Energy efficiency in U.S. residential rental housing: Adoption rates and impact on rent

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HIGHLIGHTS

- Rental units listings collected and analyzed for 10 U.S. cities.
- Energy efficient features included in 5.3–21.6% of rental units in each city.
- The most common efficient features are lighting and appliance upgrades.
- Propensity score matching and conditional mean comparison methods used.
- Generally, energy efficient features increases the units’ rent, overall from 6% to 14%.

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ABSTRACT

For 118 million residential housing units in the U.S., there is currently a gap between the potential energy savings that can be achieved through the use of existing energy efficiency technologies, and the actual level of energy savings realized, particularly for the 37% of housing units that are considered residential rental properties. Additional quantifiable benefits are needed beyond energy savings to help further motivate residential property owners to invest in energy efficiency upgrades. This research focuses on assessing the adoption of energy efficient upgrades in U.S. residential housing and the impact on rental prices. Ten U.S. cities are chosen for analysis; these cities vary in size across multiple climate zones, and represent a diverse set of housing market conditions. Data was collected for over 159,000 rental property listings, their characteristics, and their energy efficiency measures listed in rental housing postings across each city. Following an extensive data quality control process, over thirty different energy efficient features were identified. The level of adoption was determined for each city, ranging from 5.3% to 21.6%. Efficient lighting and appliances were among the most common, with many features doubling as energy efficient and other desirable aesthetic or comfort improvements. Then using propensity score matching and conditional mean comparison methods, the relative impact on rent charged in each city was calculated, which ranged from a 6% to 14.1% increase in rent for properties with energy efficient upgrades in U.S. residential housing and the impact on rental prices. Ten U.S. cities are chosen for analysis; these cities vary in size across multiple climate zones, and represent a diverse set of housing market conditions. Following an extensive data quality control process, over thirty different energy efficient features were identified. The level of adoption was determined for each city, ranging from 5.3% to 21.6%. Efficient lighting and appliances were among the most common, with many features doubling as energy efficient and other desirable aesthetic or comfort improvements. Then using propensity score matching and conditional mean comparison methods, the relative impact on rent charged in each city was calculated, which ranged from a 6% to 14.1% increase in rent for properties with energy efficient features, demonstrating a positive economic impact of these features, particularly for property owners. This was further subdivided into five types of energy efficiency upgrade and three housing types. Single family homes generally demanded higher premiums with energy efficient features, however there was not a consistent pattern across the types of efficient upgrades. The results of this work demonstrate that investment in energy efficient technologies has quantifiable benefits for rental property owners in the U.S. beyond just energy savings. This methodology and results can also be used in other cities and by property owners, utility companies, or others, ultimately encouraging further investment and positive economic impact in residential energy efficiency and in turn improving energy and resource conservation in the building sector.

1. Introduction

In the United States, buildings consume approximately 40% of energy and 72% of electricity, over half of which can be attributed to the residential building sector [1]. Buildings thus have a significant impact on the environment, accounting for up to 36% of annual
greenhouse gas (GHG) emissions, with the residential sector responsible for approximately 20–25% [2]. Thus over the life of a building, the environmental costs and resource consumption due to building operations are significant. As the world faces significant challenges and impending threats due to climate change [3], it is beneficial to determine ways to reduce the environmental impact of the U.S. building stock. This can be accomplished through energy efficiency upgrades to the existing residential buildings [4], which, compared to new energy-efficient construction, offers improved environmental sustainability and resource conservation benefits [5]. Among residential buildings, rental properties represent 43.7 million household units, approximately 37% of total residential buildings in the U.S. and more than 23% of residential energy consumption [6]. Thus the rental property market is a strong player in the energy consumed in the residential sector. It has also proven to be one of the most challenging sectors in which to successfully implement energy savings measures [7,8].

There are many residential energy efficiency programs in place, a large number of which are utility-sponsored programs that provide rebates or incentives to residential building owners who invest in more energy efficient systems and technology [9,10]. Other programs such as EnergyStar do not provide rebates, but promise lower operational costs over a product, system, or buildings lifetime [11]. Utility programs are targeted at correcting inefficiencies such as over-sized, old, and/or inefficient heating, ventilation and air conditioning (HVC) systems, limited wall or attic insulation, and inefficient appliances, lighting, windows, and/or other electronics [12]. These programs aim to directly reduce the operating costs of buildings, saving money for the building owner through lower energy bills, reducing loads on the electric grid, and decreasing environmental impacts due to less natural resource consumption and emissions from power plants [13–15]. However, despite the clear benefits of energy efficiency programs, current literature is in general agreement that energy improvements in the U.S. fall short of the anticipated adoption of efficient technologies [16–18], often described as the “energy efficiency gap”, between potential and realized savings [19].

Energy benchmarking requirements for commercial buildings in some cities in the U.S. and in many countries throughout Europe, is one potential method to help overcome the issues of information asymmetry [20]. There have been some initial efforts in this area for residential buildings in the U.S., for example some cities such as Austin, TX has implemented mandatory energy audits be completed on all homes 10 years and older during home sales transactions [21]. However for residential buildings these efforts are not yet widespread.

This efficiency gap is particularly significant with residential rental properties, in part due to the “split-incentive” phenomenon, in which neither the homeowner nor the tenant have motivation or ability, respectively, to improve the building performance [22–24]. Banfi et al. [25] and Burburud et al. [26] studied the willingness to pay (WTP) for energy efficiency improvements in rental property tenants. According to Banfi et al. [25], tenants and homeowners are willing to pay 1–13% higher rent, depending on the type of feature, generally finding a lower WTP in the renters than the residential building owners. Owners of residential rental properties are thus a key component that enables the opportunities for energy efficiency to be implemented. At the same time, their lack of action can be the missing link between connecting an energy efficiency opportunity with a building in need. Therefore, additional efforts are needed to determine how to narrow this gap in the residential rental building market, in an effort to achieve additional environmental benefits in this market segment. Given that energy on average accounts for approximately 13% of total monthly housing costs and 4% of household income for the average renter, and up to 15% of total income for low-income families (2011 American Housing Survey), finding ways to motivate improvements in energy efficiency will also benefit renters in terms of lower energy bills.

Investigating how to better motivate the homeowner to invest in energy efficiency has been cited as a key research need by multiple recent reports [18,27–30]. Initial reports have concluded that the main motivational factor for residential property owners investing in energy efficiency is saving energy, followed closely by other non-energy benefits [28,31,32]. This indicates that when residential building owners need to replace or repair energy-related items, they will consider factors beyond just cost savings in their decision [28]. Non-energy benefits in particular have not been well studied in comparison to the energy benefits. One that has been less studied is the effects of energy efficiency investments on residential rental prices, particularly in the United States.

