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Energy and Greenhouse Gas Savings for LEED-Certified U.S. Office Buildings Using Weighted Regression

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**Energy and Greenhouse Gas Savings for LEED-
Certified U.S. Office Buildings Using Weighted
Regression**

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Senior Honors Thesis

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Abstract:

In this study, we studied the energy consumption and greenhouse gas emission performance of LEED-certified office buildings. We obtained the 2016 energy consumption and greenhouse gas emission data for 4002 office buildings from nine major US cities, including 522 buildings that we identified as LEED-certified. We discovered that LEED buildings used significantly more electricity percentagewise as their energy source. We also discovered that the locations and ages of buildings have significant effect on their performance. We removed the effect of locations and building ages using weighted regression. Our result showed that LEED office buildings used 11% less site energy, 9% less source energy, and emitted 9% less greenhouse gases. Comparing to results from our previous study that didn't account for building age, LEED-certified buildings' source energy and greenhouse gas savings are significantly higher when accounting for building age, while site energy saving stays the same.

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Chapter 1

Introduction

1.1 Motivation

In the US, commercial and residential buildings are responsible for 76% of electricity use, 40% of U.S. primary energy consumption, and 33% of its energy related GHG emissions [1]. The global warming caused by greenhouse gas emission has become one of the most serious threats to the environment and humankind. In addition, mass emission of pollutants like CH₄, N₂O in big cities resulted from burning fossil fuels can also lead to serious respiratory illnesses and diseases like lung cancer [2]. Thus, finding out how we can reduce buildings' emissions has become a vital and urgent topic.

1.2 LEED

Most strategies to reduce building emissions begin with improving the energy efficiency of the buildings. Leadership in Energy and Environmental Design (LEED) was founded in 1998 by the U.S. Green Building Council (USGBC). LEED is a program that provides third-party verification of green buildings. Its

rating system grades buildings on how environmentally friendly their designs are, and it certifies buildings with different certification levels based on their grades.

LEED is the most popular green building rating system in the US. [3] In 2013, National Academies concluded that “green buildings can result in significant reductions in energy use”. [4] An early study in 2008 funded by the USGBC compared LEED and non-LEED buildings’ energy use intensity (EUI), which is energy per square foot per year, and concluded that commercial LEED-certified buildings use on average 25% to 30% less site energy, depending on their certification level, than non-certified commercial buildings. [6] However, this study was met with doubts and criticisms. [5] For example, the study only used data voluntarily provided by 121 LEED building owners, which means the sample is small and vulnerable to volunteer bias. Also, they only considered the site energy consumption while ignoring the source energy consumption of the buildings.

1.3 Site and Source Energy

The site energy consumption of a building is the energy that a building uses on site. The source energy consumption, on the other hand, accounts for the energy used on site plus all the energies used or wasted in the process of generating the energy from raw materials and transporting it to the building. For example, in 2016, a Joule of electrical energy consumed on site counts as 3.14 Joules of source energy consumption because about 2 Joules of energy are wasted in the process of generating and transmitting a Joule of electricity. Natural gas requires much less energy to refine and transport, so 1 Joule of site energy from natural gas only counts as 1.05 Joules of source energy. (The conversion rates were set by United States Environmental Protection Agency (EPA) in 2016 and were subjected to changes every year). [7] So, while electrical energy can be used more efficiently than energy released by natural gas and thus resulting in lower site energy consumption, the source energy consumption can actually be higher. Comparing to site energy, the source energy consumption provides a more holistic view of a building's total energy consumption and emission.

1.4 Our previous Study

We previously conducted a study on LEED office buildings. [8] Our sample size was much larger than any previous studies around LEED: we used data from 4417

office buildings, including 551 being LEED-certified, in ten major US cities. We compared site energy consumption, source energy consumption, and energy-related greenhouse gas emission of LEED and non-LEED buildings. The result showed that LEED office buildings on average used 11% less site energy, 7% less source energy, and emitted 7% less greenhouse gases comparing to non-LEED office buildings. These measured savings are much lower than the results of the 2008 study.

We used the floor areas as the weight when calculating averages, because our goal was to compare LEED buildings as a whole to non-LEED buildings as a whole. The energy consumption and greenhouse gas emission data were in unit per square foot. Mathematically, calculating the weighted average emission per square foot over floor area is equivalent to averaging the emission per square foot of every square foot, which is the natural way to calculate the average emission per square foot. On the other hand, unweighted averages have no physical meaning and would not provide us what we wanted. We used Gross Floor Area (GSF) as the weight, which is the sum of all areas on all floors of a building included within the outside faces of its exterior walls.

However, there were some issues that we didn't address in our previous study. One of the main issues is that we didn't take into consideration the ages of the buildings: if new buildings tend to use more energy, and LEED buildings tend to

be new, then results would underestimate the saving of LEED buildings comparing to non-LEED buildings built within the same periods. The purpose of this honor study is to address for this issue. We used regression as the main method of analysis. We used regression to repeat the analysis in our previous study. Then we compared LEED and non-LEED buildings after eliminating the potential effect of the ages of the buildings.

Chapter 2

Materials and Methods

2.1 Data Collection

We obtained 2016 municipal office building benchmarking data from the city governments of Boston, Chicago, Denver, Los Angeles, Minneapolis, NYC, Philadelphia, Portland, Seattle, and Washington DC. The data include the buildings' addresses, building types, year built, total floor areas, site EUI, source EUI, total greenhouse gas emission. However, the benchmarking data didn't tell which buildings were LEED-certified, so we had to identify which of the building data belongs to a LEED building using their addresses, size, and building type.

2.2 LEED Building Identification

We downloaded a list of LEED-certified buildings from the USGBC web site with information about their name, size, addresses, and building types, and LEED certification levels. We selected the LEED buildings in the 10 cities that were identified as office from the list. We used Google Map and Quantum Geographic Information System (QGIS) to find and display the GPS coordinates of both the

LEED office buildings and the buildings from the benchmarking data according to their addresses. Then we manually tried to find a match for each LEED building according to its name, size, and GPS coordinate.

Portland didn't provide the year built for their buildings. We wanted to analyze whether accounting for the effect of building age would change our analysis results, so in this study, we removed all Portland buildings from the data, which left us with 4002 buildings with 522 being LEED-certified.

2.3 Data Analysis Methods

Unless specifically mentioned, the data analysis in this study was done using the R statistical package.

