2020

Energy-efficient technology retrofit investment behaviors of households in lower and higher income regions

Celso MauroNhanga dos Santos
Iowa State University

Recommended Citation

Santos, Celso MauroNhanga dos, "Energy-efficient technology retrofit investment behaviors of households in lower and higher income regions" (2020). *Graduate Theses and Dissertations*. 18216.
https://lib.dr.iastate.edu/etd/18216

Energy-efficient technology retrofit investment behaviors of households in lower and higher income regions

by

Celso Santos

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Construction Engineering and Management)

Program of Study Committee:
Kristen Cetin, Co-major Professor
Cristina Poleacovschi, Co-major Professor
Ulrike Passe

Iowa State University

Ames, Iowa

2020

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

SEER	Seasonal Energy Efficient Ratio
HVAC	Heating, Ventilation, Air Conditioning
AC	Air Conditioning
EET	Energy Efficiency Technology
Dept	Department
CO_2	Carbon Dioxide
SFD	Single-Family Detached
TWh	Terawatt-hour
kWh	Kilowatt-hour
CF	Cedar Falls
Avg	Average
SD	Standard Deviation
PEP	Population Estimation Program
PC	Principal component
PCA	principal component analyses
SEER	Seasonal Energy Efficiency

ACKNOWLEDGMENTS

I would like to express my thanks to God for comforting me and making me stronger during all the hard moments. I am also extremely grateful to the Fulbright program for sponsoring my study. I would not have gotten this far if it was not for it. The completion of my thesis would not have been possible without all the support and nurturing of Dr. Kristen Cetin. I am extremely grateful for everything you have done for me. I would like to extend my gratitude to my co-major professor Dr. Cristina Poleacovschi and my committee member Dipl.-Ing. Ulrike Passe for their support throughout the course of this research.

In addition, I would also like to thank my family, friends, colleagues, Fulbright Chapter at ISU, the department faculty, and staff for making my time at Iowa State University a wonderful experience. I want to also offer my appreciation to Cedar Falls Utilities for the data used for this thesis.

ABSTRACT

Urban regions consume approximately 65% of all energy produced and emit 70% of the CO_2 to the environment. Buildings, specifically, consume approximately 40% of energy in developed countries and emit nearly 40% of CO_2. Most of this energy is used for heating, cooling, and lighting end uses. Since approximately half of building energy use is attributed to residential buildings in the U.S., improving their energy efficiency will help to reduce energy use substantially, as well as benefit households through reduced energy costs. However, little effort has focused on understanding how energy efficiency investments are made, particularly across different socioeconomic groups. Using data for residential buildings in Cedar Falls, Iowa, including energy efficiency investment data for a utility rebate program, assessors data, and U.S. Census data, residential energy efficiency investments are studied in three stages using different subdivisions of the datasets through multistage sampling analysis. Frequency analysis, correlation analysis, and principal component analysis are used to study household investment behavior in (Stage 1) the overall dataset for the city, (Stage 2) the lowest and highest income census tracts, and (Stage 3) a subset of similar housing units in the lowest and highest income census tracts. Specifically, energy efficiency investments in efficient lighting, air conditioners, furnaces, and insulation are studied.

Overall, for residential buildings in this region, efficient lighting was the most invested in technology, followed by air conditioners and furnaces, and finally, insulation. If grouping air conditioners and furnaces together, HVAC systems are the most common investment. Interestingly, air conditioners and furnaces are, by far, the most expensive technology to invest in, compared to most other energy efficient technologies used in homes, yet they are among the most common types of investments. They also appear to be an entry point to investing in energy

efficiency, as most households purchasing the studied HVAC systems have not previously utilized the available utility rebates. In addition, it is important to note that the most typical scenario for investment is due to the HVAC system is broken, irrespective of age and/or of the HVAC unit.

For the study of efficiency investments in housing units in the lowest and highest income tracts, overall, there were more efficiency investments per housing unit and in total in the high-income areas as compared to the lower-income areas. There were also differences in the type of investments. The higher income tract prioritized efficient lighting and HVAC systems as investments, similar to the overall dataset, while the lower-income tract invested most in HVAC systems followed by insulation. Some of this variation in the type of investment may be because the lower-income areas generally include older housing units, which may not be built to the modern energy code requirements. Insulation investments are also generally lower in cost compared to HVAC systems, which may be a more feasible investment for low-income households. Correlation analysis and Principal Component Analysis (PCA) results suggest two main findings. First, the cooling capacity of the air conditioners invested is most driven by housing age for the lower-income housing units and correlated most, but to a lesser extent, with housing size for the higher-income housing units. Second is that lower-income household's investment was higher proportional to cooling capacity and efficiency, thus resulting in higher rebate amounts as compared to the higher-income households, which have lower correlations with all variables. In other words, for the housing units that made investments in the lower-income regions, they invested more money in higher efficiency systems, as compared to the higher income regions who made more investments in the characteristics of the air conditioner chosen and the associated rebate were not significant factors that influenced such investments. This suggests that the policies developed for rebate programs more strongly influence lower-income households, which have less available monetary resources to make investments.

Holding age and size of the housing unit constant in the highest and lowest income tracts (Stage 3), correlation analysis for air conditioner investments also shows that lower-income households investment is more strongly associated with efficiency compared to the higher-income households, meaning lower-income households made higher investments to increase the air conditioners efficiency. These findings highlight the importance of policies and incentive programs that focus on low income and high-income housing units and the variations in investment behavior. This research can help to improve these programs through a better understanding of types, quantities, and influential factors impacting varied income levels differently.

CHAPTER 1. INTRODUCTION

The continuous growth of the world population and the number of buildings has driven cities to grow at a faster rate. Urban areas occupy only approximately 2% of the world's landmass. Yet they account for over 65% of the electricity consumed and emit approximately 70% of carbon dioxide (CO_2) emissions, and these numbers continue to grow (IRENA, 2016). Buildings, specifically, consume approximately 40% of the energy produced across most developed countries and emit approximately the same amount of carbon dioxide (US Dept. of Energy, 2019). By in large, this energy is used for heating, cooling (HVAC), and lighting, as shown in Figure 1 (AEO, 2020). Consequently, the continuous increase of this energy demand and level of CO_2 emissions poses a threat that needs to be addressed. As such, the need to reduce this demand has led to new research interests for solutions to make buildings more energy-efficient.

The residential building stock represents a significant opportunity for energy savings, as discussed in several recent studies. For instance, a study conducted by the National Renewable Energy Laboratory (NREL) concluded that by upgrading to efficient and/or renewable energy options (e.g., efficient air conditioning, LED lights, solar), single-family detached (SFD) residential buildings in the U.S. could save approximately 5.7% of the electricity estimated to be consumed in 2030 (Wilson et al., 2017). In terms of energy, including savings in natural gas, propane, fuel oil, and electricity, a total savings of 4.2 quads/year is estimated, or 24% of the total energy consumed by SFD in 2012, resulting in 24% reduction in CO_2 emissions. In other studies, it was found that by substituting less-efficient lighting with efficient lighting, changing behaviors associated with household energy use and motor vehicle operation could help to save between 11% to 30% of total energy consumed (Vandenbergh et al., 2008; US Census Bureau, 2018; Gardner et al., 2008), and approximately 20% of CO_2 emissions (Bennear et al., 2013).

