performance

This study simulated the selected home's energy performance under different conditions in four modeling runs. A series of comparisons were performed among them based on electricity use, natural gas use, and utility cost. The results are presented and discussed below.

FIGURE 3. Monthly electricity consumption comparison among three modeling runs.

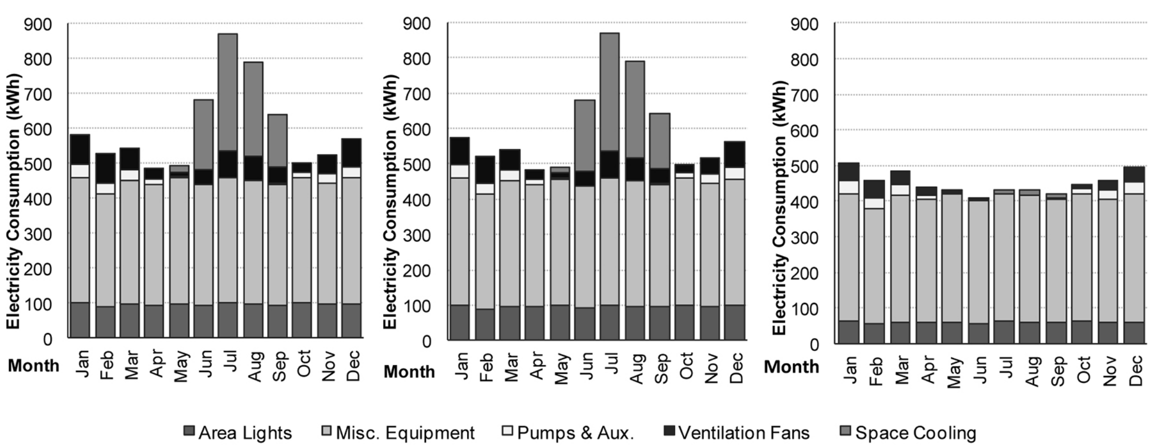


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy Savings	Percent of Reduction
The Baseline Model	582.8	525.9	543.9	484.2	492.8	679.3	869.8	788.6	638.2	499.3	521.9	570.1	7,196.8	-	-
EEM Run 2	574.9	518.5	538.3	481.4	491.1	678.0	870.3	790.6	642.6	496.2	516.7	562.8	7,161.4	35.4 kWh	0.5%
EEM Run 3	507.1	458.2	483.2	438.9	432.8	405.2	430.8	432.6	419.5	447.9	459.4	496.4	5,412.0	1,749.4 kWh	24.4%

Figure 3 illustrates the side-by-side comparison of monthly electricity consumption for the baseline model, the renovated run, and the code-compliant run. It can be seen that the difference between the renovated run and the baseline model is minor. The renovation only results in 0.5% reduction of the house's annual electricity use (i.e., 35.4 kWh), indicating the ineffectiveness of the applied EEMs in saving electricity. Figure 3 also shows that the current code run has lower electricity consumption in each month compared to the other two runs, and offers even greater savings in summer months (from June to September). Overall, the code-compliant house could save 1,749.4 kWh (24.4%) on a yearly basis beyond the renovated house.

This study analyzed the three modeling runs' detailed monthly electricity consumption based on five end-use categories to assess specific electrical saving effects of various EEMs applied. The graphical comparison of the simulation results is shown in Figure 4.

FIGURE 4. Detailed monthly electricity consumption comparison among three modeling runs.