There have been a number of studies analyzing energy efficiency impacts on sales and rental rates in other countries, but not in the U.S. A majority of the literature is focused on the impact of EPC (Energy Performance Certificates), generally adopted in Europe, on the sales prices of residential units. Less focus has been placed on the impact of rent prices in rental housing. Ayala et al. [33] analyzed the price of energy efficiency in the Spanish housing market, finding that if a home has an EPC, the home demanded a 5.4–9.8% premium compared to others. Fuerst et al. [34–36] investigated energy efficiency premiums due to EPCs in Finland (2014, 2016), England (2015) and Wales (2016), and Hyland et al. [37] in Ireland, also generally finding a positive relationship between the EPC rating and sales prices in all locations, in particular, finding a higher premium for more quality housing. Premiums range from 1.3% to 3.3% in Finland, up to 5% in England, up to 4.5% in Whales, 5.4–9.8% in Spain, and 1.8–3.2% in Ireland. For lower quality housing, the percent premiums were lower and sometimes negative. In studies that compared rental and sales prices, it was found that advertising energy efficiency in rental property listings improves the rental price values (e.g. [38]), however, not as significantly as in the sales market (e.g. [37]). Feige et al. [39] found that some sustainability features have positive effects, and some had negative effects on apartment rental prices in Switzerland, and Popescu et al. [40] also assessed multiple benefits in Romania.

To date, to our knowledge there has not been a significant effort to study the impact of energy efficiency features in the U.S. residential rental property market segment. The sources and quality of rental unit data in the U.S. are highly unregulated as compared to the public record data of the buying and selling of residential buildings. This is similar in the commercial building rental market. Similarly, as compared to other countries, there are not currently country-wide standards or requirements for energy efficiency ratings or reporting requirements. These data consistency challenges are overcome in this work through developed custom data scraping codes to collect online rental property data, enabling the collection of a previously unavailable and unique dataset for this analysis. In addition no studies in the U.S. have consider multiple cities. Most studies in other countries have also been limited to one city. The broader dataset of data included in this work enables the comparison across a diversity of cities which vary in climatic region, political views, sizes, energy prices, and rental market pricing and level of demand. This comparison does not currently exist in the literature.

The goal of this research is to determine, for a diversity locations across the United States, (i) what are the adoption rates of energy efficiency features in rental properties, (ii) does having energy efficiency features in these residential buildings demand premiums in rental asking prices, and (iii) is there a relationship between energy efficiency premiums and location-specific environmental conditions in which the building is located. Through the use of a large dataset of residential property rental data collected from online postings across a set of 10 cities in the United States, a statistical matching method is applied to answer these questions. This research is organized into several sections, including, first, a discussion of the collection methods, cleaning and quality control of the data, followed by the methodology, results and discussion, and overarching conclusions and future research needs.
2. Residential rental data collection and dataset development

2.1. Data collection

Unlike the large amount of publicly available data on the sales of residential properties, rental housing market data, including single family, multi-family and apartment-style residences, poses a significant challenge to obtain in large quantities. However, given the shift within the rental industry to online advertising methods instead of print media, the availability of data sources has improved compared to the past. Of the different data sources available that were considered that collect residential rental information in the U.S. (e.g. [41–43]), it was determined that the use of data obtained from the online, publicly-available site, Craigslist [44], was most appropriate. This site is among the popular websites used to connect renters and rental owners in the U.S. This data includes millions of rental listings across all major cities and their suburbs in the U.S, with a format that enables improved ability to collect data.

The use of this dataset has advantages and limitations. This data, among those datasets available, is the most accessible format from which to collect data. In addition, the data is presented in real time, unlike other datasets that provide data with a delay. However, this also means that significant cleaning and quality control of the data was also required (see Section 2.2), that would be more limited in the other datasets. This dataset does not capture all rental properties in each city, such as those with landlords who are unfamiliar with or do not like to use the internet, who think their potential renters will not use these means to search for properties, or who use other means of advertising. However, it is believed for the purposes of this work, as discussed by Boeing and Waddell [45] in a study on the rental housing markets in the U.S., this dataset is sufficiently appropriate. The quality of the data is generally equivalent or better than the other data sources investigated [45]. This dataset also documents asking prices, which may be above or below the actual agreed upon prices, depending on the market. However, this limitation is the also same for all other online datasets considered.

To determine which sample cities to study, factors including distributions in average rental price, city size, climate zone, energy-related regulations and costs, and geographic location were considered. The ten large cities were selected to represent a range and diversity of values for each of these criteria. The characteristics of each city are listed in Table 1.

Cities and their corresponding metropolitan areas range in size from 1.4 million to 9.5 million, with the median rent for a one bedroom rental unit, a commonly-used metric for comparison of rent across cities, ranging from $650 to $3600. The average annual site consumption and utility costs also cover a wide range of values, ranging 1500–2800 kWh in total site consumption per month (all fuels) on average.

Data was collected across a two month period (December 2016 and January 2017) for each city. The data was collected via web scraping methods using self-built code based on two R packages [46,47]. These methods were executed to download all posted details of each rental unit available at the time(s) of data collection in each of the studied cities. At any given time, the real-time posting of up to 2500 rental properties are available online for a given city. Some of these listings may be duplicates posted multiple times or have other errors, as noted below. The rental property listings available online are continuously updated as additional postings are added over time, with new postings replacing old postings in a continuous fashion. Thus for smaller cities with less rental property activity, the data available at a given time among available online listings may represent nearly an entire month of rental postings; for larger and highly populated cities, the data available at a given time of data collection may represent rental postings from a shorter period of time. The number of rental postings in each city in the final quality controlled dataset is reflective of posting frequency in each of the studied cities.

Values for the following variables were collected, including: posting title, rental price, address and/or location, number of bedrooms, number of bathrooms, unit size (m²), building type, whether or not pets are accepted, laundry availability and location, parking availability and location, and the full rental home text description. Where these values were unavailable, this missing information was filled in, if available, using data from the full text description provided in each posting. The initial dataset contained approximately 159,000 listings in the 10 cities. Compared to other studies who have analyzed the impact of energy efficiency features on rental prices, this is a large sample, and unlike other studies, included multiple cities.