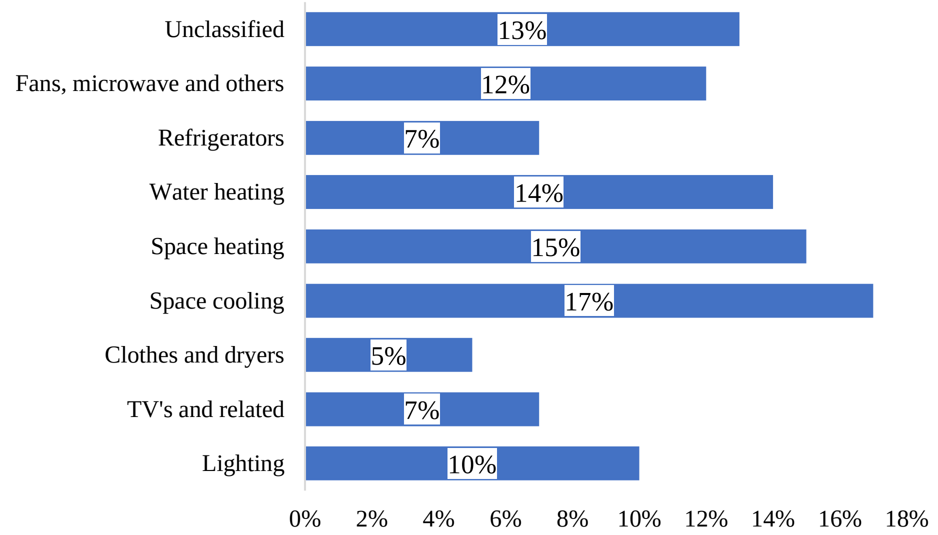


Figure 1. Residential purchased electricity intensity by percentage (Source: US EIA, 2015; Enteria and Mizutani, 2011)

Energy efficiency typically refers to the energy consumption improvement of each unit of energy services consumed by a device without affecting its performance (Gillingham et al., 2009, Jaffe et al., 2004). For instance, the energy efficiency of a heater defines how effectively it adds heat to a space per kilowatt-hour (kWh) of energy used. Even though both energy conservation and energy efficiency have the same purpose, they are not the same. Energy conservation focuses on reducing energy use through behavior change. For example, setting a lower indoor heating temperature setpoint during the winter season is a measure of achieving energy conservation. There is no direct correlation between both, thus being more energy conservative does not necessarily mean that something is more energy efficient (Gillingham et al., 2009; Clinch and John, 2001). Energy efficiency helps support the longer-term reduction of energy consumption, which can be achieved through the use of technology that can perform better than the same standard non-energy efficient solution (e.g., LED lights consume less energy than incandescent lighting).

Energy efficiency and conservation solutions in residential buildings provide households with direct and indirect benefits. The direct benefits relate to gains households can see or feel directly through energy savings, health, and in some cases, comfort (Clinch and John, 2001). Indirect, on the other hand, focuses on the benefits that the users cannot see or feel directly. For example, a decrease in greenhouse gas emissions and a reduction in the operational and maintenance cost of energy infrastructure. Nevertheless, these benefits, both direct and indirect, have been shown, for some segments of the population, to not effectively attract households to invest in energy-efficient solutions.

Despite the savings potential and cost-effectiveness of energy-efficient solutions and the long-term return on investment (ROI), it is still a significant challenge to achieve households' adoption of these solutions (Attari et al., 2010; Frederiks et al., 2015; Ha and Swinder 2012). There are financial, structural, and information barriers, as presented in the literature, that are among the main barriers (Frederiks et al., 2015; Steg, 2008; Lopes et al., 2012).

The initial investment required for energy efficiency solutions creates a financial barrier, which is a significant challenge for lower-income households (Steg, 2008; Zhao, 2012). That is, the economic challenges faced by many households requiring them to weigh the use of monetary resources differently from those at higher income levels, make this initial investment an obstacle (Lopes et al., 2012; Cetin et al., 2014; Nielsen 1993; Clinch and John, 2001). In addition, even if the up-front investment is not a factor, the information barriers or lack of knowledge (i.e., familiarity with the technology and savings potential) is identified as one of the reasons for lower investments in these solutions (Steg, 2008; Dietz, 2009; National Academy Press, 2009).

The structural barriers occur when households may see energy-efficient measures as important and even value such measures, yet they may not adopt them due to lack of motivation (Ha and Swinder, 2012; Frederiks et al., 2015). This type of barrier may occur, for instance, when the landlord lacks the motivation to switch to an energy efficiency measure even though the tenant is responsible for paying the bills. Finally, the trade-off between energy savings and personal comfort that can occur in some energy-saving scenarios may decrease interest for some households (Clinch and John, 2001). One common example of this scenario is reducing the indoor temperature setpoint during the winter or increasing it in the summer, which may help save energy, but it also may impact occupant indoor comfort. In the United Kingdon, a study found that of the 88% of households concerned about building environmental impacts, improvement in energy efficiency was typically not their top concern, but their third concern (Caird et al., 2008; Pelenur and Heather, 2014). These studies indicated that the financial investment involved is most important, followed by saving the environment. These concerns, however, do not always motivate households to act; instead, they may easily be impacted by the households' social and economic status and/or behavior. These factors, combined, limit the extent to which energy-efficient solutions are implemented today (Dietz, 2009).

The cost-benefit trade-off for the adoption of energy efficiency measures suggests that households are more sensitive to the cost of the energy efficiency measures than to the cost of energy-related impacts (Jaffe et al., 2004). Due to these barriers, energy efficiency incentive policies and standards, specifically, have been put in place to stimulate investments, and to help decrease the "energy efficiency gap," i.e., the difference between the current and optimal energy use using today's commercially available technologies (Jaffe and Robert, 1994). These policies usually target individual customers, manufacturers, and retailers. The incentive provided can either be in the form of financial benefits, which include rebates, financing, and/or discounts, or non-financial incentives, which include technical support services (i.e. installation), education and training, and information sharing (U.S. Dept. of Energy, 2010). Programs that give direct incentives or payments such as rebates, rate reductions, and discounts have been found to be more effective in terms of attracting interest compared to non-financial incentives (U.S. Dept. of Energy, 2010; Jaffe et al., 2004). While many different programs exist, and they support both residential and commercial buildings, this research focuses specifically on the city of Cedar Falls (CF) in Iowa, in the U.S., and their residential energy efficiency rebate programs.

The studied rebate program, similar to many other rebate programs, is designed to motivate households to make energy-efficient investments. That is, when households buy and install an energy-efficient device that satisfies the program requirement, they are refunded part of the investment made. The amount reimbursed depends on the type of energy-consuming device and the program requirements for that specific device. This research focuses specifically on several technologies, including LED lighting, air conditioning units, heating units (furnaces), and insulation (attic, wall, and/or foundation), which are common efficient technologies that this rebate programs target. Since financial barriers are one of the driving factors impacting the lower rate of investment in energy-efficiency measures, this research aims to study the differences in investment behaviors towards the purchase of energy-efficient technologies, in lower and higher-income areas of the studied region. We specifically aim to answer the following questions:

- What are the house/household characteristics in lower- versus higher-income areas in the studied region?
- What are the energy efficiency investment behaviors of residents of housing units in lower- and higher-income areas, and how do they compare? *(number of efficiency investments, factors impacting adoption of energy-efficient technologies)*
- How can the results of this comparison inform policy, and inform professionals who design energy efficiency incentive programs, to help target and encourage energy efficiency improvements in lower-income areas/households?

The following sections are organized as follows. Chapter 2 details the research methodology. First, the data is described, as well as how it was collected. This includes discussion about the different types of data collected from each data source, as well as quality control measures used, and finally, the data analysis methodologies using these datasets. Chapter 3 provides the results and associated discussion based on the use of the described data and methodologies. Chapter 4 includes the conclusions and discussions on limitations and opportunities for future work in this area of research.

CHAPTER 2. METHODOLOGY

In this research, a household's behavior toward investment in energy-efficient technologies is analyzed. The study first assesses the characteristics of buildings and households in lower- and higher-income areas, to understand defining differences that may impact or be associated with differences in energy efficiency investment behaviors. Next, the frequency and reported reason for a particular investment is analyzed and compared for the lower- and higher-income regions. Finally, we consider the use of the resulting findings, in terms of how they can contribute to improvements in energy efficiency rebate programs for households, particularly in the lowest-income areas. Correlation analysis, linear association between the sample variables, and principal component analyzes are performed to accomplish this analysis.

2.1 Data Collection and Quality Control

The research includes 3,327 energy efficiency rebates from January 2013 to December 2016, and demographic data from the U.S. Census Bureau, from the most recent Census (2010). These are summarized in further detail in this section.

2.1.1 Energy efficiency rebate data

To tract the energy efficiency rebate program implementation, records of applications for and implementations of energy efficiency retrofits in housing units in Cedar Falls, Iowa, are used. A summary of this data is included in Table 1. The data include information such as the households' location, the technology purchased and the associated characteristics, and the previous technology characteristics and status that the new technology replaced (where applicable, e.g., the operability (working/broken) of the air conditioning and furnace system the new system is replaced). In addition, information regarding the total cost of the retrofit, rebate amount, and the date the equipment was purchased are also included. The rebate program includes a range of types of technologies; however, for this research, we specifically considered four, including insulation (wall, attic, and/or foundation), furnace, air conditioning, and lighting retrofits. The housing units include both multi-family units and single-family housings.