Weighted Regression:

In this study, we used weighted regressions to calculate the differences between LEED and non-LEED buildings because it allowed us to analyze the effect of multiple factors at the same time. First, we created a dummy variable "isLEED", which equals to 1 for LEED building is and equals to 0 for non-LEED buildings. A regression with isLEED as its only predictor is equivalent to weighted mean

comparison. For example, if we fit the function below using R with GSF as the weight:

$$\text{SiteEUI} = \alpha_1 + \alpha_2 \times \text{isLEED} \quad (1)$$

We will get a α_1 and a α_2 that are the least square fit of the function. In this case, α_1 is equivalent to the weighted mean site EUI among non-LEED buildings, and $\alpha_1 + \alpha_2$ is equivalent to the weighted mean site EUI among LEED buildings. The coefficient if isLEED , α_2 , is the difference between LEED and non-LEED buildings, or more specifically, the effect of being LEED-certified.

We then created a dummy variable for each of the 9 cities, which equals to 1 when a building is from that city, and 0 other wise. The City variables can be added to function 1:

$$\text{SiteEUI} = \alpha_1 + \alpha_2 \times \text{isLEED} + \alpha_3 \times \text{Boston} + \alpha_4 \times \text{Chicago} + \dots \quad (2)$$

By fitting this function, we will get a coefficient for each variable, which represents the effect of that variable.

The α_2 we get from function 1 and function 2 can be different. For example, assume we just have 2 cities: Boston and Chicago. Assume Boston has 10 non-LEED buildings and 1 LEED buildings, and the LEED building uses 10 Joule less site energy per square foot than the 10 non-LEED buildings. Assume Chicago has 2 non-LEED buildings and 2 LEED buildings, and the LEED buildings also use 10

Joule less site energy per square foot than the 2 non-LEED buildings. However, buildings in Boston overall use 4 Joule more energy than buildings in Chicago. If we use function 1 to calculate the effect of being a LEED building, then α_2 will be smaller than 10 Joules per square foot because function 1 mixed the effect of City with the effect of LEED and gives an unfair analysis on LEED buildings. Function 2, on the other hand, will take into consideration the effect of the difference cities and report $\alpha_2 = 10 \text{ J/sqft}$, which is the actual effect of being a LEED building. In this study, we used function 1 when calculating the difference between LEED and non-LEED buildings from one city and used function 2 to calculate the aggregated difference among all cities.

We also created a dummy variable for each decade, which equals to 1 when a building is built in that decade, and 0 other wise. (There weren't many buildings built before 1900, so we assigned all buildings built before 1900 to one category.)

We added the dummy variable to function 2 to calculate the difference between LEED and non-LEED buildings when the effects of City and building age are both removed.

Permutation Method:

We used permutation methods to calculate the p-values of the differences between LEED and non-LEED. p-value is the probability of obtaining our sample data

assuming there's no difference between LEED and non-LEED buildings, and the difference in our data is purely by chance. A low p-value means it's unlikely that the difference in our sample is purely by chance, and there are probably some differences between LEED and non-LEED buildings. A p-value below 0.32 is considered as relatively low, while a p-value below 0.05 suggest the difference is significant.

Although R has a function that can do weighted linear regression, that function was designed to take in the variance of each number as its weight. When the weight is not variance, like in our case where weight is GSF, it still gives the correct coefficients, but not the correct p-values.

So instead, we used permutation methods to calculate the p-values of the isLEED coefficient in regression to prove whether the differences between LEED and non-LEED buildings are significant. The permutation method measures how likely it is that 2 randomly selected groups of buildings would have a such a difference. When isLEED is the only predictor, we will first calculate the coefficient of isLEED variable; let it be δ . Then we will redistribute the isLEED values of the buildings so that whether the isLEED value of a building is one or zero is completely random. For example, if I have 10 LEED buildings and 90 non-LEED buildings, I will mix all 100 buildings and randomly select 10 buildings and let their isLEED values equal 1. Let the isLEED values of the rest of buildings equal

to 0. Then I will use the new data to fit the function and get a new coefficient for isLEED. We repeat this process for a large number of times (in this study we repeat ten thousand times) and obtain the same number of coefficients for isLEED. The percentage of the coefficients whose absolute values are larger than the absolute value of delta is the p-value for delta.

When we include other variables as predictors in a function, like in function 2 where we included City variables, we can't simply redistribute the isLEED values of all buildings because the ratio of LEED building within each city is different among cities, shown in section 3.1. This means that simply shuffling all isLEED values will cause some cities to end up with more or less buildings with isLEED equal 1 than its LEED buildings. Because the effects of different cities are different, this will create slight error in p-value.

Bootstrap Method:

We used the bootstrap methods to calculate the standard errors. The bootstrap method simulates the sampling process, but instead of sampling from the population, it samples from the sample we already have.

For example, we wanted to predict the standard deviation of the weighted average site EUI of LEED buildings. We have 522 LEED office buildings as our sample.

The Bootstrap method would randomly select 522 buildings with replacement from

our sample to form a new bootstrap sample, and then calculate its weighted average site EUI. We could repeat this process for a large number of times (in this study we repeat ten thousand times) and we would obtain the same number of weighted means. The distribution of the means would be normal, and its standard deviation is the estimation of the actual standard deviation of the weighted average site EUI of LEED buildings.

Chapter 3

Calculation

3.1 Cities comparison:

We first counted the number of LEED and NonLEED buildings and their total GSF in each city and the percentage of LEED buildings among all buildings in each city. The results are shown in table 1 and table 2.

Cities	LEED	Non-LEED	Total	LEED Percentage
Boston	35	238	273	13%
Chicago	81	244	325	25%
Denver	49	144	193	25%
Los Angeles	43	689	737	6%
Minneapolis	16	93	109	15%
NYC	81	1165	1246	7%
Philadelphia	16	173	189	8%
Seattle	50	409	459	12%
Washington	151	325	476	32%
Total	522	3480	4002	15%

Table 1: Numbers of LEED and non-LEED buildings.