2.2. Data cleaning and quality control

Next the data was cleaned and quality controlled. This included the following checks:

(C1) Remove all postings whose rental prices are missing, less than $300, or larger than $6000;
(C2) Remove postings which do not include key variables: address, size (m²), number of bedrooms and number of bathrooms;

Table 1

<table>
<thead>
<tr>
<th>City</th>
<th>Population estimate (million)</th>
<th>Geographic region</th>
<th>ASHRAE climate region</th>
<th>Median rent one bedroom (dollar)</th>
<th>Average monthly residential site consumption (all fuels, kWh)</th>
<th>Average electricity rate (/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>5.79</td>
<td>South Atlantic</td>
<td>3A</td>
<td>1387</td>
<td>2185</td>
<td>10.86</td>
</tr>
<tr>
<td>Chicago</td>
<td>9.51</td>
<td>East North Central</td>
<td>5A</td>
<td>1595</td>
<td>2808</td>
<td>11.27</td>
</tr>
<tr>
<td>Washington DC</td>
<td>6.10</td>
<td>South Atlantic</td>
<td>4A</td>
<td>2172</td>
<td>2171</td>
<td>12.37</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>2.00</td>
<td>East North Central</td>
<td>5A</td>
<td>732</td>
<td>2564</td>
<td>11.28</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>2.16</td>
<td>Mountain</td>
<td>3B</td>
<td>875</td>
<td>2080</td>
<td>11.55</td>
</tr>
<tr>
<td>Miami</td>
<td>6.07</td>
<td>South Atlantic</td>
<td>1A</td>
<td>2000</td>
<td>1360</td>
<td>11.54</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>3.55</td>
<td>West North Central</td>
<td>6A</td>
<td>1435</td>
<td>2759</td>
<td>12.13</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>1.37</td>
<td>West South Central</td>
<td>3A</td>
<td>650</td>
<td>2017</td>
<td>9.09</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>6.07</td>
<td>Middle Atlantic</td>
<td>4A</td>
<td>1295</td>
<td>2354</td>
<td>13.97</td>
</tr>
<tr>
<td>San Francisco</td>
<td>4.66</td>
<td>Pacific</td>
<td>3B</td>
<td>3600</td>
<td>1502</td>
<td>18.44</td>
</tr>
</tbody>
</table>

1 U.S. Census, Metropolitan Statistical Areas (2016).
2 U.S. Census Regions and Divisions of the United States (2017).
3 ASHRAE Climate Design Information (2013).
4 Zillow Rental Index, Residential (2016).
(C3) Remove duplicated postings that share the same values in four key variables.

For the check (C1), the upper and lower bounds were chosen to remove the upper and lower price extremes of residential rental units. These bounds were chosen based on a detailed review of the data. Listing prices were in these lower and upper ranges due to (a) typographical errors which incorrectly added or removed orders of magnitude in rental rates per month, (b) those that advertised weekly instead of monthly rates, (c) listings for houses or units for sale rather than for rent, posted in the wrong location, and (d) scams and generic listings with erroneous rates (e.g. free, or $1), or from advertising without a rent. Using these bounds removed the top and bottom 0.1% of listings, the percentage of which ranged by city of study. Check (C2) was included since properties without these values cannot be included in the analysis. The check included in (C3) is sometimes called a deterministic record linkage in the sense that the matching probability has only two distinct values: one or zero. If all matching variables have the same values between two postings, then they are treated as the same rental property. If there is at least one non-matched variable, then they are treated as a different rental property. This method was spot checked to ensure that this method was performing the intended function.

The final dataset contained 36,827 valid postings with the full information for all variables, as summarized in Table 2. The average number of unique postings per city studied is approximately 3,700, and rental prices from the collected dataset generally the expected rental price trends from Table 1.

### 2.3. Identification of key energy efficiency words and phrases

To determine whether or not energy efficiency features were included in each rental unit, enabling the distinguishing between the conventional rental properties and those with listed energy efficient technologies, a set of energy efficiency related key words and phrases was developed. To determine this list of key words and phrases, a word count of all individual words and phrases up to five words in length was completed using the full text description of the rental listings for all cities. This count included both the number of times a word or phrase was used, as well as the number of rental unit listings that included that word or phrase. This list of key words was then queried for energy efficiency terms and flagged when found. Following the automated search, the list was then manually reviewed and additional terms and/or phrases were also flagged and added to the final list. When searching for these terms the search was not case-sensitive, and for phrases, all cases where multiple words were combined, hyphenated, or separated with a space were included in the search terms, as well as both singular and plural words of those listed below.

In order for a word or phrase to be considered an energy efficient feature, the word or phrase had to be associated with one of six general categories which would be upgradable features of a residential rental unit that would translate to improved energy performance. These categories and their associated search terms include the following specific categories, as listed below. A more extensive list of terms were searched for than is included in this list to encompass all types of energy efficiency upgrades, however, only those search terms that were found in the dataset are included below.

- **General energy efficiency terms**: energy efficient, energy saving, energy star, energystar, high efficiency, LEED, high efficiency, eco-friendly, eco-friendly.
- **HVAC**: programmable thermostat, smart thermostat, electronic thermostat, next learning thermostat, efficient heating, energy efficient HVAC, efficient air conditioning.
- **Windows/Building Envelope**: low-e windows, energy efficient windows, dual pane windows, double pane windows, thermal windows, no drafty windows.
- **Appliances**: energy star appliances, energystar appliances, efficient appliances, energy star stainless steel appliances, new appliances.
- **Lighting**: LED, CFL, natural light, big windows, large windows.

Each of these categories of energy efficient features is included in this list since they play an important but varying role in building energy use. If present, they should help to reduce energy use, as discussed in recent building energy modeling research (e.g. Perez et al. 2017). The HVAC system (G2) influences over half (54%) of total residential building energy use in the U.S., and the building envelope (windows, walls, roof, floor, etc) (G3) performance plays a key role in the magnitude of HVAC use as well. This is followed by energy use contributions from appliances (G4) and electronics, accounting for approximately 35%, and approximately 6% for lighting (G5) [48]. General energy efficiency terms (G1) were also included to ensure that all rental units with energy savings features were included in the dataset, even if the specific efficient features were not specifically listed. These terms do not correspond to a particular type of feature, however they do encompass indicators that these features are included in the unit without providing specifics (e.g. LEED certification requires demonstrated energy savings features, but cannot be explicitly associated with a particular category).

The overall adoption rates (%) (Fig. 1) are the percent of the total number of residential rental units in each city that included one or more energy efficient features (G1-G5). The percent of rental units identified as being energy efficient that included each type of feature (G1-G5) is also provided in Fig. 1. Each residential rental unit can be included in more than one category as many of the units included more than one type of energy efficient technology, thus the sum of the percentages of rental units identified as being energy efficient that included each type of feature may add up to more than 100%.

Overall, adoption rates of energy efficient features mentioned in the studied rental listings ranged from approximately 5% to 22% across the studied cities. The rate of adoption correlates with the rental prices and utility rates (Tables 1 and 2, respectively) in each city, with higher rent and higher average utility rates corresponding to the presence of more energy efficiency adoption described in the posting.

The cities with the highest rate of adoption are San Francisco and Philadelphia. Given the progressive building energy policies and regulations in California [49], higher energy prices (Table 1) translating to higher costs for renters paying the electricity bills, and general political views in San Francisco that tend to favor an interest energy efficiency and the environment [50], a higher adoption rate is expected. All energy efficiency categories mentioned are nearly equally mentioned in the San Franciscos rental homes, with the exception of HVAC, which, due to Californias mild climate and limited need for HVAC [51] in comparison to the other studied cities, this also is consistent with what was expected. Philadelphia has the second highest average utility rates among the locations studied, as well as the highest average monthly energy consumption, both of which can provide motivation for renters.

