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Greener and Leaner: Lower Energy and Water Consumption, and Reduced Work Orders, in Newly Constructed Boston Public Housing

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Abstract: The Boston Residential Investigation on Green and Healthy Transitions (BRIGHT) Study is focused on quantifying the effects of redeveloping public housing developments into new buildings with improved energy performance and indoor environmental quality. This report presents an analysis of utility consumption and work order requests at Old Colony and Washington-Beech, two redeveloped housing sites in Boston, Massachusetts. We compare the consumption of electricity, natural gas, and water, as well as work order data, from 2012–2014 to development-wide baseline data from 2006–2009. We found that despite the higher number of electric appliances in the new apartments (e.g., air conditioning and ranges), electricity consumption decreased 46% in Old Colony and nearly 30% in Washington-Beech when compared to the baseline data. Natural gas used for space heating decreased by more than 70% at both sites; and water use decreased by nearly 56% at Old Colony and nearly 30% at Washington-Beech. Work order categories that directly influence the residents' quality of life, such as pests, mold, windows and plumbing decreased by more than 50% in both renovated sites. In combination with previous documentation of health improvements in the redeveloped sites, these results provide further evidence of the magnitude of benefits from updating public housing infrastructure using green design principles.

Keywords: green building; work orders; public housing; energy consumption; LEED

1. Introduction

Buildings in the U.S. account for approximately 41% of the total energy consumption and 12% of the potable water consumption [1]. The residential sector alone is responsible for 22% of the total primary energy consumption in the U.S. [2]. In many cases, superfluous energy and water consumption are the result of outdated building designs, structures and systems that have been subject to years of deferred maintenance and lack of renovation or redevelopment. In fact, energy conservation measures in residential buildings could reduce energy consumption by 28% by 2020, saving approximately $41 billion annually in energy costs [3]. Furthermore, a recent empirical study from 2016 indicated an annual reduction of 43% in terms of energy consumption and energy expenditures by renovating a typical American home with green building attributes [4] and another study showing a 61% decrease in annual space heating demand (MWh) alone by adopting green building concepts [5]. Historically, the Boston Housing Authority (BHA) has covered all utility expenditures on their properties. Coverage was shifted after redevelopment of the two sites to the end-user (the residents). BHA allowed the residents a subsidy ('utility allowance') equivalent to a typical consumption based on household size. This change most likely influenced the residents' behavior with regard to their electricity usage. They might have attempted (in some cases) to save money or avoid further expenses, which in turn could influence the amount of consumed energy, water and gas. BHA handed out educating materials on energy usage to their residents. Unfortunately, it is not possible to disentangle the impact of these on the residents' utility consumption behavior. The urgency to adopt greener building designs is more compelling for public housing authorities, where scarce financial resources are too often spent on the inefficient use of energy and water and the economic burden of maintaining an aging building portfolio. These costs can strain operating budgets for public housing authorities. The vast majority of family public housing of the Department of Housing and Urban Development (HUD) was built before 1965. With infrastructure 50 years old or greater, many buildings and systems are in need of modernization [6].

Providing green and healthy, affordable housing is a particularly difficult challenge due to factors such as limited federal funding, disproportionately high energy costs relative to residents' income, aggravated environmental exposures, and residents' lack of awareness of (or clear incentives for) resource conservation [7,8]. Housing intervention studies have shed light on the difficulties of addressing these issues. Some studies have focused on technical strategies to provide zero-energy homes at very low cost, primarily through a combination of weatherization, energy-saving appliances, and on-site energy generation [9–11]. Other researchers have examined the role that resident behavior plays in successful energy interventions in affordable housing [12–14]. Researchers have also explored how interventions aimed at reducing energy consumption affect the health and quality of life of the residents [15]. Improvements in heating systems [16] and extensive renovations to green certified buildings [17] have produced decreases in respiratory symptoms, primarily in childhood asthma. Overall, these studies have demonstrated improvements in either energy and water efficiency or in resident health resulting from green design [18]; however, more compelling evidence is needed to establish that both objectives can be achieved simultaneously at a given site. Energy savings can provide greater resources for owners to operate and maintain their developments. Meanwhile, avoided personal and societal costs—in the form of decreased time out of school or work due to sickness, fewer doctor/emergency room visits, and lower prescription and over-the-counter medicine costs—can be substantial.