Cities	LEED (sqft)	Non-LEED(sqft)	Total(sqft)	LEED Percentage
Boston	23413149	46556634	69969783	33%
Chicago	85307634	77253811	162561445	52%
Denver	22473633	22590922	45064555	50%
Los Angeles	29381427	166272945	195654372	15%
Minneapolis	13035044	23831087	36866131	35%
NYC	67700677	332521339	400222016	17%
Philadelphia	11814767	54432024	66246791	18%
Seattle	23681785	40135019	63816804	37%
Washington	46296242	69275756	115571998	40%
Total	323104358	832869537	1155973895	28%

Table 2: GSF of LEED and non-LEED buildings in square feet.

The percentages of LEED buildings’ total GSF are generally larger than the percentage of LEED buildings, which indicates that LEED buildings were larger on average than non-LEED buildings.

Both building wise and total GSF wise, the total and the percentages of LEED buildings varies significantly between cities. As a result, we couldn’t simply compare the average energy consumption and greenhouse gas emissions of LEED and non-LEED buildings among all cities, because doing so could give skewed results if energy consumption and emission also varies between different cities. For example, New York City had a very high number of buildings and total GSF, but very low LEED percentages. If buildings in New York City, both LEED and non-LEED, used less energy relative to buildings from other cities, then the average

energy consumption of non-LEED buildings would appear to be lower comparing to that of LEED buildings, even if LEED buildings in New York City used less energy than non-LEED buildings. To eliminate the potential effect of different cities, when comparing buildings from all cities, we used multivariable regression with cities as dummy variables, as explained in section 2.3.

3.2 Electrical and Nonelectrical Energy:

Office buildings in the US mostly use two energy sources: electricity and natural gas. [9] The site-to-source energy conversion factor for electricity and natural gas in 2016 were 3.14 and 1.05, respectively. Assuming that all buildings used just electricity and natural gas, the electrical and nonelectrical (natural gas) consumption of each building can be calculated through site and source energy:

$$\text{Electrical} \times 3.14 + (\text{Site} - \text{Electrical}) \times 1.05 = \text{Source}$$

$$\text{Electrical} = \frac{\text{Source} - 1.05 \times \text{Site}}{2.09}$$

$$\textit{Nonelectrical} = \textit{Site} - \textit{Electrical}$$

We then calculated the average¹ ratio of site energy that's electrical energy consumption of LEED and non-LEED office buildings in each City. The results are shown in figure 1 and table 2.

1. Unless specifically mentioned, all averages and regressions in this thesis are weighted with GSF.

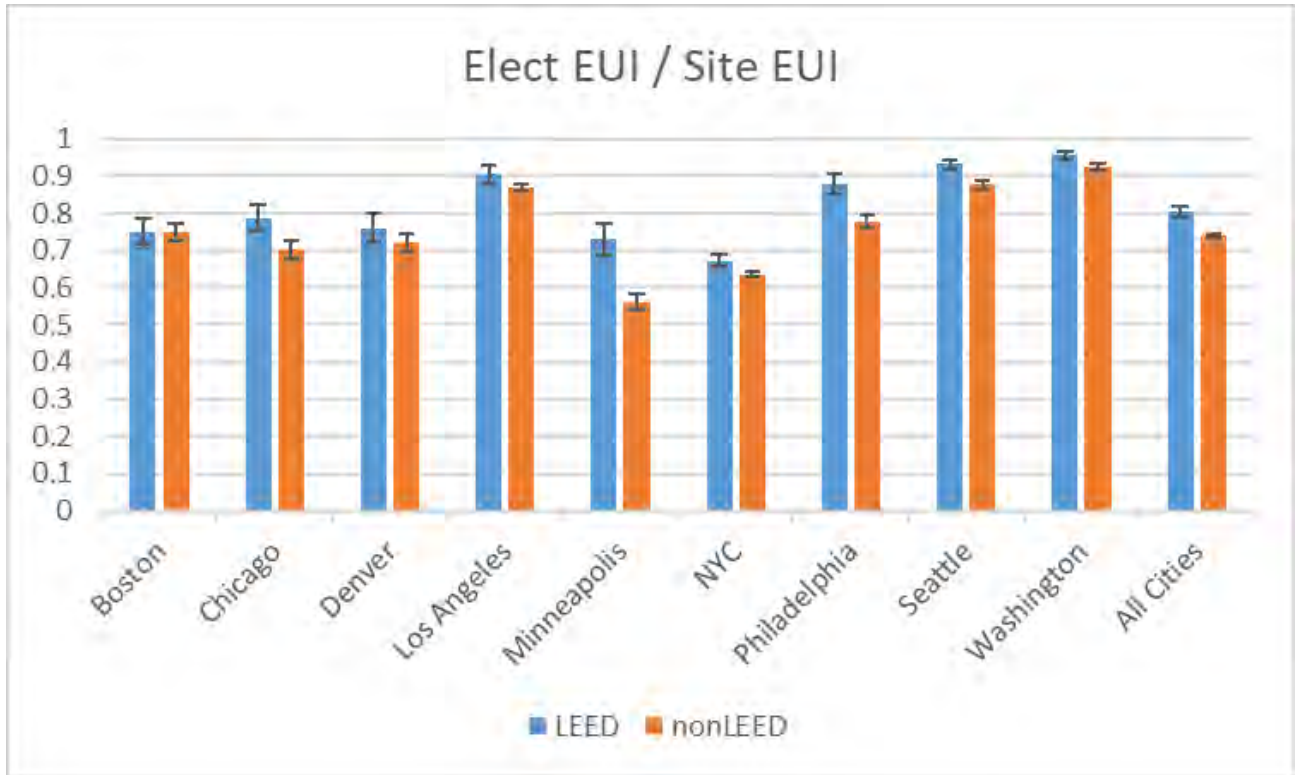


Figure 1: Electrical energy ratio of LEED and non-LEED buildings. Note that all sigma were calculated using bootstrap method, and all error bars reported in this paper correspond to one sigma.

City	LEED	Non-LEED	Difference	p-value
Boston	0.75 ± 0.03	0.75 ± 0.02	<0.01	0.99
Chicago	0.79 ± 0.02	0.70 ± 0.02	0.09	0.08
Denver	0.76 ± 0.02	0.72 ± 0.02	0.04	0.46
Los Angeles	0.90 ± 0.01	0.87 ± 0.01	0.03	0.39
Minneapolis	0.73 ± 0.02	0.56 ± 0.02	0.17	0.02
NYC	0.67 ± 0.01	0.64 ± 0.01	0.04	0.25
Philadelphia	0.88 ± 0.02	0.78 ± 0.02	0.10	0.08
Seattle	0.93 ± 0.01	0.88 ± 0.01	0.06	0.05
Washington	0.96 ± 0.01	0.93 ± 0.01	0.03	0.03
All Cities	0.81 ± 0.01	0.74 ± 0.01		

Table 2: Electrical energy ratio of LEED and non-LEED buildings.