### Table 2

Characteristics of the final quality controlled and cleaned datasets in 10 U.S. cities.

<table>
<thead>
<tr>
<th>City</th>
<th>Postings</th>
<th>Postings with energy</th>
<th>Median rent one bedroom($)</th>
<th>Avg. rent of postings ($)</th>
<th>Standard error of average rental price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>3677</td>
<td>414</td>
<td>1069</td>
<td>1251</td>
<td>516</td>
</tr>
<tr>
<td>Chicago</td>
<td>4637</td>
<td>707</td>
<td>1460</td>
<td>1701</td>
<td>816</td>
</tr>
<tr>
<td>Washington DC</td>
<td>4472</td>
<td>837</td>
<td>1696</td>
<td>1956</td>
<td>733</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>1433</td>
<td>175</td>
<td>679</td>
<td>869</td>
<td>324</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>3039</td>
<td>162</td>
<td>845</td>
<td>1163</td>
<td>516</td>
</tr>
<tr>
<td>Miami</td>
<td>5777</td>
<td>393</td>
<td>1550</td>
<td>2017</td>
<td>801</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>3676</td>
<td>454</td>
<td>1131</td>
<td>1414</td>
<td>597</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>2020</td>
<td>228</td>
<td>600</td>
<td>890</td>
<td>379</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>2666</td>
<td>576</td>
<td>1395</td>
<td>1572</td>
<td>658</td>
</tr>
<tr>
<td>San Francisco</td>
<td>5430</td>
<td>1097</td>
<td>2250</td>
<td>2836</td>
<td>1028</td>
</tr>
</tbody>
</table>
higher adoption rate Philadelphia is dominated by the relatively high percentage lighting and natural light related (64%) features, which provide a relatively lower amount of energy savings as compared to the other categories.

The lowest adoption rates are in Las Vegas and Miami. Both locations have a warmer climate and have lower average monthly energy consumption (Table 1) in comparison to other cities. This is consistent across all cities studied - the four cities with the lowest amount of energy efficiency features listed are all in warmer climates, as compared to the top cities which are in cold or cool climates. Energy efficiency may not be as high of a priority in these warmer locations, and are generally less needed than in colder climates. This is consistent with the findings of the American Council for an Energy-Efficient Economy (ACEEE), which has ranked most southern states amongst the lowest third in the nation based on their energy efficiency policies [52]. Another consideration is that some of these homes may have energy efficient features but are not listed or advertised. Research such as Gromet et al. (2013) has found that if something is labeled as energy efficient, a more conservative-leaning individual is less likely to purchase something than if it is not labeled as energy efficient. While all cities are generally liberal-leaning according to voting trends, the four cities with the lowest adoption rates are higher in terms of conservative voting trends than the remaining cities [53]. Of the 237 major cities in the U.S., Las Vegas, Atlanta, Oklahoma City and Miami are all ranked 106, 118, 22, and 207 respectively, as compared to the remaining cities which are ranked between 216–334.

Terms that would typically be considered general identifiers of energy efficient features (G1) included approximately 21–47% of the identified rental units. Of all features, efficient appliances (G4) and lighting features (G5) had the highest adoption overall at 17–64% of the efficient homes, and the HVAC (G2) and building envelope/window (G3) were lower at 4–29%. This is not surprising, as the capital investment and service life in HVAC and building envelope related features is higher and longer, respectively, than those for the other categories (G4) and (G5), and thus typically less likely to be invested in, particularly in the residential rental market. Investment in HVAC and building envelope upgrades can, however reduce energy use more than the generally lower-cost (G4) and (G5) features.

Comparing category adoption rates across all cities, generally they are similar with a few exceptions. In San Francisco the number of units with efficient building envelope/windows (G3) features is significantly higher than other cities, and efficient HVAC features (G2) is lower; in Philadelphia, lighting (G5) is significantly higher. In San Francisco, the relatively higher value of adoption in the G3 category is primarily from the mention of the phrases “double-pane” windows (14%) and “dual pane” windows (14%). In comparison to all other studied locations this percent of listings advertising the presence of these more efficient windows is nearly double the next largest percent (14% for Oklahoma City). According to U.S. EIA [9], the adoption of single-pane versus double pane glass in residential buildings in California is very similar to the national average and only slightly above those cities located in the south regions of the U.S. [6], thus this is not likely the reason for the high rate as compared to other cities. California, in comparison to the other locations studied, does have a larger percentage of sunny days and milder temperatures that lend themselves to the interest in additional windows and sources of natural light. The relatively low adoption rate of efficient HVAC system in California, however, is likely due to climate condition differences, as mentioned previously; Californias climate requires minimal heating and cooling in comparison to the other cities climates, thus minimizing the need for HVAC use in the first place. In Philadelphia, the key phrases natural light (44%) and large windows (24%) dominated the lighting category, followed by LEDs and CFLs (6%). Further analysis indicates that natural light and large windows were mentioned across all locations studied, just not to the extent of in Philadelphia.

3. Methodology

This section describes the methodology used to compare rental prices between baseline residential buildings and energy efficient residential rental units conditional on basic characteristics of residential rental units. This section is subdivided into two subsections, the first explains the variables and assumptions used, and the second includes the methodology of comparison of energy efficient and non-energy efficient rental units.

3.1. Variables and assumptions

Y: rental price proposed by residential building owner;
X: auxiliary covariates such as a number of bedrooms, number of bathrooms, pet availability, laundry and parking information;
Z: indicator function for energy efficient residential rental unit. A value of 1 is used if keywords described in Section 2 are included in
The impact on rental price of a residential property with energy efficient features is captured as:

\[ E(Y_1|Z = 1) - E(Y_0|Z = 1) \]  

(1)

where \( Y_1 \) denotes a potential rental price of the rental unit with energy efficient features, and \( Y_0 \) denotes potential rental price of the baseline residential unit. However, this treatment effect is not identifiable, because potential rental price \( Y_0 \) is not observable given the energy efficiency features.

To implement an identifiable statistical comparison, it is assumed that:

(A1) Each posting is independent of other postings;
(A2) The energy efficiency features are well captured through text description with selected keywords;
(A3) the potential outcomes and the energy efficiency features indicator \( Z \) are independent, conditional on the auxiliary variables as follows:

\[ P(Y_i, Y_0|Z, X) = P(Y_i|X) \cdot P(Y_0|X) \]  

(2)

The assumption (A1) is a natural condition in the sense that duplicated postings are removed in data cleaning process. The assumption (A2) states that there is no significant difference between the true separation and the estimated separation obtained using the selected keywords and phrases. From the assumption (A3), the following is obtained:

\[ E(Y_1|X,Z = 1) = E(Y_1|X,Z = 0) = E(Y_1|X,Z) \]  

(3)

Eq. (3) states that there is no systematic difference in the rental price conditional on the controlled covariates X with respect to the baseline residential rental units.

\[ E[E(Y_i|X,Z = 1) - E(Y_i|X,Z = 0)|Z = 1] \]  

(4)

whether the outer expectations is taken over the distribution of \( X|Z = 1 \). See Dehejia and Wahba [54] for more details.