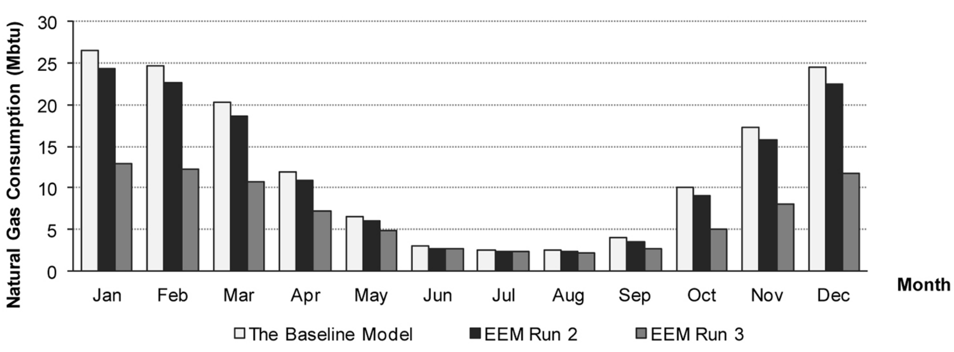
a. The baseline model b. EEM Run 2 (renovated) c. EEM Run 3 (2009 IECC)

It can be seen in Figures 4a and 4b that, the amounts of electricity used in each category of the baseline model and the renovated run are almost identical. The related EEMs, including replacing windows and doors with more energy efficient products and improved shell tightness, seem ineffective in reducing space cooling energy use. When comparing the renovated run and the code-compliant run (Figures 4b and 4c), major electricity savings were found in space cooling and area lighting. The significant cut in cooling energy (almost being eliminated in the code-compliant model) could be mainly caused by improved building envelope insulation and further enhanced shell tightness as well as a downsized, high-efficiency HVAC system. The savings in area lighting are attributed to the use of high efficiency lamps. In addition, the reduced need for space cooling also decreases the electricity consumption of fans to some degree. These findings indicate that the code-compliant EEMs are very effective in saving electrical energy at home. There is no reduction of energy use for miscellaneous electrical equipment (e.g., refrigerator), or for pumps and auxiliary devices, since no related EEMs were applied.

Figure 5 below illustrates the difference in monthly natural gas usage among the three modeling runs. The renovated run has slightly lower monthly gas consumption than the baseline model, resulting in an annual savings of 13.45 Million Btu (MBtu) or 8.7%. The reductions during winter months are slightly higher than the reductions during summer months. The above information denotes that the renovation could only lead to a small improvement in energy efficiency in terms of fuel use. Compared to the renovated run, the code-compliant run can achieve significant energy savings throughout the winter months (from October to April), leading to a yearly reduction of 57.64 MBtu or 40.9%.

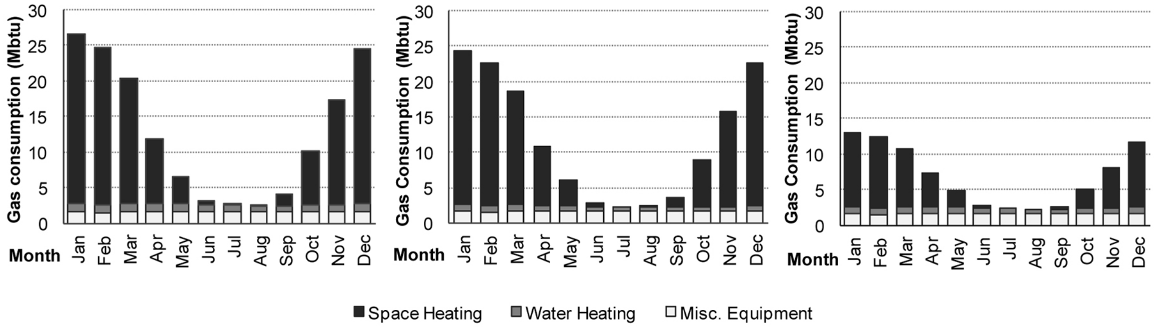
To assess the specific fuel saving effects of the various EEMs applied, a detailed comparison of monthly gas consumption based on three end-use categories was performed among the modeling runs. The comparison is shown in Figure 6. From Figures 6a and 6b, it can be seen that during winter months, the gas usage for space heating in the renovated run is consistently and slightly less than that of the baseline model. This indicates that replacing windows and doors and improving shell tightness had some positive impact on reducing space heating energy use. It is noted that the renovated run has slightly reduced monthly gas consumption