In aggregate, electricity contributes to 81% of LEED buildings' site energy consumption and 74% of non-LEED buildings' site energy consumption. We used multivariable regression with isLEED and Cities as predictors to calculate the aggregate difference, as explained in section 2.3. LEED buildings overall used 5% more electrical energy percentagewise. The p-value for the difference is 0.00¹.

3.3 Site EUI Comparison

We used regression to calculate the average site EUI of LEED and non-LEED office buildings in each City. The results are shown in figure 2 and table 3, with unit being British thermal units (Btu) per square foot per year. One Btu equals 1055 Joules.

1. p-value of 0.00 means it's smaller than 0.005.

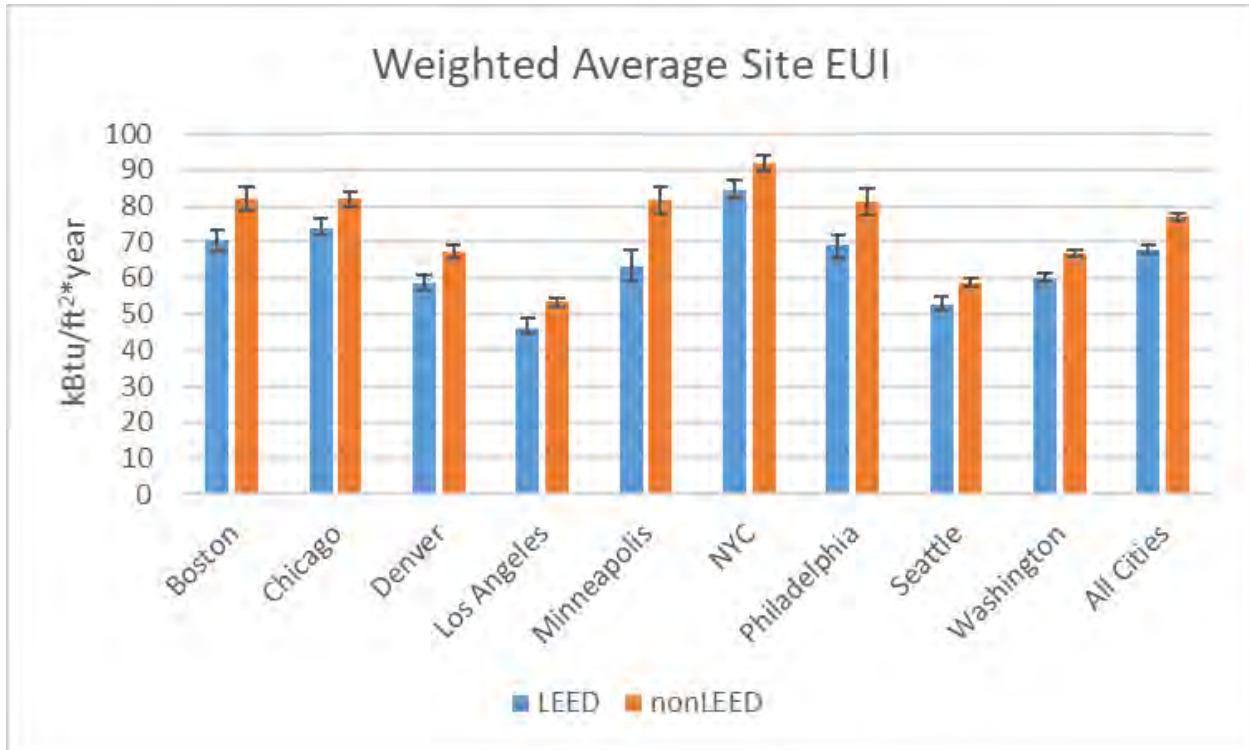


Figure 2: Weighted average Site EUI of LEED and non-LEED buildings.

City	LEED	Non-LEED	Difference	p-value
Boston	71 ± 3	82 ± 3	11	0.12
Chicago	74 ± 3	82 ± 3	8	0.05
Denver	59 ± 2	67 ± 2	9	0.02
Los Angeles	46 ± 3	53 ± 3	7	0.08
Minneapolis	63 ± 5	82 ± 5	19	0.05
NYC	84 ± 3	92 ± 3	8	0.28
Philadelphia	69 ± 3	81 ± 3	12	0.22
Seattle	52 ± 2	59 ± 2	7	0.13
Washington	60 ± 1	67 ± 1	7	0.00
All Cities	68 ± 1	77 ± 1		

Table 3: Weighted average Site EUI of LEED and non-LEED buildings, in Btu per square foot per year.

Again, we used multivariable with isLEED and Cities as predictors regression to calculate the aggregate difference. In aggregate, LEED office buildings on average

save 8.5 kBtu site energy per square foot per year, or 11% of site energy. The p-value is 0.00.

3.4 Source EUI Comparison

We used regression to calculate the average source EUI of LEED and non-LEED office buildings in each City. The results are shown in figure 3 and table 4, with unit being Btu per square foot per year.

We used multivariable regression with isLEED and Cities as predictors to calculate the aggregate difference. LEED office buildings on average save 14 kBtu source energy per square foot per year, or 7 % of source energy. The p-value is 0.00.