Table 1. Summary of characteristics of the energy-efficient technology investments in Cedar Falls, IA based on data available from 2013-2016

Technology	**Energy Efficiency Investment**				**Rebate value**		**Avg. Out of the pocket range**	**# Housing units**
	N	Total cost range ($)[6]	Avg. total cost ($)	SD ($)	Range ($)	Average ($)		
Air cond.	744	928-30,000	6,278	3,332	100-900[1]	550	284-29,700	726
Furnace	739	936-17,090	6,007	760	200-400[2]	347	536-17,094	723
Lighting	1,238	4-2,140[3]	156	253	2-700[4]	75	0-1,442	656
Insulation	606	25-28,900	1,693	2,197	15-2,810[5]	635	0-28,060	366
Total	*3,327*	--	--	--	--	--	--	*2,471*[7]

Note: SD = standard deviation

[1] *The rebate includes up to $500 for 14 SEER (Seasonal Energy Efficiency Ratio) and $100 for each additional SEER value above this*

[2] *In this category, rebates were only either $200 or $400; $400 is for a 95% AFUE minimum.*

[3] *The rebate is limited to 35 units of recessed lights per year per household maximum; the rebate is 50% of the pre-tax price and up to $20 per fixture*

[4] *This value is calculated using the total number of lights invested in and their associated costs. The average number of lights per household was approximately 7.*

[5] *In this category, the rebate ranged from $4.10 to $5.45 per square meter ($0.40 to $0.60 per square feet)*

[6] *Total costs – rebate value = out of pocket costs to the household*

[7] *Some housing units invested in more than one technology; thus this value is larger than the total number of housing units which invested in energy-efficient technologies*

The first three retrofits, including insulation (attic 39%, walls 21%, foundations 18%, crawl space 2%, band joist 15%, and other 3%), furnace, and air conditioning systems investments, impact the housings' weather-dependent energy consumption. Cedar Falls is located in ASHARE Zone 5A (cool-humid), where it is hot and humid in summer and cold in the winter. Heating and air condition energy demands and use are related to the preferences of the occupants and their setpoint settings, as well as the temperature differential between the interior and exterior of the housing units. The HVAC system is responsible, on average, for approximately 32% of the residential electricity use (Figure 1). The invested-in energy efficiency upgrades to HVAC systems are estimated to be able to save approximately 44% of the energy consumed (National Academy Press, 2009).

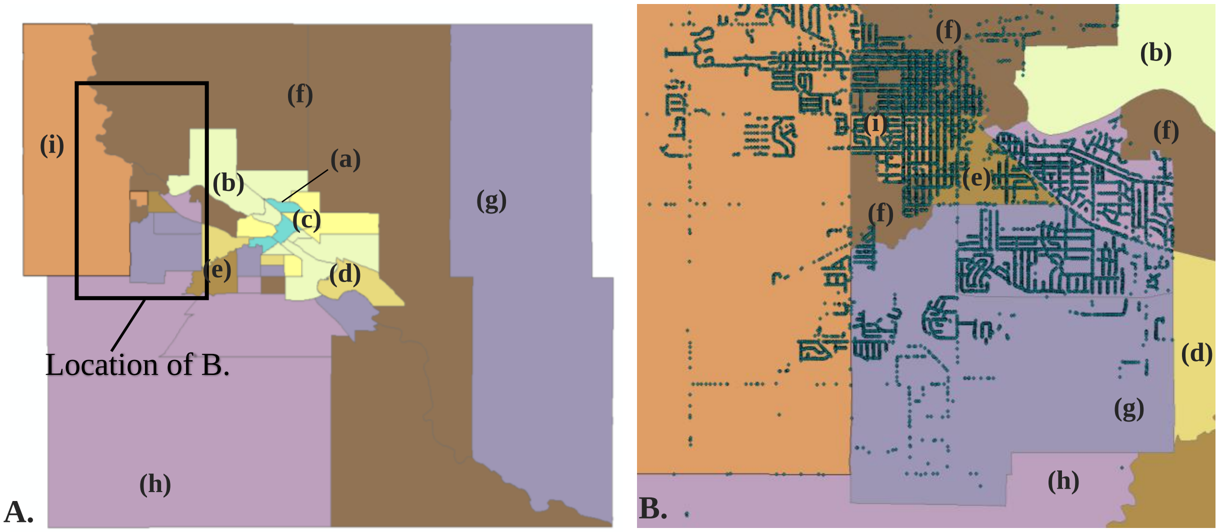
Insulation impacts the heat flux between the exterior and interior of the housing units, and thus the thermal time constant experienced by the building. Insulation generally has the most significant benefits when the difference between the interior and exterior temperatures are not close in values, i.e., most times in the cold winter, and during the hotter portions of cooling season days. Thus, energy reduction (kWh and kW) and thermal comfort can be achieved through improved building insulation (Al-Hamoud, 2004). For efficient lighting, i.e., LEDs, since non-LED lighting represents a substantial-end use contribution in the current building stock, more efficient lighting both reduces internal loads, decreasing air conditioning needs in the cooling season, and consumes less energy from its use compared to non-LEDs. The Energy Independence and Security Act of 2007 and the increasingly stringent federal efficiency standards in the U.S. have helped to decrease the use of incandescent lighting (U.S. Dept of Energy, 2019), with estimates of approximately 40% lighting energy use reduction by 2050 compared to 2019, from these regulations adoptions alone.

Quality control and data processing were required for this dataset. Some data were missing in the records, including, for some housing units, the status of the equipment before retrofitting (working/broken), the air conditioning cost, and heating/cooling capacity. Some of the reasons for the missing data were noted in the data, including factors such as fire, equipment misuse, and age. In this work, we utilized data that included all the information relevant for this study and excluded those that did not. Of the approximately 3,356 rebate records in the original dataset, 29 were excluded due to missing information regarding the working condition of the air conditioning before replacing with new units, and characteristics of the LED lighting, thus the final dataset includes 3,327 complete records.

2.1.2 US Census Data

To supplement the energy efficiency investment data, U.S. Census data from the most recent Census (2010), at the county level (Black Hawk County, Iowa) and tract group level is used, including demographic information. Based on the most recent estimates, Cedar Falls has a population of approximately 41,000 people, and nearly 15,000 households (U.S. Census Bureau, 2018), the estimation of which is based on collected data on births, deaths, and migration to calculate population change since the 2010 Census by the Population Estimation Program (PEP). However, since the most comprehensive and concrete data is associated with the Census efforts, this is what was used for this work. In 2010, Cedar Falls had a population of approximately 38,200 people and 14,000 households in 2010, and between 2013 and 2016, this population ranged from 39,600 to 40,900 people, and 14,200 to 14,500 households (U.S. Census, 2010).

The 2010 Census data was used to determine the median household income level for all census tracts in Black Hawk County, ranging from $10,000 or less to $200,000 or more. Geospatial data was obtained from America FactFinder (U.S. Census Bureau, 2010) and used to link the geographical location of the housing units from Cedar Falls utility rebate program to the median household income data from the U.S. Census (Figure 2). The result includes 38 different tracts, with nine median household income ranges. Figure 4 shows the median household income, binned into ranges of these values, labeled (a) through (i), to link the tract color codes to the associated median household income ranges. As Cedar Falls is located in the upper-left portion of Black Hawk County (see the black outline in Figure 2A, zoomed-in Figure 2B), the geographic location of the buildings in Cedar Falls who invested in energy efficiency retrofits is distributed among 12 of the 38 census tracts, which led to this research focus to be on those tracts only. However, of the 12 tracts in this region, only 9 tracts include rebate data; thus, in the final analysis, 9 census tracts are used.