3.2. Evaluation of impact energy efficient features on rent

The problem with implementing the conditional mean comparison method is that the distributions of \( X \) are generally different between three residential building types (i.e. single family, multi-family, apartments). One popular method for handling this problem is a matching approach, through the assumption that single or multiple baseline residential rental units are matched to each energy efficient residential rental units based on the auxiliary covariates. This matching approach is designed to approximate the distributions of the auxiliary covariates in the baseline residential rental units into those with energy efficient features. There are many matching methods available for the construction of matched pairs based on distance functions [55,54,56,57].

To approximate the distribution of the covariates of the baseline residential buildings into those of the residential rental units with energy efficient features, a set of weights is constructed, which is also referred as propensity scores [57], using a calibration method often used in survey sampling [58]. That is, the set of weights \( w \) can be computed by satisfying the following condition

\[ \sum_{i \in A_0} n_i^{-1} x_i = \sum_{i \in A_1} w_i x_i, \]  

(5)

where \( x_i \) is the realized vector of auxiliary covariates. Here, \( w_i \) was non-negative and its sum over \( A_i \) equals to 1. The \( w_i \) plays a role of adjusting the sample mean of \( X \) in \( A_0 \) into the sample mean of \( X \) in \( A_1 \).

There are several approaches to find the set of weights \( w \) which satisfies the condition (5) [58,59]. In this paper, the following object function is used to construct the set of weights \( w \),

\[ Q = - \sum_{i \in A_0} w_i \log \frac{w_i}{d_i}, \]  

(6)

where \( d_i = n^{-1}_i \) are the basic sample weights. The object function \( Q \) essentially computes the Kullback-Liebler distance compare to the base weights \( d_i \). Next a set \( w \) needs to be determined, which minimizes the Kullback-Liebler distance (6) while the calibration Eq. (5) holds. This problem is equivalent to minimizing the following Lagrange function,

\[ L = - \sum_{i \in A_0} w_i \log \frac{w_i}{d_i} + (n^{-1}_i \sum_{i \in A_1} \lambda x_i f_i A) \]  

(7)

where \( \lambda \) is a vector of Lagrange multipliers. The first order derivative of the Lagrange function (7) is

\[ \frac{\partial L(w_i)}{\partial w_i} = -\log(w_i) - \lambda^2 x_i = 0 \]  

(8)

and then the set of weights \( w \) is obtained

\[ w_i \propto \exp(-\lambda^2 x_i) \]  

(9)

Plugging this weight into the calibration condition (5), the following results

\[ \sum_{i \in A_0} n^{-1}_i x_i = \sum_{i \in A_1} \exp(-\lambda^2 x_i) x_i. \]  

(10)

By applying a Newton-Raphson algorithm, Lagrange multipliers are estimated which satisfy the calibration Eq. (10). Once the set of weights \( w \) are estimated, then the difference of conditional means in (4) can be estimated by

\[ \bar{y} - \bar{y}_{text description, and zero otherwise; 
A_i: a subset of A with Z = 1; 
A_0: a subset of A with Z = 0. 

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continuous variables, and the other variables are treated as categorical variables. A shared bedroom is considered as an estimated 0.5 bedrooms for the purposes of this analysis.

As the results of the construction of adjustment weights, the distributions of the covariates in two residential building types are calibrated so that they have same sample means. The marginal sample means are summarized in Table 3. Across all cities, the average number of bedrooms and bathrooms was approximately 2 and 1.5, respectively. In all cities the majority of rental units were apartments rather than multi-family units or single family units. Pets were generally allowed in the majority of units, and most have in-unit laundry or laundry hookups. Parking in a covered garage was generally available for a smaller number of units, with only one city providing covered parking for the majority of units.

Note that the distributions of the auxiliary covariates can be different from the population distributions. This implies that the simple mean comparison between two residential building groups may lead to unintended bias. Thus, a conditional comparison was implemented while controlling for the distribution of auxiliary covariates.

Nine models were then run, the results of which are reported in Tables 4–8. The first model (Table 4) is a baseline model that includes all residential rental units in the studied dataset; it is a mean comparison between the residential rental units that reported energy efficiency features (APRI) and those without (APRO). The second model (G1) through the sixth model (G5) are run separately to provide a comparison between units with each category of efficient features (G1-G5) and the baseline non-efficient units (Table 5). The last three models evaluate the premium in rent by housing type, including apartments (Table 6), multi-family (Table 7) and single family (Table 8) units.

### Table 4
Energy efficiency premiums for all residential rental units in 10 cities.

<table>
<thead>
<tr>
<th>City</th>
<th>Rental unit rates ($)</th>
<th>Energy efficiency premium ($)</th>
<th>Standardized energy efficiency premium (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No energy features (APRI)</td>
<td>Efficiency features (APRI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(S.E.)</td>
<td>(S.E.)</td>
</tr>
<tr>
<td>Atlanta</td>
<td>1408</td>
<td>1234</td>
<td>174 (26.1)</td>
</tr>
<tr>
<td>Chicago</td>
<td>1984</td>
<td>1749</td>
<td>235 (32.5)</td>
</tr>
<tr>
<td>Washington DC</td>
<td>2082</td>
<td>1948</td>
<td>134 (24.5)</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>895</td>
<td>899</td>
<td>4 (22.8)</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>1176</td>
<td>1117</td>
<td>59 (44.2)</td>
</tr>
<tr>
<td>Miami</td>
<td>2029</td>
<td>2016</td>
<td>13 (39.9)</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>1514</td>
<td>1428</td>
<td>86 (27.7)</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>943</td>
<td>893</td>
<td>50 (25.8)</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>1661</td>
<td>1562</td>
<td>99 (27.3)</td>
</tr>
<tr>
<td>San Francisco</td>
<td>3081</td>
<td>2874</td>
<td>207 (30.6)</td>
</tr>
</tbody>
</table>

4.1. Baseline model: all residential rental units

The baseline model results which compare the energy efficient (APRI) and conventional (APRO) residential rental units of all types are presented in Table 4. The second column is the adjusted average rental prices for the rental units with energy efficient features, and the third column is average rental prices for conventional non-energy efficient units. The fourth column reports the energy efficiency premium in dollars, and standard error. This is followed by the percent increase the rental unit rate with the inclusion of energy efficient features, and the p-values. A positive value for the energy efficiency premium (columns 4 and 5) indicates that the rental units with energy efficiency features demand higher rents than those that do not have these features. A p-value less than 0.05 is considered to be statistically significant.