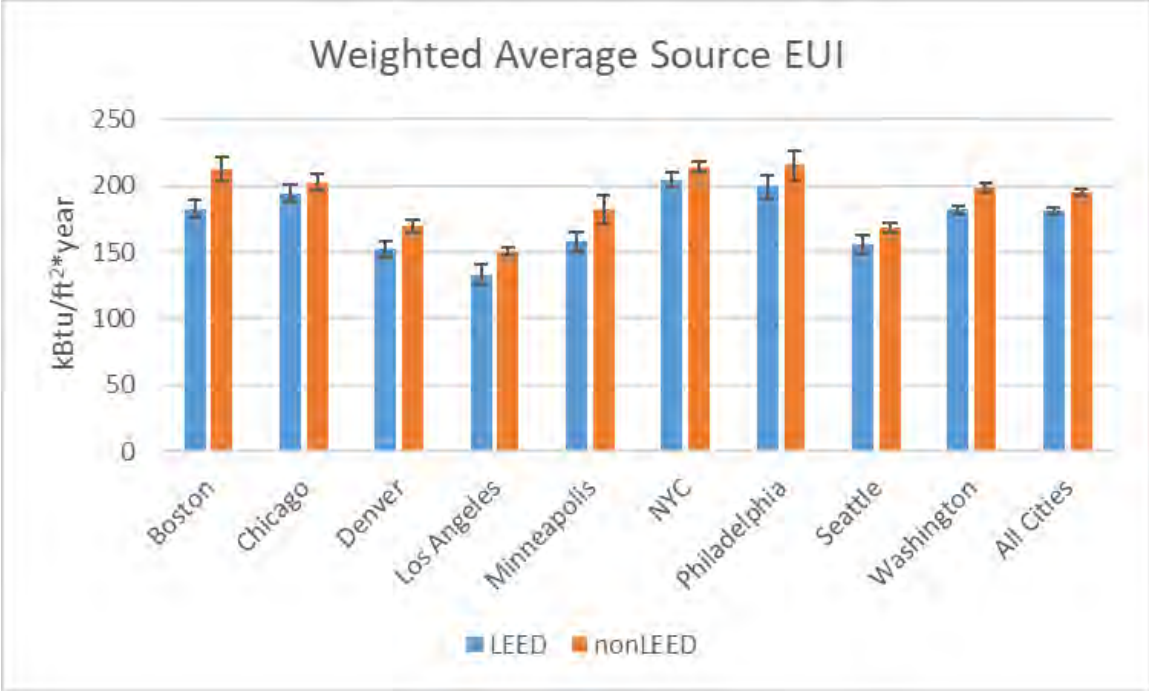


Figure 3: Weighted average Source EUI of LEED and non-LEED buildings.

City	LEED	Non-LEED	Difference	p-value
Boston	183 ± 6	212 ± 9	29	0.13
Chicago	194 ± 6	202 ± 6	8	0.44
Denver	152 ± 6	169 ± 5	17	0.07
Los Angeles	133 ± 8	151 ± 3	18	0.10
Minneapolis	158 ± 7	182 ± 11	24	0.27
NYC	204 ± 6	214 ± 4	10	0.50
Philadelphia	199 ± 8	216 ± 11	17	0.50
Seattle	156 ± 7	168 ± 4	12	0.28
Washington	182 ± 3	198 ± 3	16	0.00
All Cities	181 ± 3	195 ± 2		

Table 4: Weighted average Source EUI of LEED and non-LEED buildings, in Btu per square foot per year.

3.5 Green House Gas Intensity Comparison

We used regression to calculate the average greenhouse gas intensity of LEED and non-LEED office buildings in each City. The results are shown in figure 4 and table 5. Greenhouse gas intensity is measured in kilograms of carbon dioxide per square foot per year.

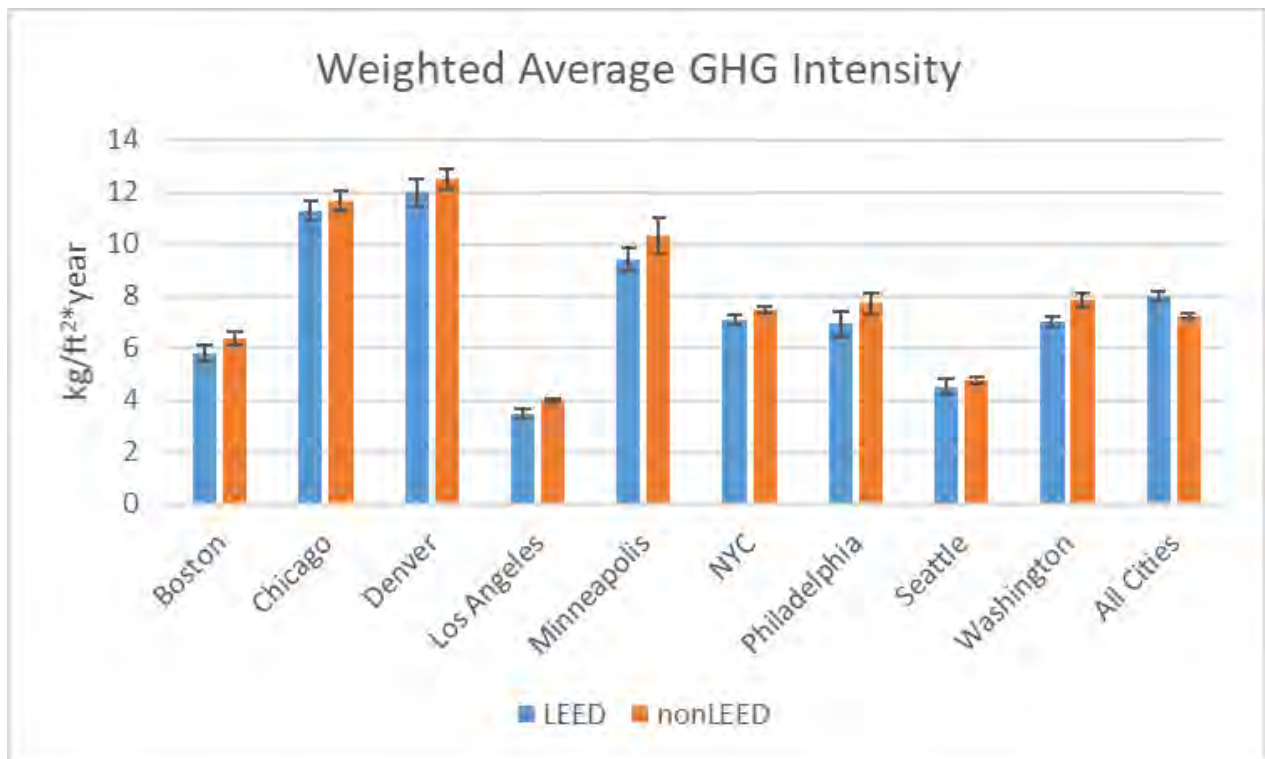


Figure 4: Weighted average GHG intensity of LEED and non-LEED buildings (kg CO₂/ft²*year).