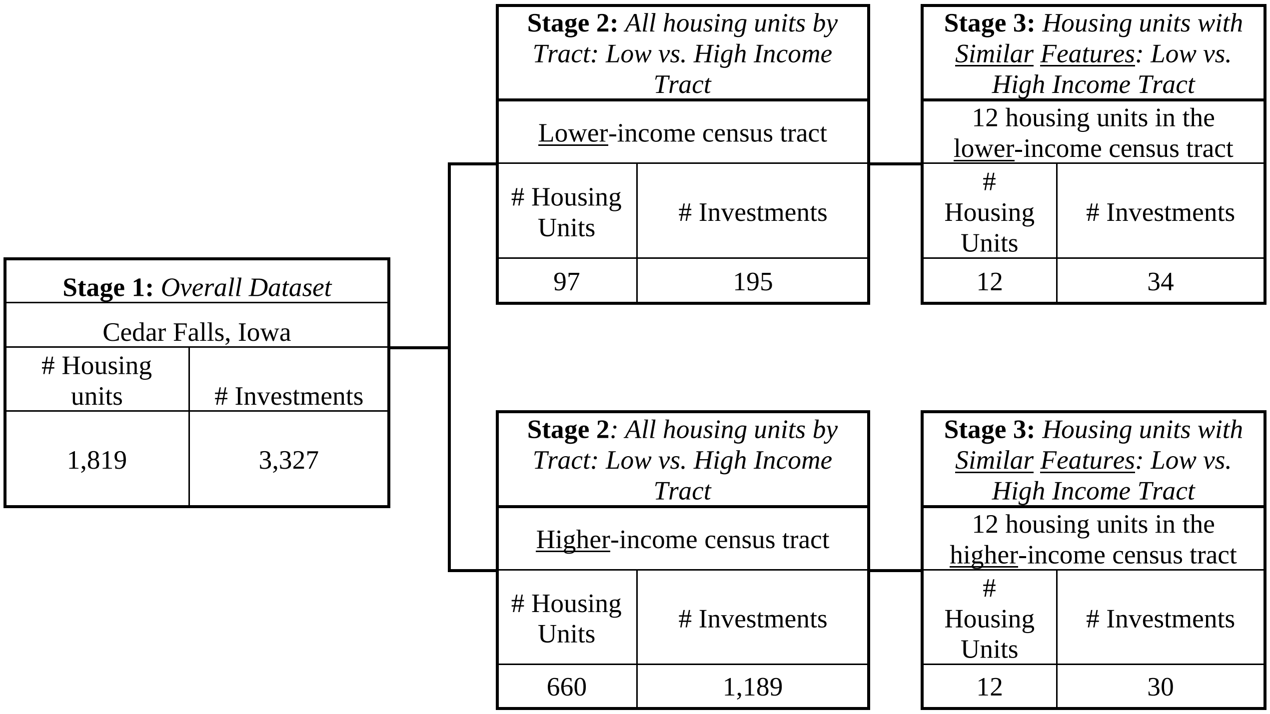
Annual Median Household Income (2010)			
🟦	(a) - $15,663 – $27,236	🟫	(f) - $57,543.01 – $62,241
🟩	(b) - $27,236.01 - $39,313	🟪	(g) - $62,241.01 – $69,219
🟨	(c) - $39,313.01 - $49,659	🟪	(h) - $69,219.01 – $77,130
🟨	(d) - $49,659.01 - $54,032	🟧	(i) - $77,130.01 - $87,825
🟫	(e) - $54,032.01 - $57,543		

Figure 2. (A) Black Hawk County, IA and (B) Cedar Falls, IA geospatial data by census tract, including median annual household income ranges based on the 2010 U.S. Census data *(Note: each range of income levels is labeled (a) through (i), with (a) being the lowest)*

One tract is in the lowest income range (a), and two tracts represent the highest income range (i). We note in this figure; however, the lowest household income tract within Black Hawk County is not located in the area of study. Within the studied area of Cedar Falls, this area includes the highest income tracts (i) on the upper left-hand portion of Figure 2B, and the second-to-lowest income tract, (b), on the upper right-hand portion of Figure 2B. However, since no investment data was available for (b), the next lowest income tract level is (e), located in the top center of Figure 2B. These two groups of tracts are the focus of significant further discussion in this work in comparing the higher and lower-income areas in Cedar Falls.

2.2 Data Analysis Methods

A multistage sampling analysis methodology was used in this research. The method consists of dividing the sample data into three progressively smaller sets of data. The data was split into three main stages, starting with the city of Cedar Falls, Iowa (Stage 1) followed by the lowest and the highest income census tracts in the study area (Stage 2), and ending with 12 housing units from the lower-income and 12 from the higher-income tracts with equivalent building characteristics (Stage 3), as shown in Figure 5. From Stage 2 to 3 the analysis focuses mostly on investments in air conditioning systems due to their high purchase cost and a high number of investments compared to other technologies. The data analysis method steps include (1) analysis of households' investment behavior and (2) comparative analyzes of investment behavior of households located in the highest income and lowest income areas. The statistical methods used for this research include descriptive statistics, followed by multivariate analysis methods, including correlation analyses and principal component analyses (PCA), as discussed in further detail in this section.



Stage 1: *Overall Dataset*	
Cedar Falls, Iowa	
# Housing units	# Investments
1,819	3,327

Stage 2: *All housing units by Tract: Low vs. High Income Tract*	
Lower-income census tract	
# Housing Units	# Investments
97	195

Stage 3: *Housing units with Similar Features: Low vs. High Income Tract*	
12 housing units in the lower-income census tract	
# Housing Units	# Investments
12	34

Stage 2*: All housing units by Tract: Low vs. High Income Tract*	
Higher-income census tract	
# Housing Units	# Investments
660	1,189

Stage 3: *Housing units with Similar Features: Low vs. High Income Tract*	
12 housing units in the higher-income census tract	
# Housing Units	# Investments
12	30

Figure 3 – Multistage data analysis: Hierarchical representation of the three stages of this research, including the number of investments and number of housing units for each stage and subset of data analyzed. *(Note: # housing unites = # of units who made energy efficiency investments, not the total # of housing units; this is the number of unique housing units; thus housing units investing in multiple technologies are only counted once)*

2.2.1 Stage 1 – Households' investment behavior

The goal is to understand overall investment decisions and behavior in preparation for comparison of this analysis to a subset of this data, specifically the higher and lower-income census tracts within the area of study. The data utilized includes 3,327 complete rebates application submitted for 1,819 housing units (1,567 owner-occupied, and 252 renter-occupied) (Table 3). Descriptive statistics and correlation analysis are first used to study the households' investment behavior for the entire region of study, regardless of income level.

To study the overall dataset, first, the order and frequency at which households made energy efficiency investments, the corresponding rebate received is determined. This is completed for all types of studied energy efficiency investments. For the HVAC equipment (air conditioner and furnace), its functional status (working/broken) prior to replacement is also studied. The order is based on the time at which the investment was made, from first (earliest) to the latest (last). The frequency of investments is calculated by determining the number of times each unique address purchased a specific energy-efficient technology, and the total number of energy-efficient technologies purchased. Next, for the HVAC equipment specifically, the original system cooling/heating capacity is compared to the newly installed system, including whether it decreased, stayed the same or increased. This provides an idea of if the old system was adequately sized or not given that newly installed systems followed proper sizing calculations.

Finally, again for all efficiency investments, the relationship between the rebate received and the amount of money invested by the households (i.e., from Table 1, the Total Cost minus the Rebate received) is studied, to understand the amount of money homeowners are willing to invest out of pocket in the tract of study, and the ratio of cost to rebate received that is of interest to homeowners. We note, that fairly low-cost LED lighting (bulb, recessed, and/or specialty bulb), was the only technology that homeowners purchased in high quantities over the studied time period, likely due in part to lower costs per item, the presence of a significant number of lighting fixture in most housing units requiring lightbulbs, and the nature of the rebate program to provide rebates for up to 35 light bulbs per year per household. In addition, for HVAC, the total incremental cost incurred by homeowners, for an increase in cooling efficiency of 1 SEER (i.e., buy a 17 SEER instead of a 16 SEER air conditioner) is calculated. This describes the relative financial impact of the purchase of HVAC equipment with more energy-efficient than the minimum required to qualify for a rebate.

2.2.2 Stage 2 – Lowest and highest income households' investment behavior

The goal of this stage is to compare the efficiency investment behaviors of the households in the higher and lower-income regions of study, to each other and to the overall dataset from Stage 1, to understand what differences may exist among these household populations. Correlation analyzes and principal component analysis are used in this step.

First, to divide the dataset into smaller regions of study, census tracts are used, from the most recent U.S. Census. As discussed in the previous section, for Black Hawk County, there are 38 census tracts, each with its corresponding demographic data, which includes household median income. In GIS v.10.7.1, the census tract shapefiles and corresponding census demographic data were joined, then grouped by median household income ranges.

