Effect of Renovation of Aged Buildings on Energy Consumption

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Abstract

Buildings from different eras may employ diverse construction techniques, materials, and electrical systems, which may significantly affect the energy consumption. This study aims to investigate the impact of upgrading different aspects in aged buildings on energy consumption. Based on the analysis, many upgrades yield less energy consumption. However, most of them are not statistically significant.

Introduction

In the post-2000 era, a growing emphasis on energy efficiency has led to breakthroughs in energy utilization in various facilities. Structures predating the year 2000 may incorporate outdated materials and devices. Renovations in these older buildings may encompass windows, roofs, lighting, HVAC (heating, ventilation, and air conditioning), plumbing, and electrical systems. These upgrades have the potential to significantly influence energy consumption efficiency.

This project primarily aims to assess whether renovated aged structures demonstrate enhanced energy efficiency compared to their non-renovated counterparts. Additionally, it also identifies how the energy efficiency of renovated buildings compares to that of new constructions. Variables such as building area, number of floors, floor height, window-to-wall ratio, and building usage are considered, along with their impact on energy consumption.

The analysis utilizes the dataset, Commercial Buildings Energy Consumption Survey (CBECS), conducted by the U.S. Energy Information Administration, comprising 6,436 records representing an estimated 5.9 million commercial buildings in the US. It contains 620 total variables describing each individual building record.

Method

We selected 37 predictor variables related to energy consumption, including aspects such as building characteristics, occupancy, climate, and renovations Their names and descriptions are provided in detail in Appendix Table 1. Some variables contain NA values, representing missing data or inapplicability. Given the description of survey questionnaires, where inapplicability often signifies non-existence, we set these values to "No". Categories in the Principal building activity (PBA) that could affect the estimates, such as buildings not requiring heating or cooling and buildings only requiring cooling, were removed. Variable Number of floors (NFLOOR) was masked to avoid identification. We used an average of 12 to represent the range of 10-14 floors, and category exceeding 13 floors was excluded. Some newly constructed buildings after 2000 also underwent upgrades. Considering our primary focus on comparing energy consumption before and after 2000, we categorized all buildings constructed after 2000 as new constructions (without upgrades).

We selected five modeled variables, recording the energy consumption in the categories of heating, cooling, lighting, ventilation, and the total consumption (in $\mathrm{k\,Btu}$) within one year for each building. These values were divided by the building area to obtain energy consumption per unit area (in $\mathrm{k\,Btu/ft^2}$) named as “EUI” as the response variable. Details for all response variables are provided in Appendix Table 1.

We used SAS to extract useful variables from the dataset and conducted the analysis in R. The dataset utilizes a jackknife survey design, where “FINALWT” represents sample weights, and “FINALWT1”–”FINALWT151” are replicate weights. With the survey design, we conducted two sets of models: simple and multiple linear regressions.

In the simple linear regression models, to compare the energy consumption of buildings with different upgrade statuses, we created a categorical variable for each upgrade status variable. Here, “1” represents non-upgraded aged buildings (constructed before 2000), “2” represents buildings constructed after 2000 (without upgrades), and “3” represents upgraded aged buildings. We set non-upgraded aged buildings as the reference. We fitted simple linear regression model using ordinary least squares (OLS) for each predictor with each response.

Multiple linear regression model, compared to the former, provides a better fit, allowing for a comprehensive evaluation of the impact of various building characteristics on energy consumption. We used selected building-related variables as predictors and energy consumption as the response to fit the model. Collinearity is a potential issue with such model. If traditional methods were used, placing several categorical variables representing building upgrade status linearly into regression with OLS, fitting would result in perfect collinearity due to the identical columns in each predictor. Instead, we use one categorical variable representing upgrade status in windows (type_RENWIN), and several continuous variables representing other upgrade status. The later continuous variables were modified with “0” as non-upgraded and “1” as upgraded. This approach enables fitting the desired multivariate model while avoiding collinearity issues. After fitting the model with all predictors, we removed insignificant predictors and re-fitted the model.