City	LEED	Non-LEED	Difference	p-value
Boston	5.8 ± 0.3	6.4 ± 0.3	0.6	0.36
Chicago	11.3 ± 0.4	11.7 ± 0.4	0.4	0.54
Denver	12.0 ± 0.5	12.5 ± 0.4	0.5	0.47

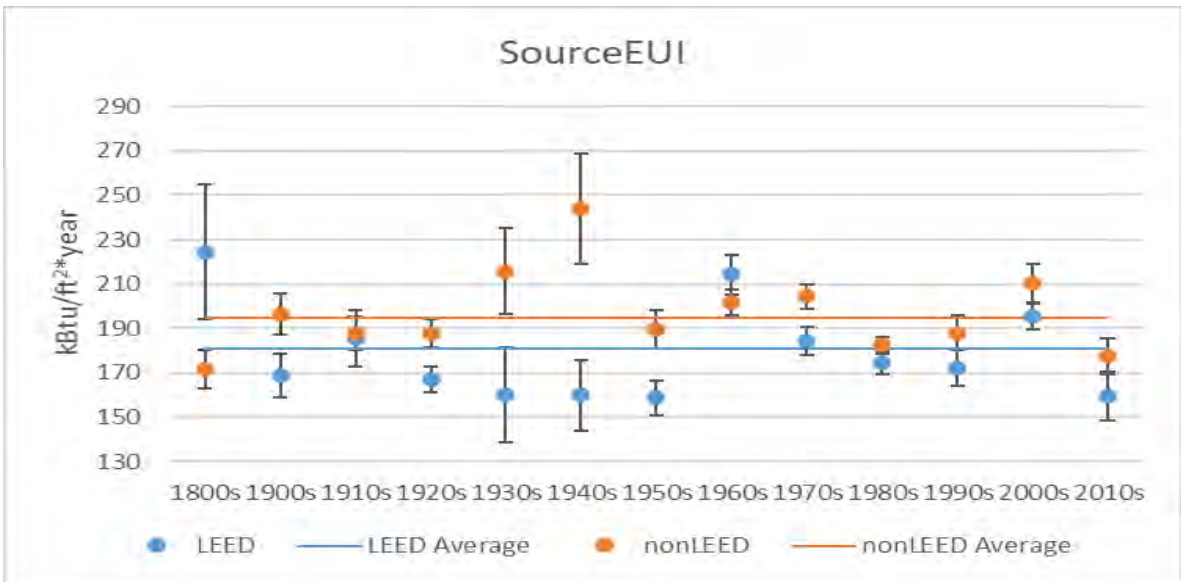
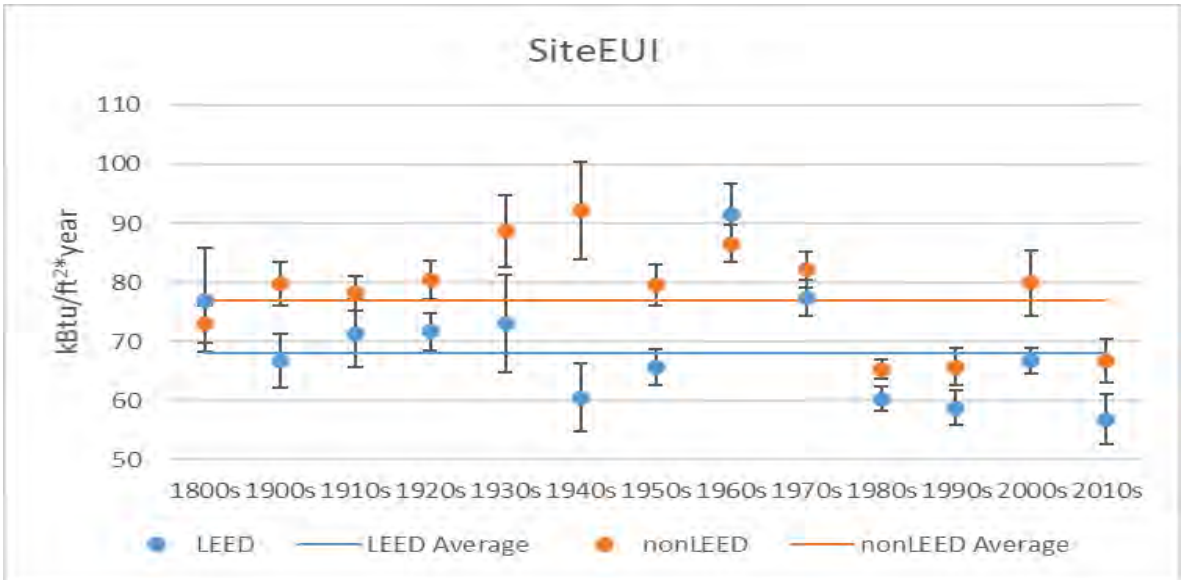
Los Angeles	3.5 ± 0.2	4.0 ± 0.1	0.5	0.08
Minneapolis	9.4 ± 0.4	10.3 ± 0.7	0.9	0.53
NYC	7.1 ± 0.2	7.5 ± 0.1	0.4	0.45
Philadelphia	6.9 ± 0.5	7.7 ± 0.4	0.8	0.46
Seattle	4.8 ± 0.3	5.5 ± 0.1	0.7	0.56
Washington	4.5 ± 0.2	4.8 ± 0.3	0.3	0.02
All Cities	8.0 ± 0.2	7.2 ± 0.1		

Table 5: Weighted average GHG intensity of LEED and non-LEED buildings (kg CO₂/ft²*year).

We used regression with isLEED and Cities as predictors to calculate the aggregate difference. LEED office buildings on average generate 0.52 kg less carbon dioxide per square foot per year, or 7.2% less. The p-value is 0.01.

3.6 Effect of Building Age

We wanted to analyze whether the age of a building effects the building's performance. Figure 5 shows the mean site EUI, source EUI, and GHG intensity of LEED and non-LEED buildings built in each decade.