Tract (i), shown in Figure 2, represents the highest median income range in this region, in the range of $77,130 to $87,825. The median annual household income is $82,470. Tract (b), also shown in Figure 2, represents the lowest income range where rebate data is available, with a range of $54,032 to $57,543. This tract has a median annual income level of $55,755. Table 2 shows a comparison of the income levels, housing age, and unit size for the highest and lowest tracts in Black Hawk County, Iowa. In this table, the median age of the lowest income area (74 years old) is 34 years older than the median age of the housing units in the higher income area (40 years old). This is also nearly twice the median age of housing units in the U.S., Iowa, and Black Hawk County, each at approximately 38 years. In terms of income level, the lowest income area has a similar but slightly higher median income ($55,755) as compared to the overall median in Black Hawk County. The median U.S. income is approximately $4,500 higher than the lower income area. The typical housing unit size in the lower-income tract (147 m^2) is approximately 39 square meters smaller than the average size in the U.S. (186 m^2). This difference is much smaller when compared to average in Iowa (152 m^2) but larger when compared to the average in Black Hawk County (231 m^2). The higher income housing size (242 m^2), however, is 95 square meters larger than lower-income housing units.

Table 2. Summary characteristics of housing units in the census tracts with the highest and lowest income in the studied region compared to the median in the county, state, and the U.S.

Location	**Income level**	**# Housing units**	**Housing unit Age**		**Household median income ($)**	**Housing unit size (m^2)**	
			SD	Median		SD	Average
Cedar Falls	Higher[1]	5,917	20	40	82,470	107	242
	Lower[1]	1,188	24	74	55,755	38	147
Black Hawk County[2]		58,320		38	52,688		231
Iowa		1,409,650		38	58,580		152[3]
U.S.		138,537,078		38	60,293		186[4]

Note: SD = Standard Deviation

[1] *The highest and lowest income census tract in the studied area within Black Hawk County; data from US Census (2010)*

[2] *Data from the Black Hawk County Assessors Office (2016), and the U.S. Census (2010)*

[3] *Data from ResStock (2020)*

[4] *Data from U.S. EIA Residential Energy Consumption Survey (2015)*

In linking the energy efficiency investment data to the census tract information, the number of investments of the tracts within the same income range is determined. This is completed by geolocating the address of each housing unit in the data in GIS, then dividing housing units into their corresponding census tracts for analysis. Table 3 provides a summary of these investments by tract income range in the studied region. Each point in the shapefile represents a housing unit that invested in one or more energy-efficient technologies. We note that housing units that invested in such technologies but did not use the studied rebate program are not shown, as no data is available on the tracking of such purchases.

Table 3. Number of energy efficiency investments by tract median household income range

Tract Median Household Income[1] ($)	**# of Tracts**	**Total Housing Units**	**Investments per Total Housing Unit**	**Housing Units w/Investments**	**# of Investments by Technology**			
					LED Light	Air Cond.	Furn.	Insul.
54,032-57,543	1	1,188	0.164	97	51	44	49	51
57,543.01-62,241	3	4,703	0.117	316	136	131	146	135
62,241.01-69,219	2	4,684	0.173	444	341	174	181	113
69,219.01-77,130	1	1,975	0.297	302	162	128	153	143
77,130.01-87,825	2	5,917	0.201	660	548	267	210	164
Total	*9*	*18,467*[1]		*1,819*[2]	*1,238*	*744*	*739*	*606*

[1] *This value is a summary number of parcel. (Note: The number of parcels here is slightly larger than the number of households because CFU provides services to some houses outside of how the Census-designated CF, and some non-residential properties.*

[2] *Here is included the housing units that made investments. The same housing units that invested in two or more technology is counted only once*

Similar to Stage 1, in this stage, we next compare the frequency at which households made energy efficiency investments and the corresponding rebate received across the lower and higher-income areas and full dataset. The relationship between the rebate received and the amount of out of pocket money invested by the household is also compared across the full dataset and two subsets. We anticipate notable differences in both frequencies of investment and ratio of money invested to rebate received across the lower and higher-income regions.

Principal component analysis (PCA) is next used to reduce the dimensionality of the data, help to identify the most influential variables and facilitate the interpretation of the dataset. PCA is commonly used to describe patterns, and variation across large, widespread multivariate dataset by reducing the data's dimensionally through feature extraction (Jollife and Cadima, 2016; Vigneau et al., 2001), i.e., the creation of new variables based on the original dataset while removing the least influential variables, effectively reducing the number of variables to a smaller set of independent, highly influential ones. The method is used in this study to help identify, within a census tract, the segmentation of households with the same investment behaviors and the possible correlation between them.

The method seeks to identify the most influential variable with maximum variance in a column of any real *n x p* matrix *X*, a dataset with *n* number of observations and *p* numerical variables, which results in a combination of eigenvalue, variance of the linear combination, and corresponding eigenvectors (Jollife and Cadima, 2016). The eigenvectors create a new variable, also called the principal component (PC). This new variable is a linear combination uncorrelated with the previous variables. The linear correlation is calculated using Equation 1:

$$Xa = \sum_{j-1}^{p} a_j x_j \tag{1}$$

where *a* is a vector of a constant (*a* = 1, 2,… *p*), and the variance is given by *Var*(*X**a**)* = ***a'Sa****,* where *S* denotes the covariance matrix of the dataset and *'* denotes transpose. Each PC stores all information from the old sample data that falls under that specific PC. The procedure next standardizes the sample of each variable *X* such that each can provide an equal contribution to the new variables, and thus helping to avoid bias, particularly with datasets which include large differences in values (e.g., 20 versus 110-year-old housing units), using Equation 2:

$$Z_{ji} = \frac{x_{ji} - X_j}{s_j} \tag{2}$$

Where: x_{ji} is the value of the variables in the *i (i = 1, 2,…i)* and *j (j = 1, 2,…j)* dimensions, *xj* is the mean value at *j* dimensions, and *S* is the standard deviation. The linear combination, also called the principal component, is computed using Equation 3:

$$X_{ak} = \sum_{j=1}^{p} a_{jk} x_j \tag{3}$$

Where, X_{ak} is the principal component, which is the sum of a_k, the *k*th eigenvector of a constant at each *j*, multiplied by the vector *x* at each *j*. *k* (*k*=1, 2, 3,… *p*) represents the number of eigenvectors. The PC is organized in descending order of importance, such that the first PC carries the largest amount of information; the second carries the second-largest, etc. If the eigenvector of a variable is perpendicular to a PC, the loading value of the variable is zero, and it is not explanatory by that PC; however, it is completely explanatory by the PC if the variable is parallel to it. Orthogonal eigenvector means the information is captured by both PCs, and the variable is explanatory by both PCs.

2.2.3 Stage 3 – 12 housing units in highest and lowest income tracts with similar characteristics

This final stage focuses on a comparison of the investment behavior of similar types of buildings located in the lower- and higher-income census tracts of study. The housing stock in the lower- and higher-income census tracts vary considerably in age and size (Table 2). Among the variables to consider, age and size cannot be changed or easily adjusted, compared to other building performance and efficiency-related variables such as the window type, level of insulation, etc. As such, the aim in this stage is to assess a comparison of the efficiency of similar age and size homes. The PCA is used in this stage to analyze the investment behavior during the four years of study between the 12 lowest income and 12 highest income housing units. The number of households in each of the two considered census tracts was reduced to 12 housing units each, under the conditions that the included housing units are between 50 to 60 years old and 102 to 185 square meters (1,100 to 2,000 square feet).

CHAPTER 3. RESULTS AND DISCUSSION

3.1 Stage 1: Investments in the Cedar Falls, IA region

In total, 1,819 individual households at unique addresses, made 3,367 investments in four types of energy-efficient technologies from January 2013 to December 2016 (Table 1, Table 3). The distribution of investments by year and technology is shown in Figure 4. As seen in this figure, even though air conditioning and furnace (HVAC) units were the most expensive technology in terms of out-of-pocket expenses to the household, with the median cost being 700% more than insulation (Table 1), the general trend is dominated by investment in HVAC (air conditioning and furnace units), followed by the less expensive LED lighting and insulation investments.