The BHA is Boston's largest residential utility consumer as they historically have paid for all utilities consumed on their properties. At the time of the study, the BHA used 90 million kWh of electricity, 10 million therms of natural gas, 250 thousand gallons of oil and 90 million cubic feet of water each year, totaling a yearly expenditure of $40 million on utility bills. BHA's goal is to reduce energy and water consumption by 25% by 2020 based on their 2008 levels. These goals are consistent with the City of Boston's Climate Action Plan goals [19]. The BHA spends 25% of its annual operating budget on utility bills. As these buildings start from a very inefficient baseline, the energy benefits of redeveloping can, therefore, be especially high for the housing authority. In an effort to modernize its building stock, reduce operating costs, and improve the health and comfort of its residents, BHA successfully competed for federal funding from the HOPE VI and the American Recovery and Reinvestment Act grants to redevelop two distressed sites: Old Colony (OC) and Washington-Beech (WB). Old Colony, was identified by BHA as one of the most distressed developments, and for this reason a top priority for upgrades and rehabilitation. Similarly, Washington-Beech was in a condition of pervasive disrepair and physical distress making living conditions undesirable, as well as having outdated systems and structural issues that led to highly inefficient usage of energy and water. For both sites, redevelopment (demolition followed by new construction) was selected as the preferred plan for modernization, over renovation. Each site's redevelopment plan incorporated green and healthy housing principles into the design, in order to achieve health and cost-effectiveness goals for BHA and its residents. To understand the many pathways in which an extensive redevelopment can have an impact on a housing development and the lives of its residents, the BHA collaborated with the Harvard T.H. Chan School of Public Health and the Committee for Boston Public Housing (CBPH).

Together, they pursued the BRIGHT (Boston Residential Investigation on Green and Healthy Transitions) study, which focused on quantifying the changes that redevelopment has produced across a variety of metrics, including indoor air quality, incidence of asthma and other respiratory effects, residents' comfort and satisfaction, energy and water consumption, and operations and maintenance work order requests. The BRIGHT study seeks to look beyond a singular objective and instead assess the multiple impacts from redevelopment in an endeavor to reveal the beneficial magnitude of renovating the building stock with green building concepts. Results from this study have previously shown significant reductions in sick building syndrome symptoms, concentrations of fine particulate matter ($PM_{2.5}$), nitrogen dioxide, and nicotine in the post-redevelopment sites. Also reported was a reduction in the air exchange rate (AER) of the redeveloped buildings. This suggests that the green buildings are air sealed and insulated from the outdoors better and are able to reduce exposures to pollutants generated indoors with dedicated mechanical ventilation [20]. In a separate analysis focused on asthma morbidity, the team observed significant improvements in occurrence of asthma symptoms, asthmatic attacks, hospital visits and school absences in children living in green renovated apartments compared to children living in conventional public housing [21]. In addition to improving the health of residents, green building design has the potential to produce significant decreases in resource consumption during operation of the buildings.

This paper adds to the existing evidence on the potential benefits from green design principles and Leadership in Energy and Environmental Design (LEED) certification. We present a comparison of utility consumption and work order requests from pre- and post-redevelopment of Old Colony and Washington-Beech. Percent change in normalized consumption of electricity, natural gas, and water is calculated, and three energy benchmarks are used to compare the performance of the renovated buildings to similar building structures. Operations and maintenance work order requests are classified into nine different categories, and their occurrence is compared pre- and post-redevelopment. Finally, this paper attempts to assess a qualified estimation of the potential economic changes from the energy- and water changes.

2. Material and Methods

Two sites were included in the BRIGHT study, namely Old Colony (OC) and Washington-Beech (WB). Redevelopment of both sites did not have the same timeline and building characteristics either pre- or post-redevelopment. As the scope of the paper was to assess the overall energy- and water consumption as well as work order savings from redevelopment of these buildings, and in the interest of simplicity, all tables and text combine both OC and WB details.

2.1. Site Description

Old Colony was located in the South Boston neighborhood. Originally it consisted of 32 resident-occupied buildings and one administrative building with a total area of 632,448 ft^2 including common areas. Six miles away, Washington-Beech was located in the Roslindale neighborhood consisting of 16 buildings with a total area of 210,060 ft^2.

Old Colony was redeveloped in three phases. Phase 1 was included as data were available at the time of writing this paper. Comparison of energy and water consumption was only based on Phase 1 buildings at Old Colony instead of the total area of Old Colony (Table 1). Building characteristics pre- and post-redevelopment are explained in full below.

Table 1. Pre- and post-redevelopment building characteristics at Old Colony (OC) and Washington-Beech (WB).