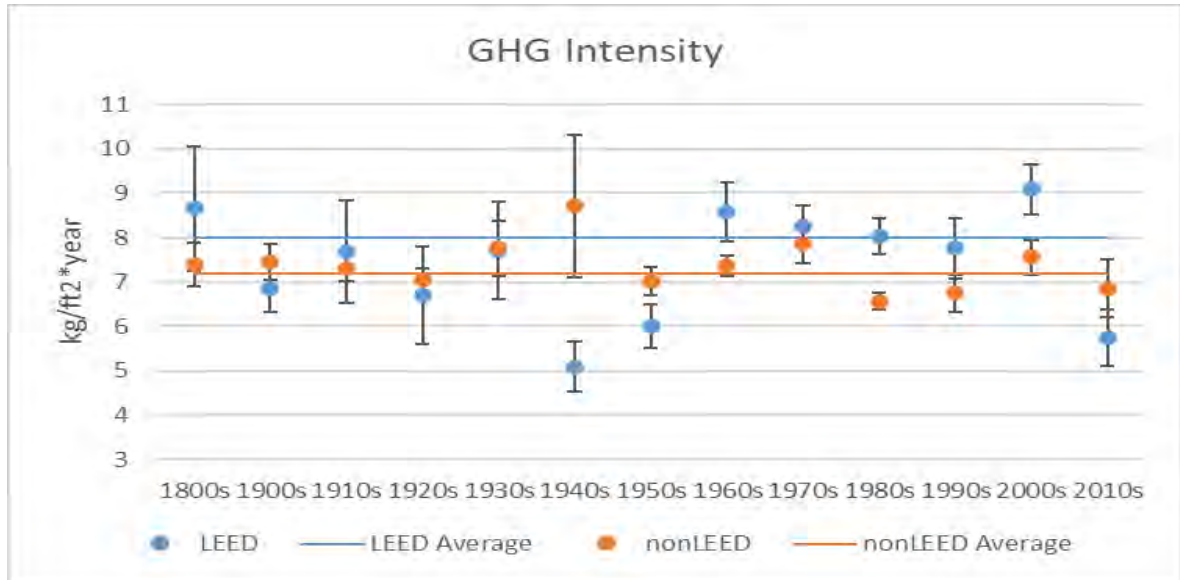


Figure 5: The average of (a) Site EUI, (b) source EUI, and (c) GHG intensity versus decades. The values of the average lines are the aggregated values from section 3.3-3.5. Note that we assigned all buildings built from 1800 to 1900 to one category because there weren't many buildings during this period.

Figure 5 shows that year built have some effect on energy consumption and greenhouse gas emission, but not very strong. There isn't any clear linear, polynomial, or exponential trend.

To better understand the effect of year built, we first calculated the percentage of LEED and non-LEED buildings built in each decade. The results are shown in table 6 and figure 6.

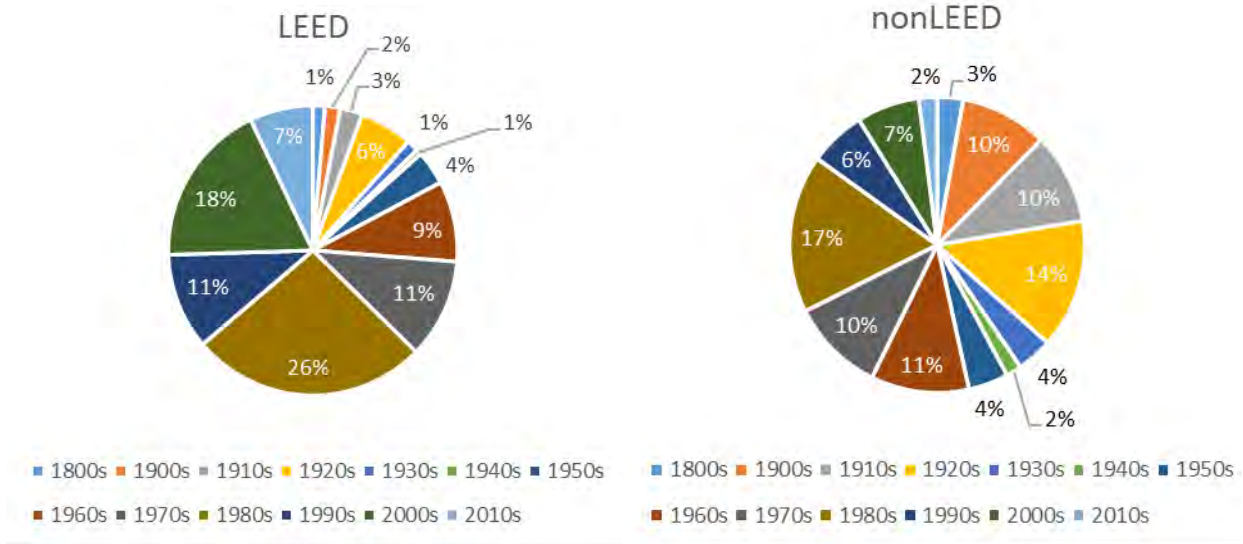


Figure 6: The percentage of buildings built in each period.

Building Year	LEED	LEED (Percentage)	Non-LEED	Non-LEED (Percentage)
1800s	7	1%	99	3%
1900s	9	2%	334	10%
1910s	13	3%	347	10%
1920s	31	6%	492	14%
1930s	7	1%	136	4%
1940s	3	1%	60	2%
1950s	20	4%	152	4%
1960s	47	9%	374	11%
1970s	58	11%	359	10%
1980s	138	26%	602	17%
1990s	56	11%	215	6%
2000s	96	18%	240	7%
2010s	37	7%	70	2%

Table 6: The numbers of buildings and the percentage of buildings in each period.

As shown in table 6 figure 8, most LEED buildings were built after 1960, while non-LEED buildings were built with a relatively consistent pace throughout the twentieth century. Considering the percentages, we can separate all the building years into 2 periods: before 1960, more percentage of non-LEED buildings were built; since 1960, more percentage of LEED buildings were built. We calculated the mean Site EUI, source EUI, and greenhouse gas intensity for LEED and non-LEED buildings in each period. The results are shown in table 7.

	Before 1960	Since 1960	Difference	p-value
LEED Site EUI	71 ± 2	68 ± 1	3	0.43
NonLEED Site EUI	79 ± 2	76 ± 1	3	0.14
LEED Source EUI	169 ± 4	183 ± 2	14	0.08
NonLEED Source EUI	185 ± 2	193 ± 2	8	0.04
LEED GHG intensity	7.0 ± 0.3	8.2 ± 0.2	1.2	0.02
NonLEED GHG intensity	6.9 ± 0.1	7.2 ± 0.1	0.3	0.16

Table 7: Comparison between buildings built before and since 1960. Site and source EUI are in unit of kBtu/ft² per year, and GHG intensity are in unit of kg/ft² per year.