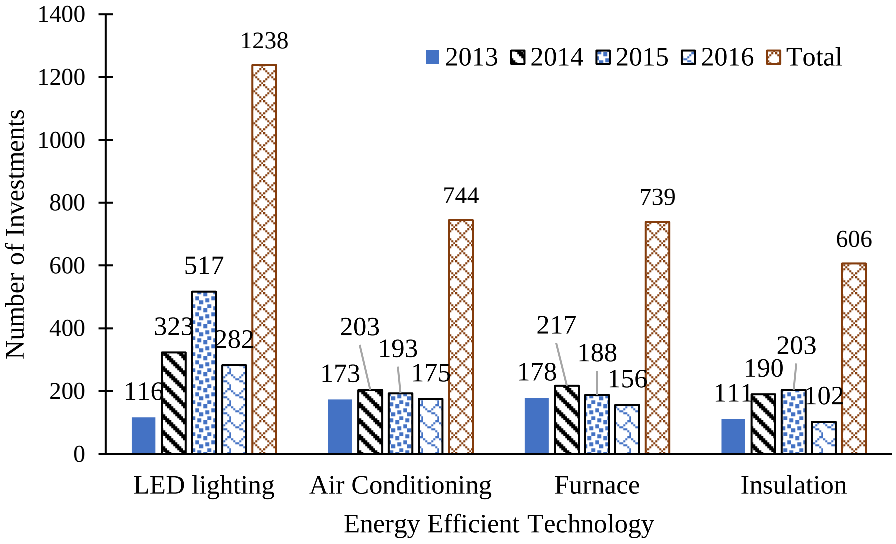


Figure 4**.** Total number of energy efficiency investments per technology each year from 2013 to 2016

Next, we looked at the number of investments across the dataset. Figure 5 and Figure 6 show, for households with different numbers of investments in the four energy-efficient technologies, the percentage that invested in each of the four technologies. This percentage value is calculated by summing the total number of investments in each technology and dividing by the number of total investments. As such, in housing units where multiple technologies were purchased, a single household may be represented under multiple technologies'. Figure 5 shows that the majority of households invested in each technology only once, including 55% of LED lighting purchases, 97.8% of air conditioner purchases, 54% of insulation purchases, and 97% of furnace purchases. The remaining percentage of air conditioner and furnace purchases were nearly all for two units, likely for larger housing units with multiple HVAC systems. LED lighting is the only technology of the four studied, where some households purchased and requested reimbirusment more than six times.

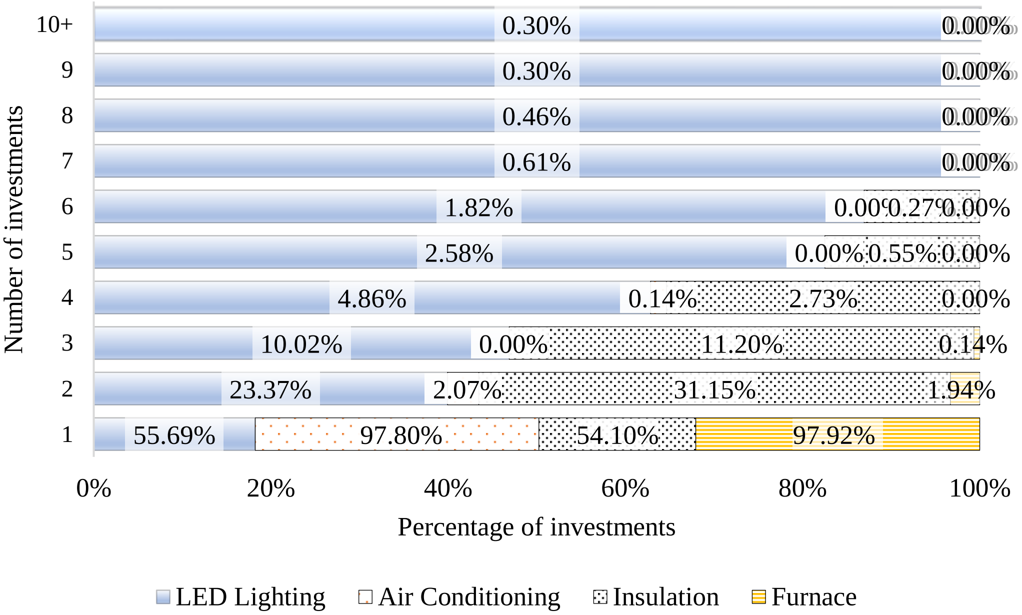


Figure 5. Total percentage of energy efficiency investments made for housing units, subdivided into a number of investments per housing unit

Of the energy efficiency investments made, approximately 80% (1,981 investments, 1,464 unique housing units) made only one one-time investment during the studied time period, and 12% made two investments (Figure 5 and Figure 6a and b). Of those who made a single investment, energy-efficient air conditioning and furnace units were the technologies purchased the most

(Figure 6b), similar to the trend for the overall dataset. In addition, approximately 75% of households that invested in air conditioning also invested in a furnace. In general, as expected, as the number of investments increases, the number of housing units in each category decreases.

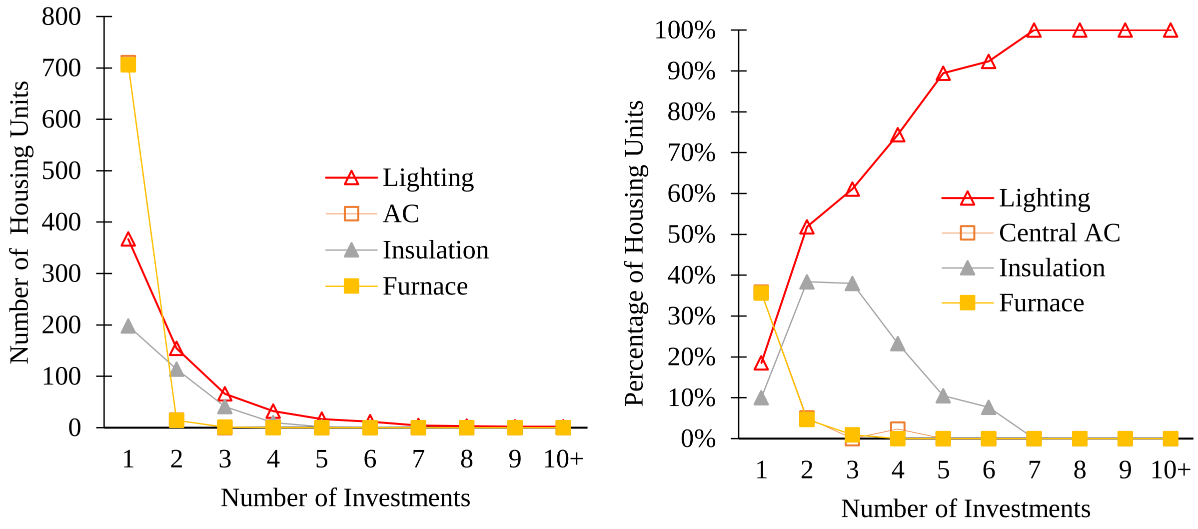


Figure 6. (a) Number of housing units investing in each studied technology investments and (b) the percentage of housing units by the number of investments

3.1.1 Lighting

Overall, considering the total number of investments per address, efficient lighting accounted for approximately 37% of these investments, making lighting a fairly common investment to make, second to overall HVAC investments; if air conditioning and furnace investments are considered separately, lighting is the most common investment. The findings are similar to those of other recent literature (Attari et al., 2010; U.S. Dept of Energy, 2010; Annual Energy Outlook, 2019), which indicate that lighting is among the most common efficiency investments. This may be justified by the low investment amount required compared to the high initial investment needed to acquire other measures such as HVAC equipment. In addition, there is typically no special expertise or technicians required for installing it or maintenance.

We also note that, of those that only made one investment, efficient lighting is the third most invested in technology, at 18% of investments, below air conditioning and furnaces (Figure 5 and Figure 6a and b). However, of households that made seven or more investments, 100% invested in lighting. In terms of order, lighting is not typically the first investment made by a household, but more highly represented after the first investment, and as mentioned, for those that make multiple investments lighting is most commonly representing those multiple investments.

The studied rebate program provided a 50% rebate, based on the purchase costs of the lighting. This was confirmed via correlation analysis (Figure 7), with R^2 of 0.95, showing the linear increase in the rebate received with the investment made. Compared to the ratios of investments to rebate of the other technologies, this ratio is the highest. The total cost per item is also lowest compared to the other studied systems, two factors of which likely influence the commonality of this investment. The correlation between the quantity purchased and the rebate received was 0.71 (Figure 7). Since efficient lighting lasts longer compared to the standard light – up to ten years, according to the manufacturer (Philips, 2018) – this may contribute to making the investment in efficient lighting very attractive.