The results of the initial model of all rental units indicate that there are rental price differences resulting from energy efficiency features, indicating positive rent premiums over the similar buildings that do not contain these features. For example, the adjusted average rent for an energy efficient residential unit in Atlanta is $1408, while that of the conventional units is only $1234. The rental difference of $174 (14.1% increase) is the premium of energy efficiency features on rent. The p-values indicate these differences are statistically significant in seven of the ten studied cities. There is a negative for Indianapolis, however it is not statistically significant.

The energy efficiency premiums vary and are influenced by the overall rental price, as well as market conditions, average utility costs, and weather conditions in the selected cities. Those cities with higher adoption rates generally have a higher energy efficiency premium ($) and %) indicating that energy efficiency is likely more valued by renters, enabling owners to demand higher prices for these features. On the contrary, sightseeing cities (e.g., Miami and Las Vegas) and cities with lower rental prices (e.g., Indianapolis and Oklahoma) have relatively larger p-values, indicating that there is no significant difference in rental prices based on the selected significant level in these locations. The highest rental prices differences for energy efficiency features overall is in Chicago and San Francisco, and the lowest values that are statistically significant are in Minneapolis and Oklahoma City. Compared to the median rent in each location, generally higher efficiency premiums are demanded in locations where there are higher rental prices (Fig. 2).

4.2. Energy efficiency feature types

Further subdividing the analysis into the five subcategories of each type of energy efficiency feature (G1-G5), additional insight can be gained. Due to small sample size for some categories (i.e. G2 in many cities), only the statistically valid data is presented (Table 5). The same procedure is implemented, using a new indicator functions such that $Z_{ij}$: indicator function for key word category j. It takes a value of 1 if text description of posting i includes key word category j, and zero.
is de and , as summarized in Table 5. In this table, those cities and features that only includes the energy conservation practices corresponding to the category $j$.

According to the indicator function, subgroups of $A_j$ is defined such that $A_{ij}$: a subset of $A_j$ that only includes the energy conservation practices corresponding to the category $j$.

The conditional mean is compared between the two groups, $A_{ij}$ and $A_{ij} = G_1,...,G_5$, as summarized in Table 5. In this table, those cities and energy efficiency features that had a large enough sample size to run a model and had statistically significant results (p-values less than 0.05) are included. Those that do not fit this criteria are not included for brevity. For each set of results the residential rental units with each type of energy efficient feature are compared to the adjusted average of rental price for the baseline residential units. This is used to determine the energy efficiency premium (normalized difference) and the p-value using conditional mean comparison in the 10 selected cities.

In all cases the energy efficiency premiums are positive (Fig. 3), indicating that the individual features each incrementally increase the rental rates typically charged for otherwise equivalent residential rental units. In general, the general terms (G1) are associated with the highest

<table>
<thead>
<tr>
<th>City</th>
<th>Rental unit rates ($) with:</th>
<th>Energy efficiency features (APR)</th>
<th>No energy efficiency features (APR)</th>
<th>Energy efficiency premium ($) (S.E.)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>General (G1)</td>
<td>3534</td>
<td>1219</td>
<td>2315 (36.1)</td>
<td>25.8</td>
</tr>
<tr>
<td></td>
<td>HVAC (G2)</td>
<td>1389</td>
<td>1266</td>
<td>123 (73.0)</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>Appliances (G4)</td>
<td>1315</td>
<td>1218</td>
<td>97 (37.1)</td>
<td>8.0</td>
</tr>
<tr>
<td>Chicago</td>
<td>General (G1)</td>
<td>2245</td>
<td>1869</td>
<td>376 (53.8)</td>
<td>20.1</td>
</tr>
<tr>
<td></td>
<td>Appliances (G4)</td>
<td>1907</td>
<td>1701</td>
<td>206 (53.1)</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>Lighting (G5)</td>
<td>1921</td>
<td>1724</td>
<td>197 (51.8)</td>
<td>11.5</td>
</tr>
<tr>
<td>Washington DC</td>
<td>Lighting (G5)</td>
<td>2079</td>
<td>1911</td>
<td>168 (43.1)</td>
<td>8.8</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>General (G1)</td>
<td>2169</td>
<td>1996</td>
<td>173 (72.0)</td>
<td>8.7</td>
</tr>
<tr>
<td>Miami</td>
<td>Lighting (G5)</td>
<td>1529</td>
<td>1399</td>
<td>130 (43.8)</td>
<td>9.3</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>Appliances (G4)</td>
<td>853</td>
<td>787</td>
<td>65 (37.2)</td>
<td>8.3</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>Lighting (G5)</td>
<td>1698</td>
<td>1557</td>
<td>141 (34.9)</td>
<td>9.1</td>
</tr>
<tr>
<td>San Francisco</td>
<td>General (G1)</td>
<td>2991</td>
<td>2875</td>
<td>116 (49.9)</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Lighting (G5)</td>
<td>3387</td>
<td>2881</td>
<td>506 (52.6)</td>
<td>17.6</td>
</tr>
</tbody>
</table>

Note: For brevity, not all features and/or cities are listed since models could not be developed in these locations due to sample size (listed as “N/A” if no models could be used for that city), or results that were not statistically significant.

Table 6  
Energy efficiency premiums for apartment rental units.

<table>
<thead>
<tr>
<th>City</th>
<th>Rental unit rates ($) with:</th>
<th>Energy efficiency features (APR1)</th>
<th>No energy efficiency features (APR0)</th>
<th>Energy efficiency premium ($) (S.E.)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>1423</td>
<td>1226</td>
<td>197 (32.2)</td>
<td>16.1</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>1990</td>
<td>1747</td>
<td>243 (35.3)</td>
<td>13.9</td>
<td>0.00</td>
</tr>
<tr>
<td>Washington DC</td>
<td>2055</td>
<td>1928</td>
<td>127 (25.4)</td>
<td>6.6</td>
<td>0.00</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>858</td>
<td>887</td>
<td>81 (31.3)</td>
<td>5.9</td>
<td>0.00</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>1031</td>
<td>1008</td>
<td>23 (26.2)</td>
<td>2.3</td>
<td>0.19</td>
</tr>
<tr>
<td>Miami</td>
<td>1873</td>
<td>1874</td>
<td>1 (37.9)</td>
<td>0.1</td>
<td>0.49</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>1461</td>
<td>1380</td>
<td>81 (31.3)</td>
<td>2.6</td>
<td>0.12</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>783</td>
<td>763</td>
<td>20 (16.9)</td>
<td>2.6</td>
<td>0.12</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>1649</td>
<td>1568</td>
<td>81 (29.0)</td>
<td>5.2</td>
<td>0.00</td>
</tr>
<tr>
<td>San Francisco</td>
<td>2825</td>
<td>2676</td>
<td>149 (33.4)</td>
<td>5.6</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 7  
Energy efficiency premiums for rental units in multi-family buildings.