As shown in table 7, buildings built since 1960 consumed statistically significantly more source energy and emits more greenhouse gas, but they consumed relatively less site energy.

We used regression to eliminate the effect of building age. First, we used Decade as a new categorical variable besides isLEED and Cities, with each decade being a dummy variable, as explained in section 2.3. In this case, the LEED buildings saved 9 ± 1 kBtu/ft² per year, or 12%, of site energy, 18 ± 1 kBtu/ft² per year, or 10%, of source energy, and 0.7 ± 0.1 kg/ft² per year, or 10%, of greenhouse gas emission.

We then used year built as a numerical variable besides isLEED and Cities. In this case, the LEED buildings saved 10 ± 1 kBtu/ft² per year, or 11%, of site energy, 19 ± 1 kBtu/ft² per year, or 9%, of source energy, and 0.7 ± 0.1 kg/ft² per year, or 9%, of greenhouse gas emission.

The weighted average year built is 1977 for LEED buildings, and 1961 for non-LEED buildings. If we only consider non-LEED buildings built since 1928, then they also have a weighted average year built of 1977. We removed all non-LEED buildings built before 1928 and used regression with isLEED and City as variables. In this case, the LEED buildings saved 10 ± 1 kBtu/ft² per year, or 13%, of site energy, 20 ± 1 kBtu/ft² per year, or 10%, of source energy, and 0.7 ± 0.1 kg/ft² per year, or 10%, of greenhouse gas emission.

Chapter 4

Analysis and Discussion

Section 3.2 shows that LEED office buildings used relatively more electricity percentagewise than non-LEED office buildings. As mentioned in part 1.3, a Joule of electrical energy consumed on site corresponds to about 3 Joules of source energy consumption while a Joule of natural gas only counts as 1.05 Joules of source energy. As a result, LEED buildings' savings in source energy consumptions and greenhouse gas emissions were not as impressive as its saving in site energy consumption, as shown in section 3.3, 3.4, and 3.5.

Section 3.3 shows that LEED buildings in every city have lower average site energy consumption than non-LEED buildings. The p-value for the difference is smaller than 0.32 in all nine cities, and smaller than 0.05 in four cities. Over all cities, LEED buildings used 11% less site energy than non-LEED buildings, with a p-value of 0.00. This is a strong evidence that LEED buildings indeed used less site energy, but the saving is much less than the savings of 25% to 30% that were indicated in the previous study. [6]

Section 3.4 shows the comparison between the source energy consumptions of LEED and non-LEED buildings. Although the average source energy consumption

of LEED buildings is lower than that of non-LEED buildings, the differences were not statistically significant in eight out of nine cities, with Washington DC being the only city where the p-value of the difference in consumption is lower than 0.05. In aggregate, LEED buildings used 7% less source energy than non-LEED buildings, with a p-value of 0.00. This is a much smaller percentage than that of site energy.

In section 3.5, the comparison between greenhouse gas emissions of LEED and non-LEED buildings is very similar to that of source energy consumptions, with Washington DC being the only city to show a significant difference. Over all cities, LEED buildings emitted 7.2% less greenhouse gas of 0.01. Note that the average of LEED buildings' greenhouse gas emission is actually higher than that of non-LEED buildings even when the average greenhouse emission for LEED buildings in each city is lower. This is because the numbers of buildings and the percentages of LEED buildings varies significantly between cities, as shown in section 3.1. We used multivariable regression to adjust for this issue.

These results confirmed one of our suspicions that simply comparing the site energy consumption of LEED and non-LEED buildings does not tell the whole story. LEED buildings' saving in site energy consumption was inflated because they were more reliant on electricity as their power source. If reducing greenhouse

gas emission is the ultimate goal, then source energy consumption should be used as the indicator instead of site energy consumption.

However, there are some benefits of using electricity instead of natural gas. For one, power plants are usually built in sparsely populated areas. The emission of pollutants like CH_4 , N_2O in sparsely populated areas will cause less harm to people's health than emission in big cities where population density is very high. Also, the site energy to source energy conversion rate is expected to drop in the future. Renewable sources of electricity like wind power and solar power that cause much less emission is becoming more prevalent, and newly developed technologies can significantly improve the efficiency of electricity transmission.

[10]

We also studied the effect of year built on buildings' energy and emission performances. As shown in figure 5, the performances of buildings are affected by the year they were built, but there is no clear linear, polynomial, or exponential trend. We want to use multivariable regression to eliminate the effect of year built by using year built as an additional variable in the regression. However, the effect of year built can be caused by many complicated factors, like economic and political conditions when the building was built, which were highly inconsistent, so we believed that it could be inappropriate to include it as a numerical variable. So, in addition to using year built as a numerical variable, we made each decade a

dummy variable, which equals to 1 if the buildings were built in this decade and equals to 0 otherwise. In addition, we also compared LEED buildings with non-LEED buildings with the same average building age.

The results of the 3 methods are similar. After we accounted for building age, LEED buildings on average saved 11~13% site energy and 9~10% source energy and emitted 9~10% less greenhouse gases. Comparing to our results before adjusting for year built, the site energy saving of LEED building is the same, while source energy and greenhouse gases saving are much higher. This is because LEED buildings on average were built relatively more recently than non-LEED buildings. As shown in figure 6, more than 3 quarters of LEED buildings were built after 1960, while only about half of non-LEED buildings were built after 1960. Table 7 shows that buildings built after 1960 have relatively higher source energy consumption and emitted much more greenhouse gases. As a result, the source energy and greenhouse gas saving of LEED buildings appears to be lower without considering the effect of building age. However, site energy saving was almost the same. We believed that this is because while new buildings consumed more source energy, they also relied more on electricity, which lowered its site energy consumption, and the two effects offset each other.

Chapter 5

Conclusion

We collected the 2016 energy consumption and greenhouse emission data for 4002 office buildings, including 522 LEED-certified buildings, from nine major US cities. We used multivariable regression weighted by floor area understand the difference between LEED and non-LEED buildings. We discovered that LEED buildings relied more on electricity, which inflated their site energy saving. We also discovered that LEED buildings were relatively new, which deflated their energy and greenhouse gas saving. We concluded that, when accounting for building age, LEED office buildings on average used 11% less site energy, 9% less source energy, and emit 9% less greenhouse gases comparing to other office buildings in the same cities. This is still significant but much less that previous studies suggested. [6]

Chapter 6

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