FIGURE 5. Monthly natural gas consumption comparison among the three modeling runs.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Energy Savings	Percent of reduction
The Baseline Model	26.55	24.71	20.36	11.89	6.61	3.06	2.55	2.53	3.99	10.06	17.35	24.55	154.22	-	-
EEM Run 2	24.33	22.65	18.66	10.90	5.99	2.76	2.35	2.30	3.53	9.00	15.80	22.49	140.77	13.45 MBtu	8.7%
EEM Run 3	13.00	12.32	10.71	7.24	4.94	2.75	2.35	2.27	2.63	5.09	8.14	11.69	83.13	57.64 MBtu	40.9%

FIGURE 6. Detailed monthly gas consumption comparison among the three modeling runs.



a. The baseline model b. EEM Run 2 (renovated) c. EEM Run 3 (2009 IECC)

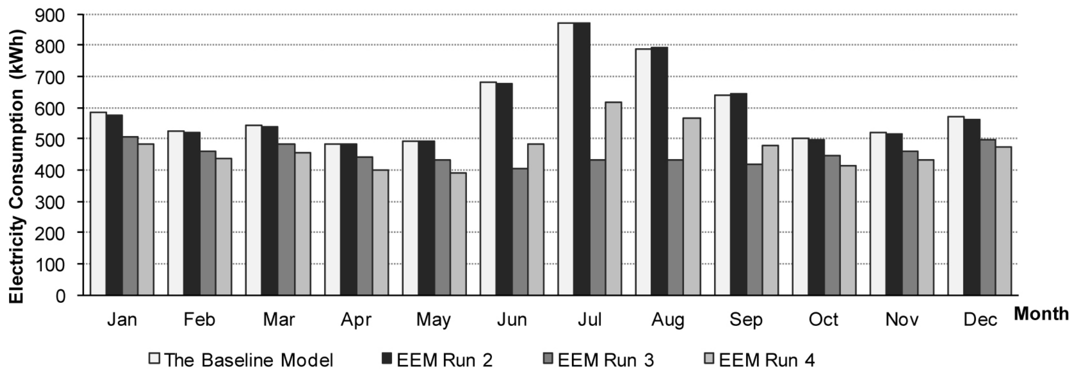
for water heating than the baseline model. This is due to the improvements in the DHW system and the reduced hot water use by using low-flow showerheads and faucets. A significant decrease of space heating energy use during the heating season can be seen between the code-compliant and renovated runs by comparing Figures 6b and 6c. This confirms the effectiveness of improving building envelope insulation and shell tightness, installing a downsized, high-efficiency HVAC system, and using a programmable thermostat in saving space heating energy. There is no reduction in gas-fired miscellaneous equipment (e.g., gas stove) among the three runs, with no related EEM(s) applied.

Based on the simulation results from eQUEST, annual energy consumption values (electricity and gas combined) of the baseline model, renovated run and code-compliant run were calculated as 178.78 MBtu, 165.21 MBtu, and 101.60 MBtu, respectively (1 kWh = 3413 Btu). Compared with the existing house, the renovated one achieved approximately 7.6% energy savings. However, to meet 2009 IECC requirements, its energy consumption needs to be further reduced by another 38.5%. The eQUEST simulations also provided an annual utility bill (only including electricity and gas) for each modeling run. The renovated house could save the tenant only $93 per year, bringing the bill down from $2,129 to $2,036. If renovated to 2009 IECC, the energy cost could be further decreased to $1,192, saving another $844 a year. This information also implies that the house before renovation could consume 76.0% more energy compared to the same house if renovated to the current building energy code and cost the tenant $937 more per year in utility costs. This proves the need for energy retrofits.

When the renovation costs were estimated, it was obvious that this level of savings would lead to a long payback period for the applied EEMs. For example, replacing all the existing windows with high-performance ones alone could cost 2-3 thousand dollars for materials and installation. It is also costly to meet the code requirements by following a compliant path (such as adding insulation and downsizing the HVAC system). Therefore, more cost-effective EEMs need to be explored for making the house more energy efficient with minimum renovation costs. Considering CMHA's budget constraints, the research proposed to implement several economical EEMs to further improve the house's energy performance beyond the current renovation. These measures were simulated in EEM Run 4.