<table>
<thead>
<tr>
<th>City</th>
<th>Rental unit rates ($) with:</th>
<th>Energy efficiency features (APR1)</th>
<th>No energy efficiency features (APR0)</th>
<th>Energy efficiency premium ($) (S.E.)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>1548</td>
<td>1212</td>
<td>335 (139.2)</td>
<td>27.7</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>1932</td>
<td>1894</td>
<td>38 (106.4)</td>
<td>2.0</td>
<td>0.36</td>
</tr>
<tr>
<td>Washington DC</td>
<td>2139</td>
<td>2017</td>
<td>122 (77.8)</td>
<td>6.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>913</td>
<td>915</td>
<td>2 (59.3)</td>
<td>0.2</td>
<td>0.49</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>1108</td>
<td>1288</td>
<td>180 (62.8)</td>
<td>14.0</td>
<td>0.00</td>
</tr>
<tr>
<td>Miami</td>
<td>1894</td>
<td>2006</td>
<td>111 (70.6)</td>
<td>5.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>1502</td>
<td>1454</td>
<td>48 (54.1)</td>
<td>3.3</td>
<td>0.19</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>1080</td>
<td>869</td>
<td>212 (158.2)</td>
<td>24.3</td>
<td>0.09</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>1723</td>
<td>1577</td>
<td>147 (87.1)</td>
<td>9.3</td>
<td>0.05</td>
</tr>
<tr>
<td>San Francisco</td>
<td>3395</td>
<td>3224</td>
<td>171 (81.8)</td>
<td>5.3</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 8  
Energy efficiency premiums for single-family rental units.

<table>
<thead>
<tr>
<th>City</th>
<th>Rental unit rates ($) with:</th>
<th>Energy efficiency features (APR)</th>
<th>No energy efficiency features (APR)</th>
<th>Energy efficiency premium ($) (S.E.)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>1447</td>
<td>1270</td>
<td>178 (68.5)</td>
<td>14.0</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>1859</td>
<td>1383</td>
<td>476 (149.0)</td>
<td>34.4</td>
<td>0.00</td>
</tr>
<tr>
<td>Washington DC</td>
<td>2457</td>
<td>2380</td>
<td>77 (175.4)</td>
<td>3.2</td>
<td>0.33</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>1103</td>
<td>1095</td>
<td>9 (91.9)</td>
<td>0.8</td>
<td>0.46</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>1832</td>
<td>1614</td>
<td>218 (206.8)</td>
<td>13.5</td>
<td>0.15</td>
</tr>
<tr>
<td>Miami</td>
<td>2415</td>
<td>2255</td>
<td>160 (105.0)</td>
<td>7.1</td>
<td>0.06</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>1840</td>
<td>1691</td>
<td>149 (110.5)</td>
<td>8.8</td>
<td>0.09</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>1280</td>
<td>1247</td>
<td>33 (57.0)</td>
<td>2.7</td>
<td>0.28</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>1647</td>
<td>1418</td>
<td>229 (139.5)</td>
<td>16.1</td>
<td>0.05</td>
</tr>
<tr>
<td>San Francisco</td>
<td>3579</td>
<td>3234</td>
<td>345 (75.4)</td>
<td>10.7</td>
<td>0.00</td>
</tr>
</tbody>
</table>
energy efficiency premiums in each city. However, if comparing the specific features (G2-G5) only, for those cities where there are multiple energy efficient features that showed statistically significant premiums, those features that have the highest impact on energy efficiency (HVAC, building envelope/windows) demand similar or higher rental premiums than the lower cost, less energy savings features.

More than any other feature across all cities, energy efficiency in lighting features is found to be statistically significant. The relatively higher premiums demanded for energy efficient lighting features (G5), appear to be associated mostly with improved availability of natural light, which is indicated using the key phrases such as “natural light”, “large windows” or “big windows” in the listing text. The availability of natural light reduces the need for artificial light and the associated energy consumption, however among the energy efficiency upgrades, this is likely to reduce the energy use by the least amount. One reason that could explain the higher premiums demanded by lighting features is that, beyond lighting energy savings, larger windows and natural light are also associated with improved occupant comfort. Also generally, larger windows and natural light are often preferential to potential renters even if they do not provide lighting energy savings. This is consistent with the findings of Feige et al. [39] in Switzerland, which found that sustainability features that also improve comfort, health, or other non-energy benefits, increase rental prices more than other energy efficient features. The highest premiums for lighting associated features are in San Francisco and Chicago.

To assess the impact on rental premiums of efficient lighting as compared to available natural light, the natural light-related key words were removed from the analysis and the methodology was rerun. The overall statistically significant energy efficiency premiums (Table 4) in the studied cities increase in Atlanta, Chicago, Oklahoma City, and decrease slightly in Washington DC and Minneapolis, with an average of ± $29 difference in rent premiums. The energy efficiency premiums for the individual categories (G2-G5) also change slightly. With the removal of the natural light terms, the lighting (G5) related energy efficiency premiums decrease in San Francisco to $380; in all other cities the G5 results are not statistically significant. Thus without considering natural light in this category, the energy efficient lighting demands somewhat lower premiums, however efficient lighting still
shows a positive premium.

It is also noted that generally there is an increase in the monthly rental premium that can be demanded by energy efficient features and the monthly rent in each of the studied cities (Fig. 4). The general trend shows that, for those features that are statistically significant, the incremental increase in the monthly rental rate increases the rental premium by approximately 10% of that incremental increase. Generally across the cities studied, increases in rental prices for G4 and G5 (lighting and appliances) show a strong relationship with an increase in the monthly rental rate in each city, with the exception of San Francisco.

4.3. Residential property types

In addition to various energy features, we further examine rent differentials due to different investors and property types, including single family, multi-family, and apartments. Single family homes are classified as detached buildings that are separated from other structures and designed to meet the needs of one family. Multi-family residential includes condos, townhomes, and duplexes in which a single building houses multiple housing units each owned individually. The third category, apartments, typically have a single owner. In this dataset most units are multi-family or apartments, as discussed in Table 2. All rental units not labeled as any of the listed terms were not considered in this comparison. Tables 6–8 presents the results of rent differences between energy efficient units and conventional rental units for single-family, multi-family, and apartments, respectively.

The average monthly rent of all rental housing types is similar within each city, however the rental premiums ($/month and %) vary by city. Across the studied cities, the energy efficiency premiums ($/month) are higher, in general, for single family rental units as compared to multi-family units and apartments, with the highest increases in rent occurring in Chicago, San Francisco, and Philadelphia, all cities with higher observed adoption rates in the studied listings. For multi-family units and apartments, San Francisco, Philadelphia and Atlanta have the highest increases in rent. Considering the percent increase in rental price across the studied homes over the baseline monthly rent (Fig. 5), the single family homes appear to demand the highest percent increase in rent as compared to the other housing types, with the exception of Atlanta, in which the single family homes have the lowest increase. In the cities with the highest increase from apartments, in some cases the multi-family and others the single family have the second highest rent increase.

