Examining the energy performance of older and historic buildings using municipal benchmarking data

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Abstract – Until recently, nationally representative survey data has been the primary source of information on the energy performance of buildings in the U.S., relative to their year of construction. The emergence of municipal energy benchmarking ordinances and public availability of benchmarking datasets now makes it possible to explore these relationships at the local level, and to link this data with information about a building's historic designation status. This paper presents results from an initial statistical analysis examining the relationships between building energy use, year of construction, and historic designation status. First, municipal benchmarking data from six U.S. cities is used to examine local trends in the relationship between building age and energy performance. Second, an exploratory analysis of the energy performance of designated historic compared to non-historic buildings in New York City is presented. The methods described in this paper could be applied more widely to benchmarking datasets from other cities.

Keywords – energy benchmarking; energy use intensity (EUI); year of construction; listed historic buildings; linear regression

1. INTRODUCTION

Over the past decade, an increasing number of U.S. cities have adopted legislation requiring building owners to disclose and benchmark their energy consumption on an annual basis. The scope of these policies are similar from city to city, targeting large commercial and multifamily residential buildings – typically those greater than 50,000 ft^2 (4,645 m^2) – and including some form of transparency, in which the benchmarking data is made publicly available [1]. Owners are required to report energy consumption based on 12 months of utility bills, and submit other descriptive information such as building type, floor area, and year of construction. Whereas previous work examining the relationship between year of construction and building energy performance in the U.S. has been based largely on nationally representative data [2], these new municipal benchmarking datasets provide an opportunity to identify local trends in the energy performance of older and historic buildings.

Existing analysis of the relationship between year of construction and building energy performance using municipal benchmarking data has been limited to official annual reports issued by the cities. Palmer and Walls [1] summarize these reports; they find that data for Washington DC, Minneapolis, Chicago, and Philadelphia show no relationship between site energy use intensity (EUI, computed by normalizing annual energy consumption by floor area) and year of construction, but in New York and Boston older office type buildings have a lower EUI than newer ones. However, the findings in these reports are limited to graphical trends and do not provide statistical analysis. Kontokosta [3] does provide statistical analysis of the 2012 benchmarking data for New York, including year of construction and historic designation status in multiple regression models for office and multifamily residential buildings. The analysis showed that, using the natural log of source EUI as the response variable, the two oldest age categories of buildings were statistically significant predictors for both building types, with older buildings having lower EUIs.

In contrast to previous work, the present study provides statistical analysis of the relationship between year of construction and EUI for multiple U.S. cities, allowing for comparison of trends. The present study also moves beyond year of construction, examining the energy performance of designated (listed) historic buildings at both the local and federal designation level.

2. DATA AND METHODS

2.1 MUNICIPAL BENCHMARKING DATA IN THE U.S.

Municipal benchmarking data was downloaded from the U.S. Department of Energy (DOE) Building Performance Database (BPD) [4]. The datasets contain information on a range of variables for each benchmarked building, including annual metered energy consumption, building address, building type, and year of construction. They include both the raw benchmarking data submitted to DOE by the city, and a version cleansed by DOE; the cleansed versions were used for this study. As of September 2017, data for seven cities was available for download: Boston, Chicago, Minneapolis, New York, Philadelphia, San Francisco, and Washington DC. The data for New York and San Francisco did not contain information on a building's year of construction, but benchmarking data for New York was matched with records in New York City's Property Land Use Tax Lot Output (PLUTO) database [5] to obtain information on year of construction, resulting in datasets for six cities that could be analysed in this study. Energy consumption in the benchmarking data was from the calendar year 2014 for all cities except New York and Washington DC, which contain data from 2013.

2.2 RECORD LINKAGE WITH LISTED HISTORIC BUILDINGS

The municipal benchmarking data does not contain information about whether a building is a designated historic building. However, the benchmarking data does contain street addresses for each building, which were then matched with street addresses in auxiliary databases to determine a building's historic designation status. New York had the best available auxiliary data on historic designation, so this matching process was only completed for the New York benchmarking data.

Three auxiliary databases were used to provide information about historic designation for buildings in the New York benchmarking data: the PLUTO database, the National Register of Historic Places (NRHP) [6], and the New York State Cultural Resource Information System (CRIS) [7]. The PLUTO database provided information about a building's local designation status, i.e., whether a building was a designated historic landmark or located within an historic district designated by the New York City Landmarks Preservation Commission (LPC). The NRHP database provided information about a building's individual federal designation status, i.e., whether a building was individually listed on the NRHP. The CRIS database provided information about a building's federal district designation status, i.e., whether a building was listed as contributing within a federally designated historic district. A fuzzy string matching algorithm through an add-in in Microsoft Excel was used to perform the address matching.