Figure 7 shows the side-by-side comparison of monthly electricity consumptions between the four modeling runs. It can be noted that EEM Run 4 (proposed) achieves consistently

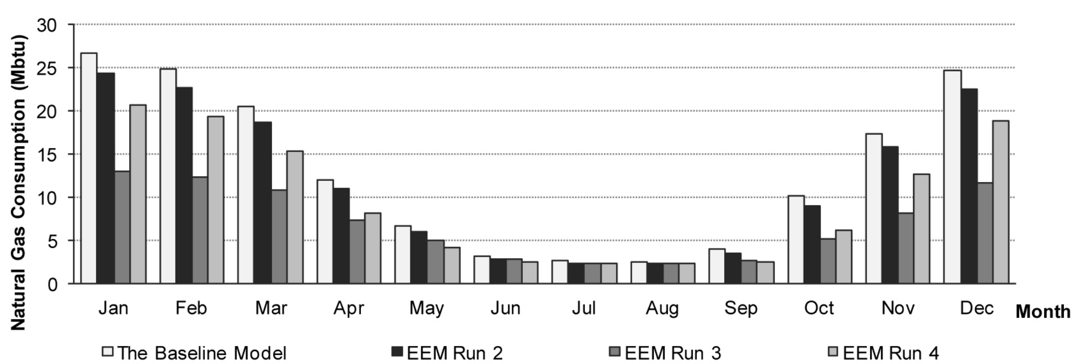
FIGURE 7. Monthly electricity consumption comparison among the four modeling runs.



lower monthly electricity consumption than EEM Run 2 (renovated) and the significant savings occur during the summer months (from June to September). The savings resulted from energy efficient lighting, a programmable thermostat, and improved shell tightness. Simulation data shows that the proposed EEMs save the renovated house 1,530.5 kWh per year, a 21.4% reduction. When compared to EEM Run 3 (2009 IECC), these measures lead to more electricity consumption in summer months but less in other months. Overall, EEM Run 4 has slightly higher annual usage (218.9 kWh higher) than the code-compliant run.

Another side-by-side comparison (see Figure 8) shows that EEM Run 4 has consistently lower monthly gas usage than EEM Run 2 (renovated). The savings are more obvious during winter months. This is attributed to the improved shell tightness and lower thermostat temperature set point in winter and when the house is not occupied. The annual savings reached 26.56 MBtu, an 18.9% reduction. When compared to the code-compliant run, Run 4 has slightly lower usage in May, June, and September, but higher consumption from October to April. This results in an annual usage of 114.21 MBtu, 31.08 MBtu higher than the code-compliant run. When savings in electricity and gas are combined, the house with the proposed EEMs would consume 133.43 MBtu of energy and perform 19.2% better than the renovated house (165.21 MBtu), indicating the effectiveness of these inexpensive energy retrofit measures.

FIGURE 8. Electricity and gas consumption comparison among the four modeling runs.



Payback Period Analysis

According to the predicted energy bills, sealing leakage, changing the thermostat, and replacing light bulbs could lead to annual energy cost savings of \$65, \$193, and \$99, respectively. The cumulative annual utility bill savings are \$357 beyond the renovated house. Table 6 shows the payback period analysis results. It can be seen that all of the proposed EEMs have short payback years ranging from 0.35 to 2.65 years. The break-even point for the three EEMs together is less than a year. This proves that the proposed EEMs are very cost-effective strategies for home energy improvement.

In addition to these EEMs, this research also evaluated a few other low-cost possibilities such as adding external window awnings for summer shading and installing interior window blinds. However, these EEMs were dropped because the house has no windows on its east and west walls and there are only two small south-facing windows. A simulation in eQUEST showed that these measures only led to a very small amount of energy savings, lowering the annual utility bill by around \$10. In addition, making use of landscape or garden trellises to shade west-facing walls was not selected due to the limited space at the building site (a big portion of the space outside the west wall is a paved parking lot). The energy-saving impact of this measure is also hard to quantify in energy simulation. Replacing roof shingles with light colored ones or a reflective metal roof, though recommended by LEED to reduce a building's heat gains in the summer, could not lower the annual utility bill for the renovated house according to the simulation result. The application is also not economical if the existing roof is still in good condition.