The increase in rental rates for apartments and single family homes correlates weakly with an increase in the rental prices (Fig. 6), similar to the trend found in Fig. 2 across all studied homes. As the average rental unit price increases by $100, this demands a $5.65 (single family) and $7.18 (apartments) increase in the premium for energy efficiency charged across all cities studied, and almost no increase for multi-family.

Private individual (single family and multi-family) and institutional investors (apartments) behave differently because of their financial situations and expectations, their ability to invest, their decision making processes, and their objectives of an investment are different and thus excepted impact the energy efficient investments. In the United States, more than 40% of renters live in the single family type homes [60]. As Hope and Booth [7] discuss, the private rented sector represents the most difficult to improve in terms of energy efficiency, and find that 40% of private sector landlords respond that there is no personal benefit to them from installing energy efficiency measures. The findings of this work, particularly the higher rental premiums for single-family units which are typically owned by private investors, would be very encouraging to these private landlords by providing empirical evidence of profitable energy efficiency investments. For company-type investors, there is also a demonstrated increase in rental rates, which should also be motivating.

5. Conclusion

Given the current increasing concern regarding climate change and the strong need to reduce environmental impact of the built environment, this study provides some significant findings regarding the U.S. residential market, energy efficiency, and rental prices that should help to further motivate energy efficiency investments. A diverse set of 10 cities in the U.S. were the focus of this study, using an initial dataset of over 169,000 rental listing data collected through online postings, to study adoption rates of energy efficient features, as advertised in the rental listings, and the impact of these energy efficient features on rent. Conditional mean comparison was used through computed propensity scores to preserve same auxiliary variable distributions between the baseline residential buildings and the energy efficient residential units. Selection biases were controlled with a matching method.

The limitations of this work include data collection from online posting of user-generated content which are not without potential errors, as noted, that may influence the dataset. However this method of data collection has been used in previous research on rental housing...
markets, and therefore is believed to be sufficient for this work. The dataset was also collected over a shorter period of time, which may introduce coverage problems, however, our findings are still valid since the differences between efficient and non-efficient rental units are systematically preserved compare to the differences at the population level. The time period of collection, while limited, is also consistent with other studies using the same online database, as mentioned.

Through the study of the overall dataset, as well as five categories of energy efficiency measures, and three property types, the following summarize the main conclusions of this study:

- Adoption rates of energy efficient features included in the rental postings of studied rental unit range from 5.3% to 21.6% across the 10 cities;
- Higher adoption rates generally occur in locations with higher rental prices, higher average utility rates, and comparably more liberal-leaning cities. San Francisco was among the highest in adoption rates, with the highest diversity of energy efficient features, and also the location with the highest average rent, and electricity costs. Las Vegas and Miami were among the lowest, with energy efficiency features dominated by efficient appliances;
- Among adoption rates of the specific categories of energy efficient features, generally lighting and appliance features are more commonly included in the listings than HVAC and building envelope upgrades, which makes sense due to the lower monetary investment needed to implement these changes. The results also indicate that features that double as energy savings features as well as improvements in appearance, convenience, or occupant comfort (e.g. energy efficient stainless steel appliances that double as being energy efficient and look nicer) are commonly mentioned;
- Generally rental properties with energy efficiency measures demand a rental premium over those that do not, however the rate of this premium varies by city of study, ranging from 6% to 14.1% for those that were found to be statistically significant. San Francisco and also Chicago have the highest rental price differences, but Atlanta and Chicago have the higher percent increase in rent;
- Studying each of five energy efficient feature categories, in all cases the premiums were also positive; in some cities those features that require more capital investment demand higher premiums, and in others they do not. There does not appear to be a consistent pattern across the studied cities;
- Single family homes generally demand higher energy efficiency premiums as compared to multi-family or apartments; however the cities where apartments have the highest percent increase in rent also have the highest overall rental premiums for energy efficient features.

The results of this work should provide motivation to both private and company-type landlords of residential rental properties to further invest in energy efficient features in rental homes of all types. Further investment should reduce the energy use intensity of the typically less efficient rental housing market, increasing rental rates to benefit rental

![Fig. 5. Percent increase in rent for homes that have energy efficient features for all rental units considered, single family units, and multi-family units for 10 U.S. cities. Note: those bars with no patterned fill indicate that the values calculated were not statistically significant (p-value > 0.05).](image)

![Fig. 6. Increase in the rent for all rental units, single family, and multi-family units over the average rent in each of 10 U.S.](image)
owners, reducing utility bills to benefit the renters, and also reducing the environmental impact of this building segment that has otherwise been the most challenging to improve in terms of efficiency.

Further efforts are needed to assess investment costs as compared to rate premiums, providing further evidence to rental owners. As a preliminary effort, the average statistically significant premiums for efficient HVAC, envelope, appliance and lighting features across the studied cities are $74, $51, $65 and $167 per month, respectively. A high-level analysis of the estimated total costs, including equipment and installation, of energy efficiency retrofits derived from the Residential Efficiency Measures Database [61], indicates that the average costs of these retrofits in these four broad categories is $658, $5,100, $1,710, and $317, respectively. This assumes a 93 m² rental unit, 15% window area, and that all windows, lights and essential large appliances are replaced. The rough payback period for these investments achieved from overall higher rental rates is 9 months, 8 years, 2 years, and 2 months, respectively. This does not account for the fact that in many locations rental building owners can receive rebates from their respective utility companies, further reducing the payback periods. Broadly, these payback periods are relatively short, with the exception of other factors, and would benefit from further study moving forward.

For the renter, the net premium resulting from increased rental rates but decreased utility bills will likely vary based on location and many other factors, and would benefit from further study moving forward. The rental increase may be close to the savings achieved in a typical new-construction home; particularly for rental properties, which historically are lower quality, less efficient, and less maintained, such upgrades may have substantial benefits rivaling the average rental premiums, particularly in climates with extreme cold and heat. There are many factors that influence the achieved energy use cost savings, including climate, electricity and gas rates, building type and properties, etc. These values range significantly across the homes studied in this research. Extensive additional analysis is needed of the properties and variations in the rental housing characteristics and utility costs to accurately assess these values of costs savings to tenants, as well as to determine what the net impact on the occupants of these properties would be. Thus, additional research efforts are needed to determine what the net impact on the occupants of these properties would be, with the goal of determining what efficiency improvements provide the most benefits to all players in the rental housing market, and the environment as a whole.

Ultimately this works towards determining what efficiency improvements provide the most benefits to all players in the rental housing market, and the environment as a whole. The challenge of overcoming the energy efficiency gap particularly in the rental market, is among top areas of interest and need; investigating non-energy benefits such as rental premiums has been cited as an area of interest by the U.S. government agencies in recent years. The results of this work are a first step toward supportive evidence that quantitatively demonstrates these non-energy benefits. These results and insights can be used by utility companies who develop and implement energy efficiency programs, builders and energy efficiency retrofit contractors, and policy makers to drive interest and policies in energy efficient technologies in the rental market.

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