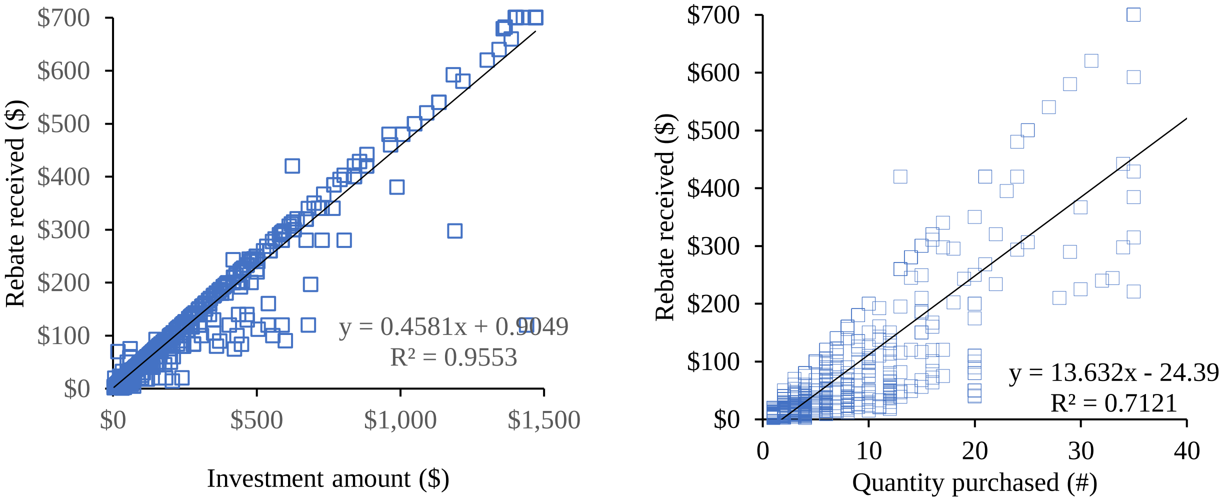


Figure 7**.** Comparison of (a) the amount invested in energy-efficient lighting and rebate received, and (b) the number of lights invested in and the rebate received.

3.1.2 Air Conditioning and Furnace (HVAC)

For the entire dataset, the air conditioning and furnace are, in combination, the most common investment. Specifically, for those households who made one investment (1,981), 1,416 of them invested in this technology. Both the air conditioning and furnace correspond to approximately 74% (37% each) of all purchases in that category (Figure 6). This is an impressive amount, given the high cost of the initial investment. For those households who are replacing existing systems, their high cost may impact their decision on when to change it.

Table 4 and Figure 8 shows that over 68% of households changed the air conditioner only after it was broken, and 29% changed even though their system was still operational. Only 2% were newly installed and not replacing already existing equipment. Of those that changed with the appliances still running, however, 65% had the efficiency of less than 13 SEER, which is the currently required SEER rating for qualifying for the rebate program. Only 1% had a SEER rating of over 13, and 33% were unknown due to missing efficiency data (Table 4). Removing the housing units with missing efficiency rating values, less than 1% had a SEER rating greater than 13, and the average SEER rating of the replaced systems was 9.5, with some systems with SEER ratings as low as 5 or less. The large majority had a SEER rating in the range of 8 to 10. Since the impact of mis-installed or improperly maintained equipment, such inaccurate sizing, air leakage in the ducts, and low/high refrigerant charge (among others), were not checked before the replacement of the old system, this effort cannot determine how this may have impacted the number of units with efficient below SEER 13 (over 70%). Because the typical life span of an air conditioner and furnace is approximately 15 to 20 years (U.S. Dept of Energy, 2019), these types of problems may impact the operational efficiency of the equipment, as compared to the rated efficiency (Kleine et al., 2011). In the most severe cases, mis-installation and/or improper maintenance can cause the system to break.

Table 4. Summary comparison of old (replaced) and new efficient air conditioning units

N	*Old Air Condition System*					*New Air Conditioning System*				
	Capacity		Condition (#)			Capacity		Unit Size Change		
	SEER	Tons	Working	Broken	New	SEER	Tons	Increase	No Change	Decreased
8	>=4	1-5	3	5		14-17	1.5-4	38%	38%	13%
8	5	1-3	-	8		14-15	2.5	63%	25%	13%
15	6	1-3	6	9		14-18	1.5-3	20%	67%	13%
17	7	1.5-3	4	13		14-16	1.5-2	18%	18%	59%
117	8	1-3.5	34	83		14-20	1.5-3.5	13%	63%	21%
12	9	1.5-3	3	9		14-16	2-3	25%	67%	8%
278	10	0.5-5	85	193		14-25	1.5-5	7%	77%	15%
26	11	2-4	3	23		14-18	2-4	-	85%	15%
21	12	2-4	5	16		14-18	2-3.5	10%	71%	14%
20	13	1.5-3	3	17		14-22	1.8-4	10%	20%	70%
5	14	2.5-3.5	-	5		16	2.5-3	-	60%	40%
3	15	3	-	3		14-17	2	-	-	67%
3	16	2-5	1	2		14-16	1.5-5	-	67%	33%
211[1]	-[1]	1.5-3	72	121	18	14-33	0.75-5	2%	18%	6%
744	9.5	2.4	29%	68%	2%	15.5	2.3	20%	52%	17%
Totl.	*Avg.*	*Avg.*	*%*	*%*	*%*	*Avg.*	*Avg.*	*Avg.*	*Avg.*	*Avg.*

[1] *These include new installation units (no previous unit existed), units destroyed by fire, and other units of which the SEER capacity was not possible to determine.*

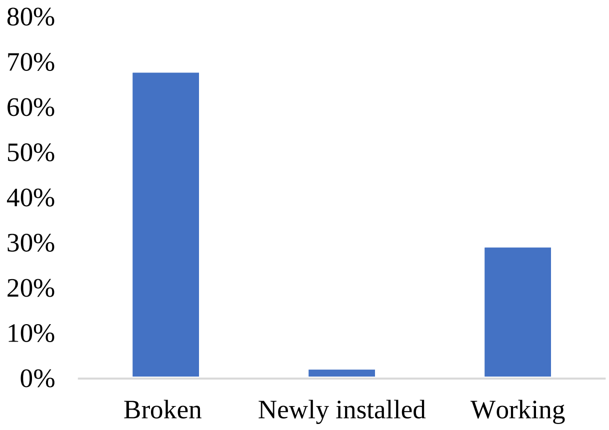


Figure 8. Air conditioning system status before they were replaced with a new system

In Table 5 the total cost incurred to increase the air conditioning efficiency is calculated. Across the dataset, approximately 90% of investments were in HVAC systems with SEER values of 14, 15, and 16. In addition, approximately 35% of the households purchased only the air conditioning, i.e., no simultaneous purchase of furnace, thermostat, plenum and/or return drop. Within the qualifying range of SEER ratings for the new units, the purchased units with lower efficiencies and no extra features resulted in low rebate, as expected. Households that invested in equipment with higher efficiency received higher rebates. The cost per SEER is also estimated in Table 5. On average, those that increased the efficiency from 15 to 16 SEER paid the most for this the incremental increase in SEER, and those that increased from 18 to 19 paid the least per SEER. Those that increased the unit's efficiency from 17 to 18 received the average lower rebate per SEER comparing to households that increased from 19 to 20 that received the higher rebate per SEER.