From the above analysis, it becomes evident that by applying effective and cost-efficient energy conservation technologies, more savings in energy use could be achieved with limited investment. It is worth mentioning that this research is just an early attempt. There may be other energy conservation measures that have not yet been studied. Considering the budget constraints for HUD and PHAs, this study recommends that a detailed study be performed by the public agencies to explore economical and effective EEMs and prepare detailed guidelines for energy retrofit practices. In this way, the highest energy savings for public housing can be achieved and the renovation costs can be minimized.

Limitations

It was expected that using some default values in eQUEST modeling could lead to small deviations in the simulation results. There was also no simulation model calibration due to the lack of real energy performance data for the house before and after the renovation. However,

TABLE 6. Payback Period Analysis of the Proposed Energy Efficiency Measures

EEM	Material cost	Total cost	Yearly energy cost savings	Payback period
1. Sealing leakages	\$86	\$172	\$65	2.65 years
2. Changing thermostat	\$69	\$138	\$193	0.72 years
3. Replacing bulbs	\$35	\$35	\$99	0.35 years
Subtotal	**\$190**	**\$345**	**\$357**	**0.97 years**

the research findings were still considered reliable when the following factors were taken into account:

- Most default values used in the baseline model were consistently used in all other modeling runs, so their impacts on the predicted energy performance were almost identical, e.g., the same electric consumption of miscellaneous equipment in the four modeling runs.
- The study focused on comparing the differences in predicted energy consumption between the modeling runs to determine the amount of energy reduced by various EEMs applied. The energy savings in kWh, Btu, and utility cost ($) would not be affected very much when the similar deviations existed in all the four modeling runs.
- Small variations could exist when the saving percentages were calculated. For example, when 500kWh of electricity is saved over 5,000kWh, the rate of energy saving is 10%. If 5% deviation exists in the baseline number (i.e., the house's real consumption could be 4,750 or 5,250kWh), the actual rate of saving is 10.5% or 9.5%, a 0.5% deviation.
- In addition, the air change rates (ACH) for the baseline model and EEM Run 2 and Run 4 were estimated based on average construction quality. If a calibrated blower door test could be done for the existing house and the renovated house, the accuracy of energy simulation could be improved.

CONCLUSIONS

This comparative study investigated the energy saving potentials from recent public housing green renovation projects performed in Columbus, Ohio due to the allocated federal stimulus package money. The eQUEST energy simulation and analysis results showed that the green renovation performed by CMHA could only improve a selected house's energy performance by 7.6% in a year. The applied EEMs (e.g., replacing windows) were not very cost-effective due to the longer payback period. When compared with the requirements of the current building energy code (2009 IECC), another 38.5% reduction in the house's annual energy consumption needs to be achieved beyond the current renovation. However, upgrading the house to the current code was also not a cost-effective option. It would be costly to replace the HVAC system and add insulation to the building envelope.

This research proposed several economical and effective EEMs that can be added to the renovated house to further reduce its energy use. These measures include improving shell tightness by sealing all leakages in the building envelope, replacing the thermostat with a programmable model, and installing energy efficient lighting fixtures (e.g., compact fluorescent bulbs). This could achieve an additional 19.2% in energy savings. Adopting these measures does not require large investment and the increased renovation costs could be paid back in approximately one year based on a simple economic analysis.

In addition to providing more cost-effective home energy performance improvement strategies to PHAs, this research also offered insights for the government agencies such as HUD to make wise decisions on future planning of public housing energy retrofits. The research recommended that HUD provides detailed guidelines on the application of more effective and economical energy conservation measures. This would ensure that the proper EEMs are adopted and the planned savings could be realized.

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