2.3 ANALYSIS METHODS

Using the benchmarking data for each of the six cities, summary statistics were computed for the two primary variables of interest in this study: site EUI and year of construction. Pearson correlation coefficients were computed to quantify the strength and direction of the linear relationship between the two variables, and simple linear regression models using ordinary least squares were developed to examine the relationship between site EUI and year of construction. The natural log transform of EUI was used as the response variable to address issues of non-constant variance and non-normality of the model residuals, leading to the following regression model form:

$$\ln(y) = \beta_o + \beta_1 x_1$$

where y is site EUI, x_1 is year of construction, and β_0 and β_1 are the estimated regression coefficients. The estimated regression coefficient for year of construction can be interpreted as representing an $(e^{\beta_1} - 1) * 100$ percent change in mean annual EUI for each one-year increase in a building's year of construction.

To analyse the energy performance of historic vs. non-historic buildings, the benchmarking data for New York, after being matched with PLUTO, NRHP, and CRIS datasets, was divided into six groups:

- *All* – includes all of the buildings in the New York benchmarking data;
- *All Historic* – buildings designated under any of the four types of historic designation below;
- *LPC Historic District* – buildings located within historic districts, as designated by the LPC;
- *LPC Historic Landmark* – buildings designated as historic landmarks by the LPC;
- *NRHP Listed Building* – buildings listed individually on the NRHP;
- *NRHP Contributing in District* – buildings listed as contributing within designated historic districts on the NRHP

Summary statistics were computed for each of the groups. Welch's t-test (unequal variances t-test), which is known to be robust to departures from normality, was used to test for statistically significant differences in the means of the different groups. The test statistic is given by:

$$t = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where $\bar{x}$, s^2, and n are the means, variances, and sample sizes (less missing data) of the two groups being compared.

3. RESULTS

3.1 RELATIONSHIP BETWEEN YEAR OF CONSTRUCTION AND EUI ACROSS SIX U.S. CITIES

The results of the analysis examining the relationship between building year of construction and EUI are presented in Tables 1–3 and Figure 1.

Table 1 provides summary statistics for the two primary variables of interest: site EUI, and year of construction. The median, mean, and standard deviation values for each variable are provided, along with the number of buildings in each benchmarking dataset (missing values were omitted when computing the summary statistics). Comparing EUI across the six cities, Washington DC has the lowest median EUI, followed by Boston and Philadelphia. Washington DC also has the lowest mean EUI, followed by New York. Note that in all cities the median is lower than the mean, indicating that the distribution of EUI is right-skewed for all cities. While these EUI comparisons do not control for climate, all of these cities are located in relatively similar ASHRAE climate zones (ranging from 4A to 6A). Comparing year of construction across the six cities, New York has the oldest median and mean year of construction, followed by Philadelphia; Washington DC has the newest building stock. Note that in all cities except New York the median is larger than the mean, suggesting that the distribution for year of construction is left-skewed.

Overall, EUI and year of construction appear to be fairly similar across the six cities, and are within typical ranges for the U.S. commercial building stock as a whole. According to the 2012 CBECS data [8], the median site EUI for commercial buildings between 200,001 and 500,000 square feet is 77.1 kBtu/ft^2 (243.2 kWh/m^2) across all climate zones and building types, and 53 % of the U.S. building stock was constructed prior to 1979.

Figure 1 provides kernel density plots for year of construction for each of the six cities. Each line represents a different city; Boston, Chicago, and Minneapolis are plotted together at left, and New York, Philadelphia and Washington DC are plotted together at right. The plots indicate that the distribution of year of construction is multimodal for all six cities, and approximately left-skewed for all cities except for New York. The distributions for Boston, Chicago, and Minneapolis are all fairly similar, with a peak in the early 20th century and a second peak in the late 20th century. The distribution for Washington DC is shifted to the right (i.e., newer) and the distribution for Philadelphia is flatter and shifted to the left (i.e., older) compared to the other cities. As with Table 1, the similarity between the six cities is notable.