	OC Pre	OC Post (Phase I)	WB Pre	WB Post
Construction (year)	1941	2011	1951	2009–2011
Total area, m^2 (ft^2)	9735 * (104,790) *	12,853 (138,345)	19,515 (210,060)	20,181 (217,223)
# of Low- and Mid-rise units†	136 (Phase I bldgs.) **	82	274	72
# of Townhome units	0	34	0	134
# of Buildings total	7	5	16	18
Maximum story walkup	Three-story	Three-story	Three-story	Five-story
Type of stove	Gas	Electric	Gas	Electric
Ventilation system	Switch-controlled apartment ventilation	Heat recovery ventilation systems; fans in bath/kitchens	No ventilation	Continuously running exhaust in bath/kitchens; Demand-controlled ventilation in low-rise units
Heating system	Centralized steam boiler system	High-efficiency hydronic boilers; temp-limited thermostats	Natural gas-fired boilers	High-efficiency hydronic boilers; temp-limited thermostats
On-site energy supply	No	On-site solar photovoltaic (PV)	No	No
Water faucets	High-flow	Low-flow	High-flow	Ultra-low flow/ Low-flow
Air conditioning (AC)	Resident-owned AC units	Centralized AC systems	Resident-owned AC units	Centralized AC systems
Lighting	N/A	Energy Star lamps and fixtures; Occupancy control sensors	T8 or T12	Energy Star lamps and fixtures; Occupancy control sensors
Dishwasher	No	Yes	No	Yes
Washer	No	Yes ***	No	Yes
Dryer	No	Yes *** (Electric)	No	Yes
Electricity consumption paid by	Landlord	Tenant (utility allowance)	Landlord	Tenant (utility allowance)
LEED certified	N/A	Platinum	N/A	Gold

* Phase 1 buildings only, total area in OC pre-redevelopment was 52,416 m^2 (564,205 ft^2). ** Phase I buildings only, total number of units in OC pre-redevelopment was 850. *** Only in townhouse apartments. # Number. EER (Energy efficiency ratio) is the number of British Thermal Units (Btus) the air conditioner can move every hour over the power (in Watts) the air conditioner draws. Utility allowance is calculated using data on the typical in-unit consumption and all in-unit appliances at OC are Energy-Star certified. T8/T12 are types of tube fluorescent light bulbs, measured in eighths of an inch. A T8 bulb is eight eighths of an inch in diameter where T12 is twelve eighths. † Low-rise can be considered apartment buildings with common corridors up to three stories. Mid-rise can be considered apartment buildings with common corridors and (often) elevators, up to eight stories. LEED (Leadership in Energy and Environmental Design). N/A; Information Not Available.

2.1.1. Pre-Redevelopment

OC and WB were constructed in 1941 and 1951, respectively. Both developments were primarily composed of three-story walkup buildings equipped with obsolete heating systems and poorly insulated building envelopes.

At OC, the centralized steam boiler system was a major source of inefficiency because it was unable to disaggregate thermal energy demand for space heating and domestic hot water (DHW). This meant the system operated year-round at high output, even during the summer months when DHW was the only load. Space heating at WB was slightly more efficient due to the more recent installation of independent heating boilers that were capable of shutting down in the absence of heating demand. Nevertheless, at both properties, the outdated heating distribution and control systems hindered adequate temperature control inside the apartments, often leading to uncomfortable indoor environments and high-energy costs. These conditions were exacerbated by poorly-insulated building envelopes and lack of temperature controls within units. As a result, it was common at OC and WB pre-redevelopment to see residents propping open windows during winter. In the absence of central air conditioning, some residents resorted to using inefficient window air conditioning (AC) units to cope with the high indoor temperatures, sometimes even during the heating season.

Lighting fixtures installed in the common spaces and inside the apartments were significantly less efficient than modern, commercially available products. The units at WB had a maximum capacity of 35 amps, which meant residents could not run more than a few appliances at a time without causing a circuit overload, resulting in a nuisance for residents and management staff when electrical breakers were frequently tripped.

The use of old, high-flow faucet aerators, showerheads and toilets contributed to high water consumption rates, as did frequent leaks and breaks in the water supply lines. Building heating systems at WB were more than 50 years old and well beyond their useful life, while the tar and gravel roofs were at least 20 years old and installed over existing deteriorated roof systems. Poor insulation of exterior walls, which were primarily uninsulated masonry cavity walls, as well as roofs, foundations and windows allowed the infiltration of cold air and water, leading to high-energy bills and the accumulation of moisture. Additionally, the combination of outside moisture and a lack of proper ventilation, as units lacked exhaust fans in kitchens and bathrooms, resulted in the formation of mold in the units and hallways. A 2006 Real Estate Assessment Center inspection by HUD found mold and mildew in half the development's 16 buildings.

2.1.2. Post-Redevelopment

At both sites, the redevelopment constituted a complete demolition of the original buildings and construction of new buildings. The original 16 buildings at WB were replaced with one mid-rise and 17 low-rise buildings, for a total of 206 new apartments. In phase I, one mid-rise building and four townhome buildings replaced seven three-story walkup buildings, for a total of 116 new apartments at OC.