We used t-test to examine the statistical significance of parameters. If the p-value from the t-test is less than 0.05, we consider the parameter statistically significant. The coefficient of determination R^2 was used to measure the goodness of fit.

Regression Results

Simple Regression

Table 1 Results from simple linear regression models. Bold p-values are statistically significant. Red coefficients are negative.

	TotalEUI (TOTEUI)		CoolingEUI (CLEUI)		HeatingEUI (HTEUI)		Ventilation EUI (VNEUI)		Lighting EUI (LTEUI)	
	coef	p-value	coef	p-value	coef	p-value	coef	p-value	coef	p-value
RENWIN1(Ref)	74.5538	**0.0000**	7.4017	**0.0000**	21.7229	**0.0000**	5.8327	**0.0000**	6.7567	**0.0000**
RENWIN2	16.9723	**0.0010**	1.7562	**0.0149**	0.5782	0.7441	1.9952	**0.0010**	2.4508	**0.0009**
RENWIN3	10.7065	0.1846	(1.2031)	0.1043	7.4688	**0.0246**	0.9759	0.1322	1.0172	0.0696
RENRFF1(Ref)	74.7283	**0.0000**	7.1783	**0.0000**	22.6213	**0.0000**	5.6885	**0.0000**	6.8107	**0.0000**
RENRFF2	16.7979	**0.0008**	1.9795	**0.0084**	(0.3202)	0.8596	2.1394	**0.0002**	2.3968	**0.0013**
RENRFF3	5.4649	0.4003	0.4635	0.5159	(0.2954)	0.8611	1.3450	**0.0363**	0.3216	0.4466
RENLGT1(Ref)	72.1042	**0.0000**	7.4519	**0.0000**	21.1174	**0.0000**	5.5915	**0.0000**	6.7132	**0.0000**
RENLGT2	19.4220	**0.0003**	1.7059	**0.0209**	1.1837	0.5098	2.2363	**0.0003**	2.4943	**0.0005**
RENLGT3	16.2594	**0.0018**	(0.8268)	0.1258	6.4376	**0.0013**	1.5615	**0.0007**	0.7036	0.0577
RENHVC1(Ref)	74.0282	**0.0000**	7.3261	**0.0000**	21.7769	**0.0000**	5.5273	**0.0000**	6.6750	**0.0000**
RENHVC2	17.4980	**0.0012**	1.8318	**0.0100**	0.5242	0.7836	2.3005	**0.0002**	2.5325	**0.0005**
RENHVC3	7.6515	0.1936	(0.2655)	0.6250	3.4808	0.1712	1.8338	**0.0006**	0.8673	**0.0330**
RENPLB1(Ref)	74.5123	**0.0000**	7.2431	**0.0000**	7.2431	**0.0000**	5.7804	**0.0000**	6.8522	**0.0000**
RENPLB2	17.0138	**0.0010**	1.9147	**0.0056**	1.9147	0.9551	2.0474	**0.0007**	2.3553	**0.0014**
RENPLB3	9.1351	0.1782	0.1669	0.8245	0.1669	0.5462	1.1871	**0.0305**	0.1409	0.7165
RENELC1(Ref)	73.5681	**0.0000**	7.1752	**0.0000**	22.1673	**0.0000**	5.7746	**0.0000**	6.7614	**0.0000**
RENELC2	17.9581	**0.0005**	1.9826	**0.0052**	0.1338	0.9397	2.0532	**0.0007**	2.4461	**0.0008**
RENELC3	17.2330	**0.0337**	0.7125	0.3882	3.1278	0.1539	1.3211	**0.0222**	0.8652	0.1225

Note that variable with “(ref)” means reference level, which may also be interpreted as intercept. Variable with “1” means non-updated aged building. Variable with “2” means new construction building. Variable with”3” means updated aged building.