Table 1. Count and summary statistics for site EUI and year of construction by city

City	N	Site EUI, kBtu/ft2 (kWh/m²)			Year of Construction		
		Median	*Mean*	*Std. Dev.*	*Median*	*Mean*	*Std. Dev.*
Boston	1,372	78.2 (246.7)	102.1 (322.0)	88.7 (280.0)	1972	1961	41
Chicago	243	88.0 (277.6)	109.0 (343.8)	72.9 (229.9)	1971	1963	33
Minneapolis	307	93.5 (295.0)	100.8 (317.9)	55.0 (173.6)	1975	1965	34
New York	14,315	83.8 (264.4)	92.8 (292.6)	120.8 (381.0)	1942	1949	29
Philadelphia	1,159	78.0 (246.1)	100.6 (317.4)	97.9 (308.8)	1963	1957	37
Washington D.C.	1,592	67.2 (211.8)	76.9 (242.6)	53.1 (167.5)	1975	1973	28

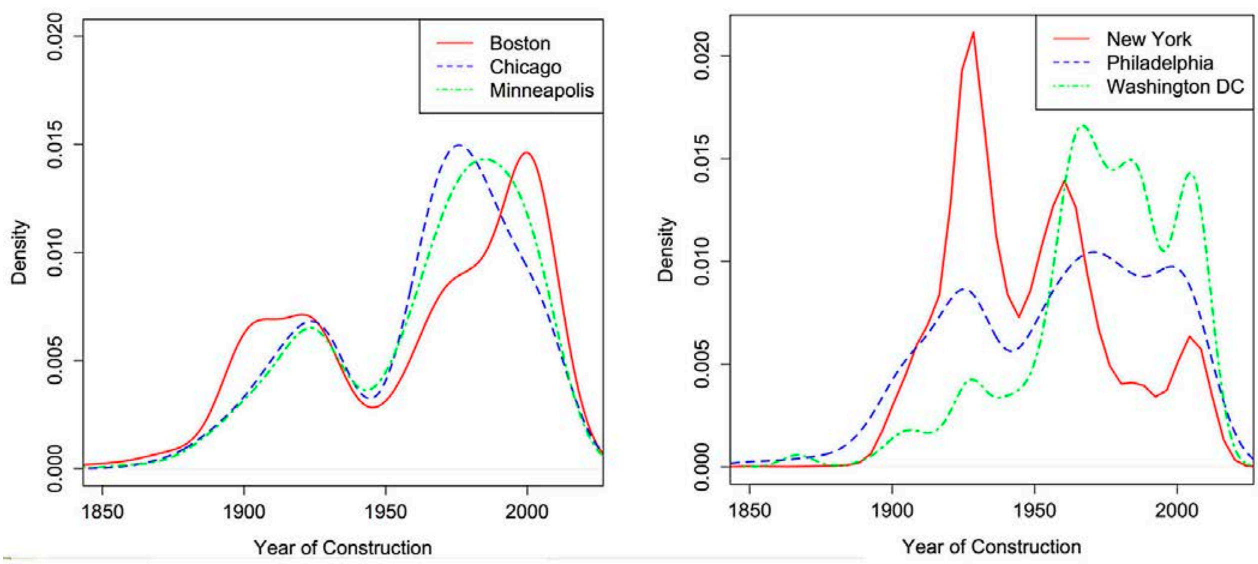

Figure 1. Density plots of year of construction by city.

Table 2. Pearson correlation coefficient for EUI and year of construction by city

City	All Buildings	By Building Type		
		Office	*Multifamily*	*K-12 Schools*
Boston	0.14	0.19	-0.01	0.32
Chicago	0.13	-0.20	-	0.29
Minneapolis	-0.07	-0.06	-	-0.09
New York	0.04	0.18	< -0.01	0.11
Philadelphia	0.11	-0.01	-0.14	-0.16
Washington D.C.	-0.08	-0.10	-0.26	-

Table 2 lists the Pearson correlation coefficient, r, for each of the six cities. Coefficients are given for all of the benchmarked buildings in each city, and are also divided by building type for each city. Correlation coefficients with an absolute value greater than 0.9 are typically considered strong, and between 0.7 and 0.9 are considered moderate. A positive correlation coefficient indicates a positive linear relationship between the two variables, i.e., EUI increases as year of construction increases, and a negative coefficient indicates a negative linear relationship.