The new Phase I at OC buildings were designed to be as energy efficient and environmentally friendly as possible in order to improve the health and quality of life of their occupants. The buildings achieved LEED Platinum certification in 2012, meeting strict standards for energy/water efficiency, thermal comfort, ventilation, and eco-friendly materials. Electric stoves replaced gas stoves in the older buildings and were expected to reduce ambient concentration of pollutants that could cause respiratory problems. Low-flow water fixtures (toilets, kitchen and bathroom) seeked to reduce the daily water consumption per unit and energy required to heat water. All in-unit appliances was Energy Star certified. High-efficiency boilers provides space heating and in-unit heat recovery ventilation (HRV) systems creates healthy levels of ventilation while minimizing energy losses. Last but not least, solar photovoltaic panels were installed on the rooftops of certain buildings at OC to further decrease source energy consumption bringing the property's net electricity consumption nearly to zero.

To reduce thermal transfer between interior and exterior space, both properties contained highly insulated walls, floor slabs and foundations, high-efficiency windows, and well-sealed building envelopes, as well as high-albedo rooftops on some buildings. At both properties, space heating and DHW were provided by high efficiency boilers and controls, with temperatures individually controlled in each apartment by thermostats limited to a maximum set point of 22 °C (72 °F). Apartments in the mid-rise building at OC were mechanically ventilated through Energy Star exhaust fans in the bathrooms, while common areas and low-rise apartments were equipped with demand control ventilation. OC also has HRV systems that reduced the energy required to condition the outdoor air supply. At WB cooling in the mid-rise building was provided from mid-June to mid-September via central air conditioning with a 9.7 Energy Efficiency Ratio (EER). The townhouse building at WB were equipped with wall sleeve air conditioning systems in each living room and in at least one bedroom per apartment. As for outdoor water usage at WB, an Environmental Protection Agency (EPA) certified irrigation system, with moisture sensors and controllers for each watering zone, was implemented to reduce water waste.

Additionally, residents at the new developments were responsible for paying their own electricity bills, whereas pre-redevelopment bills were paid directly by BHA. This was thought to provide an incentive for residents to reduce their electricity consumption to turn off unused appliances and lighting, or decreasing the use of air conditioners and electric heaters.

2.2. Analysis of Energy and Water Consumption, and Frequency of Work Orders

Changes in electricity, natural gas and water consumption were calculated as the percent difference between pre- and post-redevelopment multi-year average consumption for the total site (Equation (1)).

$$\text{Utility total site}_{\Delta}(\%) = \left(\frac{\text{Consumption}_{\text{pre-renovation}} - \text{Consumption}_{\text{post-renovation}}}{\text{Consumption}_{\text{pre-renovation}}}\right) \times 100 \quad (1)$$

Baseline averages were calculated from at least three years of pre-redevelopment data, while two years of post-redevelopment data were used to estimate the test period averages. The baseline and the test period data were obtained from BHA's historical utility records and by the private companies currently managing the sites, respectively. Electricity and natural gas consumption were normalized by building square footage for comparison purposes. Electricity data and results for Old Colony do not reflect the production by the solar photovoltaic (PV) systems on the roofs of some buildings in Phase I. In order to adjust for variations in weather conditions, natural gas consumption for each year was disaggregated into baseload energy and heating energy by regressing monthly gas consumption against heating degree days (HDDs) for that year. The resulting heating load values were normalized by square footage and then averaged. Baseload gas values, taken as the y-intercept of each best-fit line, were normalized by the number of bedrooms in each property and then averaged. Water consumption data encompass both indoor and outdoor consumption. Each monthly consumption value was normalized by the total number of occupants in each month, summed into annual totals, and then divided to obtain average gallons per capita per day (GPDC). The most relevant metric for energy use intensity (EUI) for electricity is kilowatt-hours per square foot (kWh/ft^2), fitting with industry standard practice. EUI is a measure of the building's energy performance. It is an expression of the total energy consumption as a function of the total size of the site [22,23]. In this study, EUI was calculated by the total energy consumption divided by the total size of site (ft^2) at OC and WB separately. The raw data for utility consumption were processed in the following manner: First, consumption was translated from the billing period format into month format by dividing total consumption for each billing period by the number of days in that period. The resulting daily averages were then allocated into months, and summed to create yearly consumption totals and divided by the average occupied square footage of each year. This technique was applied to both baseline and Phase I data at OC as with pre- and post-renovation at WB. EUI results are presented as both kWh/m^2 and kBtu/ft^2 presented in Table 2.

Table 2. Old Colony (OC) and Washington-Beech (WB). Pre- and post-redevelopment utility consumption and energy use intensity (EUI) and change (%) Water consumptions was measured as gallons per capita per day (GDCD).