Simple linear regression models were separately fitted for each of the six upgrade status predictors against the energy consumption for total, cooling, heating, ventilation and lighting consumption. The parameters and corresponding p-values for the predictors are summarized in Table 1 and corresponding R^2 are in Appendix Table 4. These results highlight significant differences in total energy consumption between new constructions and non-upgraded aged ones, with all p-value less than 0.05. Overall, new constructions tend to consume more energy compared to aged buildings. Box-plots for different upgrade status can be found in Appendix Fig 1.

Aged buildings that have undergone upgrades in lighting (p-value = 0.02) and electrical systems (p-value = 0.03) exhibit significant differences in total energy consumption compared to non-upgraded, resembling the patterns of new constructions. The impacts of the remaining four types of upgrades windows (p-value = 0.18), roofs (p-value = 0.40), HVAC (p-value = 0.19) and plumbing (p-value = 0.18) on total consumption are not statistically significant. Upgrading windows and HVAC systems show a decreasing effect (negative parameters) on cooling consumption, but their p-values are not significant (p-values = 0.10 and 0.63). Upgrading HVAC systems significantly influences ventilation energy consumption (p-value < 0.01), with upgraded buildings resembling new constructions in this categorical consumption. However, its impact on heating energy consumption is not substantial. While upgrading lighting does not have a significant negative impact on consumption in lighting.

Multiple Regression

We employed all the predictors listed in Appendix Table 1 to individually fit multiple linear regression models for five consumption responses. The summarized results are presented in Appendix Table 2. Insignificant predictors were removed, resulting in reduced models summarized in Appendix Table 3. Among all the reduced models, the total energy consumption model achieves the highest R^2=0.48. The R^2 values for the ventilation and cooling consumption models are 0.47 and 0.40, respectively. The lowest R^2 is observed in the heating model, at only 0.17.

The building's principal activity significantly influences energy consumption in the categories of cooling, heating, and ventilation. Buildings categorized in the food service (“PBA”=6 and 15) exhibit significantly higher energy consumption. The number of floors significantly affects cooling energy consumption (with four p-values < 0.05), but no trend is observed. The floor height (FLCEILHT) of a building significantly influences heating consumption (p-value < 0.01), while no significant impact was observed in the cooling consumption. The use of building materials other than brick, stone, stucco or transparent glass (WLCNS $\neq$ 1 or 6) reduces consumption in heating. Buildings with interior wall surrounded by decorative glass, demonstrate the best insulation effect (coef = -11). Window-to-wall ratio significantly impacts cooling energy consumption, showing a noticeable positive correlation trend (increasing coef’s). The use of reflective window glass (REFL) significantly reduces energy consumption in both cooling and heating, but tinted glass (TINT) does not exhibit a similar effect. The influence of factors such as weekly opening hours (WKHRS), the number of employees (NWKER), and the frequency of hot and cold weather (HDD65, CDD65) on various consumption categories aligns with expected common sense. Some upgrade variables yield negative parameters, indicating a potential reduction in energy consumption after upgrading. However, these reductions are not statistically significant.

Conclusion

The study reveals significant disparities in total energy consumption between new constructions and non-renovated aged buildings. Some upgrades yield negative parameters, indicating a decrease in energy consumption. However, most of them are not statistically significant, suggesting that the renovation does not significantly increase the efficiency. Food service consume much more energy than other types of usage. Window-to-wall ratio and the type of glass and wall have significant impact on temperature regulation consumption, suggesting the better material to be used in future constructions.

Limitations

The study acknowledges certain limitations, such as the potential exclusion of latent variables, leading to unaccounted-for factors. The use of total energy consumption (TOTEUI) as a response variable may mask influences specific to certain categories. However, this model has higher R^2 value than categorical response model, suggesting the need for additional variables in future models.

Appendix tables and code can be found on GitHub: https://github.com/AlanGalaxy/506Project