Overall, the results show that the linear relationship between EUI and year of construction is weak across all of the six cities, and all of the building types. Most of the coefficients in the table have an absolute value less than 0.20. The largest coefficients are for K-12 schools in Boston and Chicago, which both have a positive correlation coefficient of around 0.30 (indicating an increase in EUI with newer buildings), but these correlations are still considered weak. There are both negative and positive correlation coefficients across all cities and building types, however, there are a few trends. The coefficients for multifamily residential buildings are all negative, suggesting that newer buildings have a lower EUI, although these coefficients are weak, and close to zero in some cases. In two of the cities – Washington DC, and Minneapolis – the correlation coefficients are all negative, again indicating that newer buildings in these cities have a lower EUI, but these coefficients are also all weak.

Table 3 provides the results for six simple linear regression models, one for each city (within each city all building types were used), with ln(EUI) as the response variable and year of construction as the predictor variable. The estimated regression coefficients are given for each model, along with the standard errors, t-statistic, p-value, and an indicator of the level of significance for the test (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). The R^2 is also listed for each model, to indicate model goodness of fit. Model coefficients shown are based on units of kBtu/ft^2; the coefficient for the intercept would change for metric units, but the coefficient for year of construction and significance test would not.

The results show that there is a statistically significant linear relationship at $p < 0.05$ between year of construction and EUI in five of the cities – Boston, Minneapolis, New York, Philadelphia, and Washington DC. For Boston, New York, and Philadelphia, the estimated regression coefficients for year of construction are positive, indicating an increase of 0.25 %, 0.10 %, and 0.30 %, respectively, in annual EUI for each one-year increase in year of construction. For Minneapolis and Washington DC, the estimated regression coefficients for year of construction are negative, suggesting a 0.34 % and 0.21 % decrease, respectively, in annual EUI for each one-year increase in year of construction. For all of the models, however, the R^2 is small, suggesting that year of construction is not a very good predictor of EUI, explaining less than 2 % of the variation in EUI in most cases.

Table 3. Simple linear regression results for ln(EUI) and year of construction by city

City	Variable	Estimate	Std. Error	t-statistic	p-value	Sig.	R^2
Boston	Constant	-0.5925	1.1621	-0.510	0.610		0.015
	Year of Constant	0.0025	0.0006	4.221	<0.001	***	
Chicago	Constant	2.1129	1.8097	1.168	0.244		0.007
	Year of Constant	0.0012	0.0009	1.349	0.179		
Minneapolis	Constant	11.0122	2.5409	4.334	<0.001	***	0.022
	Year of Constant	-0.0034	0.0013	-2.599	0.010	**	
New York	Constant	2.3312	0.4366	5.339	<0.001	***	0.002
	Year of Constant	0.0010	0.0002	4.612	<0.001	***	
Philadelphia	Constant	-1.7704	1.6643	-1.064	0.288		0.011
	Year of Constant	0.0030	0.0009	3.586	<0.001	***	
Washington D.C.	Constant	8.2452	1.6291	5.061	<0.001	***	0.008
	Year of Constant	-0.0021	0.0008	-2.498	0.0127	*	

3.2 ENERGY PERFORMANCE OF LISTED HISTORIC BUILDINGS IN NEW YORK CITY

The results of the analysis examining the energy performance of listed historic buildings in New York City are presented in Tables 4 and 5.

The total number of buildings and distribution of building type for each group of designated historic buildings in New York is provided in Table 4. Approximately 12 % of the buildings (1,779) in the benchmarking data have some kind of historic designation. Since building type is a major determinant of EUI, it is important to understand whether the distribution of building types differs greatly between historic and non-historic buildings. The results show that the distribution of building types for designated historic buildings is similar to the distribution in the benchmarking data overall. However, designated historic buildings have a higher proportion of office type buildings compared to the overall benchmarking dataset, and buildings contributing within districts have a higher proportion of multifamily buildings compared to the overall benchmarking dataset. LPC listed landmarks have a much lower proportion of multifamily buildings compared to all the other groups.