	OC Pre	OC Post	WB Pre	WB Post	Change OC (%)	Change WB (%)
Electricity						
kWh/m^2 (kBtu/ft^2)	95.3 (31.3)	53.3 (16.9)	92.7 (29.4)	65.0 (20.6)	−46	−29.9
Natural Gas						
Space Heating kWh/HDD/m^2 (Btu/HDD/ft^2)	0.33 (17.4)	0.08 (4.4)	0.32 (16.8)	0.09 (4.7)	−74.7	−72
Baseload kWh/Bedroom/Day	252.4	63.1	132.5	94.6	−74.8	−28.7
Water						
GPCD	123.4	54.4	97.6	68.7	−55.9	−29.6
m^3/capita/day	0.467	0.206	0.369	0.260	−55.9	−29.6
Energy use intensity (EUI)						
kWh/m^2 (kBtu/ft^2)	702.5 (222.7)	177.6 (56.3)	532.8 (168.9)	210.1 (66.6)	−74.7	−60.6

HDD: Heating Degree Day. GPCD: Gallons Per Capita per Day. kWh: kilo Watt per Hour. Btu: British Thermal Unit. kBtu: kilo British Thermal Unit.

Changes in the rate of work order requests (i.e., maintenance requests) were determined as an indicator of the quality of the buildings' infrastructure. Work order datasets from BHA and from the managing companies were cleaned and standardized into consistent categories; only requests directly pertinent to the residents' quality of life were considered for this analysis. These were grouped into nine categories: Appliances, Mold/Mildew, Pests, Plastering/Tiles, Plumbing, Heating, Windows, Toilets, and Lighting. Work order monthly totals in each category were normalized by the total number of occupied apartments in each month and then averaged over the pre- and post-redevelopment periods.

2.3. Benchmarking of Energy and Water Consumption

To improve the interpretability of the energy and water consumption metrics, we compared the results to different benchmarks. Three sets of benchmarks for electricity and gas are presented in order of increasing stringency. The first set is meant to capture the performance of the entire BHA portfolio, and includes energy performance metrics of BHA buildings based on a third-party audit conducted by Ameresco. These metrics were estimated using data collected prior to the baseline period considered in this study (July 2004–June 2007). Since no extensive redevelopments were performed in that period, these estimates were representative of the overall consumption levels for each development.

The second set of benchmarks comes from the U.S Energy Information Administration's (EIA) 2009 Residential Energy Consumption Survey (RECS), which provides regional estimates of energy and water consumption for different building configurations. These benchmarks are estimated from a statistically representative sample (n = 12,083) from 113.6 million housing units nationwide [24].

The third set of benchmarks for electricity and natural gas consumption is derived from a study by WegoWise, Inc. aimed at characterizing the energy consumption of affordable multifamily housing in the state of Massachusetts between 2010 and 2013. The data from 11,265 buildings used in the study represents 75% of the affordable housing in the state [6]. The values in Table 3 represent the 75th percentile of building performance in the WegoWise database. (Reliable benchmarks for baseload gas consumption could not be located; therefore, this paper provides benchmarks for space heating only.)

Table 3. Benchmarking electricity, natural gas for heating, and water consumption in the redeveloped sites.

Electricity	**Benchmark kWh/m^2**	**OC Post-Redevelopment (phase 1) (%)**	**WB Post-Redevelopment (%)**
Ameresco	95.3	−44.1	−31.9
RECS	64.7	−17.6	0.5
WegoWise	41.0	30	58.5
Heating Gas	**Benchmark kWh/HDD/m^2**	**OC Post-Redevelopment (phase 1) (%)**	**WB Post-Redevelopment (%)**
Ameresco	0.52	−83.9	−82.8
RECS	0.18	−54.2	−51
WegoWise	0.12	−33.3	−28.8
Water	**Benchmark m^3/capita/day (GPCD)**	**OC Post-Redevelopment (phase 1) (%)**	**WB Post-Redevelopment (%)**
EPA	0.38 (100)	−45.6	−31.3
Mass WCS	0.25 (65)	−16.3	5.7

Water consumption was compared to one national and one local benchmark. EPA estimates the national average consumption in residential buildings, including indoor and outdoor consumption, at approximately 100 GPCD (0.379 m^3/capita/day) [25]. The second benchmark was a regional figure provided by the Massachusetts Water Conservation Standards (WCS), a set of guidelines published in 2006 and subsequently updated in 2012 by the Massachusetts state government. The standard proposes limiting residential water consumption to 65 GPCD (0.246 m^3/capita/day), including indoor and outdoor uses [26].

2.4. Saving Potential

Achievements from green design and construction techniques efficiency gains were translated into costs savings. We used data available from utility bills to calculate average cost per square foot for both pre- and post-redevelopment periods. Square footage was chosen as the basis for normalization since it is a common measurement for energy consumption comparisons. [4,27]. In the case of electricity, cost data were not available for the post-redevelopment period. As a substitute, we determined the pre-redevelopment electric rate and applied that to the post-redevelopment consumption data to estimate total yearly costs. Where building square footage changed, we multiplied both pre-and post-redevelopment cost-per-square- foot values by the post-redevelopment square footage for each property.