Table 4. Building type proportion by designation status

Designation Status	N	Building Type					
		Office	*Multifamily*	*K-12 Schools*	*University*	*Hotels*	*Other*
All	14,315	0.09	0.62	0.01	< 0.01	0.01	0.27
All Historic	1,779	0.15	0.62	0.01	0.01	0.02	0.19
LPC Historic District	1,397	0.11	0.71	0.01	< 0.01	0.02	0.15
LPC Historic Landmark	335	0.31	0.26	0.01	0.02	0.06	0.34
NRHP Listed Building	90	0.21	0.60	0.02	0.01	–	0.16
NRHP Contributing in District	134	0.16	0.67	–	0.01	0.01	0.15

Table 5 provides summary statistics and results of the two-sample t-test comparing mean site EUI of historic and non-historic buildings. For each group, the total number of buildings (less those missing EUI data) is given, along with the median, mean, and standard deviation for EUI. The t-statistic and p-value for the test are listed, along with an indicator of the level of significance for the test. The results show that the mean and median site EUI is significantly lower for historic buildings (at $p < 0.001$) in all cases except individually landmarked buildings, both at the local level and at the federal level. For these two cases, the mean EUI of historic buildings is higher than for non-historic buildings, but there is no statistically significant difference between the two. One possible reason for these results could be differences in building type; Table 4 shows that individually landmarked buildings have a higher proportion of office buildings, and LPC landmarked buildings have a lower proportion of multifamily residential buildings.

Table 5. Summary statisics and results of two-sample t-test for site EUI by designation status

Designation Status	n	Site EUI, kBtu/ft^2 (kWh/m^2)			t-stat	p-value	Sig.
		Median	*Mean*	*Std. Dev.*			
All	10,329	83.8 (264.4)	91.8 (289.5)	66.7 (210.3)	-	-	-
All Historic	1,369	78.2 (246.7)	82.3 (259.7)	38.7 (122.0)	–8.49	< 0.001	***
All Non-Historic	8,960	84.8 (267.5)	93.2 (294.0)	69.9 (220.4)			
LPC Historic District	1,125	76.8 (242.3)	80.0 (252.4)	36.9 (116.4)	–10.01	< 0.001	***
Non-LPC Historic Dist.	9,204	84.9 (267.8)	93.2 (294.0)	69.3 (218.6)			
LPC Historic Landmark	204	87.9 (277.3)	96.7 (305.0)	46.6 (147.1)	1.51	0.133	
Non-LPC Historic Land.	10,125	83.7 (264.1)	91.7 (289.2)	67.0 (211.4)			
NRHP Listed Building	70	82.6 (260.4)	92.8 (292.9)	43.5 (137.1)	0.21	0.837	
Non-NRHP Listed Building	10,259	83.8 (264.4)	91.8 (289.4)	66.8 (210.7)			
NRHP Contrib. in Dist.	107	74.1 (233.8)	79.4 (250.5)	31.5 (99.3)	–4.00	< 0.001	***
Non-NRHP Cont. in Dist.	10,222	83.9 (264.7)	91.9 (289.9)	66.9 (211.1)			

However, this difference in building type proportion is likely not responsible for the differences in EUI between these populations, as these buildings have similar mean EUIs in the benchmarking data as a whole – offices: 89.81 kBtu/ft^2 (283.33 kWh/m^2); multifamily: 89.75 kBtu/ft^2 (283.14 kWh/m^2).

4. DISCUSSION AND CONCLUSIONS

Comparing trends in year of construction and site EUI across six U.S. cities demonstrated that the median and mean values for these variables were generally similar across all cities. Examining the relationship between year of construction and site EUI showed that these two variables have only a weak linear relationship across all cities and building types. While year of construction is a statistically significant predictor in most cities, the R^2 values for all of the models are very low, indicating that year of construction is not a strong predictor of EUI. These conclusions with local data mirror previous work with nationally representative data in the U.S. showing year of construction to be a similarly weak predictor of EUI.

Address matching the benchmarking data for New York with auxiliary databases resulted in a new dataset containing metered energy performance for both historic and non-historic buildings. Statistical tests showed that designated historic buildings have significantly lower mean EUIs compared to non-historic buildings, although this trend does not hold for individually listed buildings, both at the local and federal level. The reason behind this trend is not clear, but initial analysis showed that differences in building type between historic and non-historic buildings do not appear to be the cause.

Overall, this study demonstrates the potential uses of municipal benchmarking data in understanding the older and historic building stock. This study represents a preliminary attempt to compare trends in building age and EUI across multiple U.S. cities using consistent statistical analysis. While simple regressions were used in this study, future work could consider multiple regression to control for other variables such as building type. This study also piloted a method for matching energy benchmarking data with auxiliary data about a building's listed historic status. While the present analysis of designated historic buildings was limited to New York because of the large quantity of publicly available data about its historic building stock, future work could explore the feasibility of expanding this method to other cities.

5. REFERENCES

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