3. Results

3.1. Energy and Water Reductions

Table 2 summarizes the pre- and post-intervention utility consumption in OC and WB, respectively. Consumption of all three utilities decreased at both sites. Despite the higher number of electric appliances in the new apartments (e.g., stoves and dishwashers), electricity consumption decreased 46% in OC and nearly 30% in WB when compared to the baseline data. Higher electric savings at OC were partly due to the more inefficient baseline conditions.

A larger difference was observed in natural gas consumption. Post-redevelopment OC consumed almost 75% less natural gas used for space heating compared with pre-redevelopment conditions, and almost 75% less natural gas used for baseload applications. This decrease can be attributed primarily to the replacement of the old centralized steam boiler system that operated year-round to supply hot water since DHW and space heating systems were combined. A portion of the decrease can be attributed to the replacement of gas stove ranges with electric ones. Comparable efficiency gains in natural gas consumption were observed in post-redevelopment WB that, despite having their boiler systems updated more recently, also consumed 72% less than the baseline heating energy. Baseload natural gas consumption at WB decreased nearly 29%. The smaller reduction in baseload at WB may be attributed to the relatively efficient hot water system installed in the pre-redevelopment buildings in 2004.

Water consumed after the redevelopments decreased substantially at both sites. Again, the differences were more accentuated in OC due to higher baseline values. Reductions of nearly 56% and 30% at OC and WB, respectively, were a result of the low-flow fixtures installed onsite, the reduction of make-up water demand by the buildings' heating systems, and reductions in leaks and breaks.

3.2. Comparison to Benchmarks

Electricity consumption at post-redevelopment at OC was 44.1% lower than the Ameresco benchmark, while consumption at post-redevelopment at WB was 31.9% lower. This indicated that both buildings were performing significantly better than the older, un-renovated developments in the BHA portfolio. Compared to a benchmark taken from a broader sample of buildings, such as the RECS value of 64.7 kWh/m^2 (20.5 $kBtu/ft^2$), the electricity consumption at OC was only 17.6% lower while the consumption at WB is 0.5% higher. Both renovated sites performed worse than the WegoWise electricity consumption benchmark of 41.0 kWh/m^2 (13 $kBtu/ft^2$), 30.0% higher at OC and 58.5% higher at WB, meaning that OC and WB fall short of the 75th percentile for affordable multifamily buildings in Massachusetts (Table 3).

However, natural gas for space heating at the renovated sites was lower than all three gas benchmark shown in Table 3, including the most stringent WegoWise benchmark (33.3% lower for OC and 28.8% lower for WB). Heating gas consumption decreased to less than 20% of the consumption from BHA sites in the Ameresco audit. It should be noted that the Ameresco benchmark values have not been disaggregated into heating load and baseload. This means that the benchmarks were artificially higher than the consumption results from OC and WB. However, since the results were lower than both the RECs benchmark and the WegoWise benchmark, it can be assumed that they would be lower than a disaggregated Ameresco benchmark as well. Additionally, baseload gas consumption at both properties decreased significantly post-redevelopment. With regard to water consumption, OC (54.4 GPCD, 0.206 m^3/capita/day) was able to meet the state target of 65 GPCD or less. WB did not meet the standard (68.7 GPCD, 0.260 m^3/capita/day), consuming 5.7% more than suggested.

3.3. Work Order Results

The renovated sites proved to be not only more efficient in their utility consumption but also less resource-intensive in their daily operations and maintenance. Figure 1 displays percent changes in average monthly work order requests between the pre- and post-redevelopment buildings. Out of the nine categories selected for this study, the average work orders per month decreased in six and seven categories at OC and WB, respectively. Work orders related to apartment appliances rose in both renovated sites as a consequence of the addition of new appliances that were not provided to residents before the redevelopment. Requests associated with lighting systems were higher at both renovated sites. Although the new apartments were lit by longer-lasting, energy-efficient lamps, the increase in work orders might be explained by the higher overall density of hard-wired light fixtures that were maintained by BHA staff. A slight increase was also observed at OC in work orders related to the heating system. At both OC and WB, work orders related to heating spiked in year one after the redevelopment was completed. This is likely because residents who had been accustomed to overheated indoor environments felt the current set point limit of 22 °C was relatively cool. After year one, the data show a gradual decrease in heating work orders at both properties. Overall, work order categories decreased by more than 50% at both renovated sites.

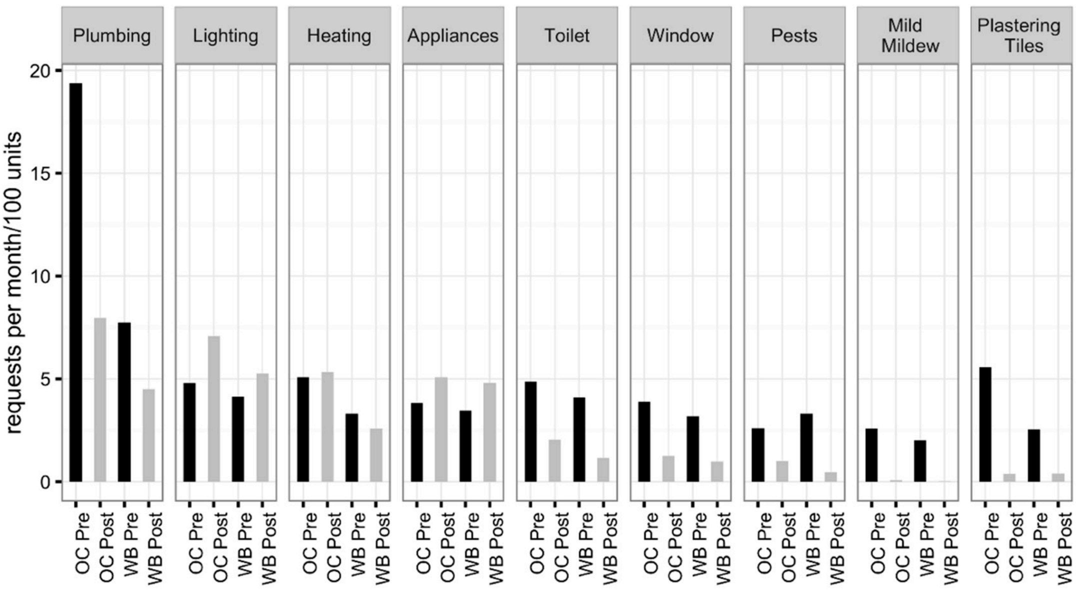

Figure 1. Average monthly work order requests per development in pre- and post-renovated conditions.

3.4. Saving Potential

Green design and construction techniques achieved significant reductions in normalized consumption rates at both properties compared to their pre-redeveloped conditions. The monetary savings in Table 4 suggest that the new OC and WB developments were spending approximately $584,000 less ($5033 less per post-redevelopment apartment) and $448,000 less ($2177 less per post-redevelopment apartment), respectively, than they would be if they were consuming utilities at pre-redevelopment rates. Using electricity and natural gas emission factors reported by the state of Massachusetts, the total annual reduction in electricity and gas consumption led to averted greenhouse gas emissions of 1291.5 and 1463.3 metric tons of CO_2 equivalent for OC and WB, respectively. It is important to note that due to the difference in building square footage, this approach represented an indirect comparison between costs at the pre- and post-redevelopment developments. Additionally, this approach did not account for changes in utility rates from year to year, inflation or the presence of third-party supply contracts.

Table 4. Annual pre- and post-redevelopment costs from electricity, natural gas for heating and water consumption per apartment.

Site	Utility	Pre	Post	Savings
OC	Electricity	$2004	$1073	$930
	Gas	$3208	$644	$2564
	Water	$2493	$954	$1538
	Total	$7704	$2671	$5033
WB	Electricity	$1561	$1160	$401
	Gas	$1896	$563	$1333
	Water	$1424	$981	$443
	Total	$4880	$2703	$2177

4. Discussion

Our results have shown the reduction of utility consumption and work order requests associated with the redeveloping of two affordable housing sites. These benefits might be expected to decrease the economic burden of managing these properties, however it is important to also recognize that many work order categories (e.g., pests, issues with mold, windows and plumbing) have also been associated to the residents' health and quality of life [28,29].

In separate analyses, we have shown that indoor environmental quality and health can be improved through green affordable housing, making the benefits multilevel and not limited to lower energy expenditures [20,21]. This analysis has shown that these improvements also represent significant cost savings, which could be considered as potential benefits in the allocation of public resources for the redevelopment or new development of subsidized housing. This is especially true for low-income communities, where healthcare expenditures may be drawn largely from publicly-funded insurance programs. The average annual income for Boston public housing residents is approximately $15,000 and they pay 30% of their adjusted income in rent [30]. Therefore, providing affordable, healthy housing with low operating costs represents to the tenants, an opportunity to have more available income at their disposal [31].

Since the baseline conditions at both developments reflected the typical state of older housing developments in the northeast, we anticipate that similar efficiency goals could be realized at other sites of similar age, design and condition [32].

Despite the substantial reduction in electricity consumption, neither sitesperformed better than the WegoWise electricity benchmark of 41.0 kWh/m^2 (13 kBtu/ft^2) corresponding to the 75th percentile of affordable multifamily buildings in Massachusetts. This result could be explained by the inclusion of numerous electricity-dependent systems such as electric dryers, air conditioning, heat-recovery ventilation (at OC) and fan coil units, as well as the change from gas stoves to electric stoves. In addition, the WegoWise benchmark reflects both older affordable buildings (which are less likely to include this equipment) and newer buildings relying more heavily electricity not entirely comparable to the two sites included in this paper. Nevertheless, both properties beat an estimate of the 75th percentile benchmark for total energy consumption. To illustrate this, we estimated the EUI, which is an indicator of the total energy consumption in a building as a function of its size. EUI at both redevelopments was estimated by combining the area-normalized average electricity and gas usage post-redevelopment (Table 2) and comparing it to the combination of the same metrics reported by WegoWise. While EUI values were not included in the WegoWise report, we considered that summing the top-performing quartiles values of electricity and gas consumption published in the report would offer a reasonable reference for EUI in affordable housing buildings in the same region. The estimated EUI values in Table 2 were 17.2% lower (for OC) and 2.1% lower (for WB) than the EUI of 214.5 kWh/m^2 (68.0 kBtu/ft^2) derived from the WegoWise report.

The shift towards building systems that were more reliant on electricity but more efficient overall may be beneficial in cases where a portion of the development's overall energy consumption could be offset by renewable energy sources, as were the case with the photovoltaic array installed at OC. This would eliminate the need to transport large quantities of power over transmission and distribution lines, decreasing the development's total carbon footprint and environmental impact. Future studies should take into account not only how redevelopment affects the demand of energy but also how energy is supplied to account for the whole energy life-cycle as suggested by Truong et al. [33].

Economic benefits of reduced work order requests might be difficult to quantify and are not included in this paper. Instead, we assume that green and healthy buildings permit maintenance resources typically allocated to resolving problems at a site under distress to be used for other capital or operating needs. Additionally, the reduction in daily demands on maintenance staff permits the implementation of preventative maintenance programs to ensure longer-lasting positive results in energy efficiency, pest management, and other categories. Further, we expect decreases in time requesting and waiting for a work order, as well as decreases in distress and adverse health symptoms for the occupants.

Historically BHA has covered all utility expenditures on their properties. After redevelopment at the two sites, coverage was shifted to the end-user (the residents). BHA allowed the residents a subsidy ('utility allowance') equivalent to a typical consumption based on household size. This change could have influenced the residents' energy usage behavior as they attempted (in some cases) to save money or avoid further expenses, which in turn could have influenced the amount of consumed electricity, water and gas. Upon completion of the new buildings, BHA handed out educating materials on energy usage to their residents. Unfortunately, it was not possible to obtain information of and disentangle the impact of these on the residents' utility consumption behavior.

Data for this study is limited in terms of spatial resolution, limiting our ability to normalize according to household types or occupancy and, therefore, it is not possible to disentangle how residents' behavior might impact energy- and water- consumption as well as the work order frequency. Furthermore, while most relocated residents returned to the site post-redevelopment, our analysis lacks precise data on tenant retention rates. We know that resident behavior has an impact on energy- and water consumption [13,34]; therefore, changes in the resident population could affect our results. Moreover, it is not possible to break down energy consumption by specific systems such as the solar photovoltaic, heat-recovery ventilation or air-conditioning systems, which might have shed light on the magnitude of their impact.

For future redevelopment studies, understanding the life-cycle impact of retrofits versus full redevelopments will be important. Given the age and condition of OC and WB, the best-suited intervention for these sites was a full redevelopment. However, as other studies suggest [35,36], energy retrofits in existing buildings have also led to positive improvements in energy conservation over the estimated lifespan of a building, but some studies are limited in their applicability; for example, one study was limited to a modeling analysis of just one apartment [37] and another did not compare pre- and post-construction energy consumption on the same apartments [5] as in the BRIGHT study.

5. Conclusions

To our knowledge, this is the first study documenting the potential economic savings from affordable green housing in Boston, MA, USA. This paper shows the economic savings from green buildings at two Boston Public Housing sites namely Old Colony and Washington-Beech up to $5033 and $2177 annually per apartment, respectively. Furthermore, the study documents the magnitude of energy consumption savings from electricity (30%–46%), gas (72%–75%), and water consumption (29%–56%) as well as work order requests (>50%) by redeveloping an existing distressed public housing development to either LEED Platinum or Gold certification. Our findings suggest that green redevelopment at Old Colony and Washington-Beech can provide benefits for residents and owners with reduced energy, water and work-order savings, potentially providing direct resident benefits and greater resources to operate and maintain the developments. Adding these findings to the BRIGHT study, we identify the various beneficial outcomes associated with the redevelopment of existing building stock into green buildings. Redevelopment of new buildings should go beyond the base code and use evidence-based practice to achieve global, societal and individual benefits simultaneously.

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