Table 5: Households investments in energy-efficient air conditioning systems and rebate received per SEER value of the new system

SEER[1]	*N*	*Costs of new system ($)*		*Rebate received ($)*		*Total costs per SEER*	*Rebate per SEER*
		Average	*SD*	*Average*	*SD*	$\lvert C_N-C_{N-1}\rvert$	$\lvert R_N-R_{N-1}\rvert$
14	249	$3,973	$1,616	$411	$136	--[3]	--[3]
15	55	$5,446	$2,379	$505	$139	$1,473	$90
16	373	$7,230	$2,352	$636	$121	$1,784	$130
17	30	$10,677	$2,705	$600	$146	$1,275	$36
18	17	$10,677	$2,705	$614	$135	$1,564	$14
19	3	$11,811	$3,632	$700	--[2]	$1,134	$86
20	6	$10,208	$3,872	$700	--[2]	$1,603	$240
23	3	$11,244	$3,257	$600	$141	--[4]	--[4]
24	2	$10,010	$1,910	$700	--[2]	$1,234	$100
25	2	$11,325	$970	$700	--[2]	$1,315	__[2]

[1] Units with SEER 21, 22, 29 and 33 are excluded because (a) only one unit had this efficiency, or (b) housing units with this size unit were new and thus the new system was not replacing an existing unit

[2] The value presented is equal to zero

[3] Since there is no previous average cost of a new system (C_N) before 14 SEER, this value cannot be calculated

[4] The previous unit size with data is over 1 SEER different; therefore the cost per SEER and rebate per SEER cannot be calculated

Note: C_N is the average cost of a new system and R_N average rebate received

3.2 Stage 2 - Household's characteristics and households' investment behavior in the higher- and lower-income census tract

Multistage sampling was used to reduce the data to only those in the low-income and high-income tracts. Overall, 757 housing units in total were studied in this Stage, with 660 being in the higher-income tract and 97 in the lower-income tract. Overall, there are a smaller number of housing units that made efficiency investments in the lower-income tract in comparison to the higher income tract. When normalized by the total number of housing units in each tract, the investment rate per unit is 0.20 for the highest income tract and 0.164 for the lowest income tract, indicating that more investments are made per housing unit in the higher income areas as compared to lower-income areas. Previous research shows disproportional energy expense burden for lower-income households because of less quality housing units, which is typically less efficient, thus increasing the cost of energy bills (Jessel et al, 2019; Kontokosta et al., 2018). Recent research findings have found that lower-income households spend 8% to 17% more on electricity bills than the higher-income households, despite housing units of higher-income households consuming more energy (Jessel et al., 2019; Poortinga et al., 2017; EIA, 2015).

However, it is also of interest to note that in comparing which investments are made mostly in each tract, the lower-income tract invested most in HVAC systems, followed by insulation, then lighting (Figure 9a). The higher income tract, however, prioritized efficient lighting and HVAC systems investments with the least common investment being insulation (Figure 9b). This difference may be due to the age and associated efficiency of the existing systems of the housing units in each location. The housing units in the lower-income tract are smaller in size (145 m^2) and older (74 years) than those in the higher income tract with a median size of 226 m^2 and 40 years old (Table 3). Older housing units are not likely to be built with much insulation, if any, compared to more modern housing units that are required to follow adopted energy efficiency codes. Since insulation plays a critical role in both energy consumption and comfort, particularly in extreme weather conditions, for those older housing units, particularly those that are smaller in size, at a relatively low cost. These comfort, cost, and age factors maybe some of the reasons for higher numbers of investments in insulation in lower-income regions.

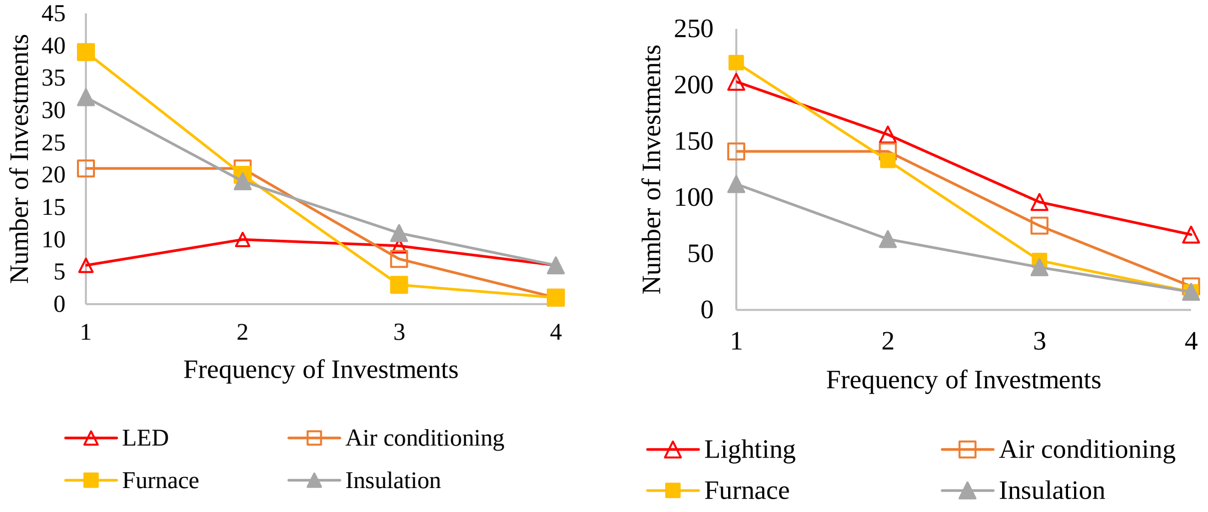


Figure 9. (a) Number of lower-units units investing in each studied technology investments on the left and (b) number of higher-units units investing in each studied technology investments on the right

In further analysis, principal component analysis and correlation analysis focusing in investments in Central AC, as a weather-related technology, was carried out. Over all 761 homes that invested in AC during the 4 years, and 335 of these homes were classified as high income while 42 as low income.

In further analysis, principal component analysis and correlation analysis focusing on investments in air conditioning was carried out. Overall, 744 housing units invested in air conditioning during the four years period of study. Of these investments, 267 were made by housing units in the higher income tracts, and 44 were made in the lower-income tract. These groups of housing units are studied further in the following subsections.

3.2.1 Lower-income tract housing units

The lower-income tract investment behavior is studied through correlation analyses and PCA. For the correlation between variables (Table 6), there is a strong correlation between the rebate received and the air conditioning efficiency (0.67). That is, as expected, the higher the efficiency of the air conditioner that households invested in, the higher the rebate amount they received. We also find a weak correlation between the total project cost and air conditioner efficiency (0.47) and between the total project cost and rebate amount (0.40). These make sense, given the structure of the rebate program for air conditioners. These correlations are also generally observed for the studied higher-income areas, but with slightly lower correlation coefficients.

Table 6. Correlation analysis between the studied variables for air conditioner investments for housing units in the lower-income tract

	Age of Home	**Size of Home**	**SEER**	**Project Cost**	**Rebate Amount**	**Cooling Capacity**
Age of Home	1.00	0.0038	0.08	0.06	0.11	**0.55**
Size of Home	0.001	1.00	-0.08	-0.001	-0.16	0.29
SEER	0.09	-0.08	1.00	0.47	**0.67**	0.12
Project Cost	0.06	-0.001	0.47	1.00	0.40	**0.50**
Rebate Amount	0.11	-0.16	**0.67**	0.40	1.00	0.03
Cooling Capacity	**0.55**	0.29	0.13	**0.50**	0.03	1.00

In addition, while there is a weak correlation observed between the air conditioner cooling capacity and the housing unit size (0.29), there is a stronger correlation between the air conditioner cooling capacity and the housing units' age (0.55). This suggests that the age of home plays a more important role than the size of home in determining if a larger cooling capacity of the air conditioner is needed in the lower-income areas. Given that older housing units are typically leakier (i.e. higher infiltration rate), with a lesser amount of insulation, there can be significantly more heat loss in comparison to newer housing units built to more recent energy codes. In addition, since the housing units in the lower-income areas are older, this may justify a higher amount of investments in insulation compared to the higher-income areas.

For further analysis, the PCs are calculated in order to understand the most influential variables, and how much of the six variables are captured by each principal component. As shown in Figure 10, 63.6% of all variables are explained through PC1 and PC2. That is, PC1 (37.5%) and PC2 (26.1%) explain most of the variance in the dataset. Figure 10a presents the 97 scaled data of households that invested in air conditioners. Housing units size has a loading value of approximately 0.00 for PC1 (Figure 10b), meaning since the eigenvector is perpendicular to PC1 and parallel to PC2, this variable is only explanatory for PC2, and the correlation between them is stronger compared to PC1. Project cost, on the other hand, is only explanatory for PC1, so the correlation between them is stronger compared to PC2. This suggests that the cluster of housing units in PC1 may presents a smaller variation in size compared to those in PC2.

The cooling capacity, rebate amount, and air conditioning efficiency have the highest magnitude and are orthogonal to the PCs, and as such, they are described by both PC1 and PC2. Their eigenvector is on the positive quadrant of PC1 and has a magnitude of over 0.5 with PC1, meaning this PC well explains them, and their correlation is positive, as can be seen in Table 7. The rebate amount and the air conditioning efficiency are on the negative side of the PC2, meaning their correlation with that PC is also negative.

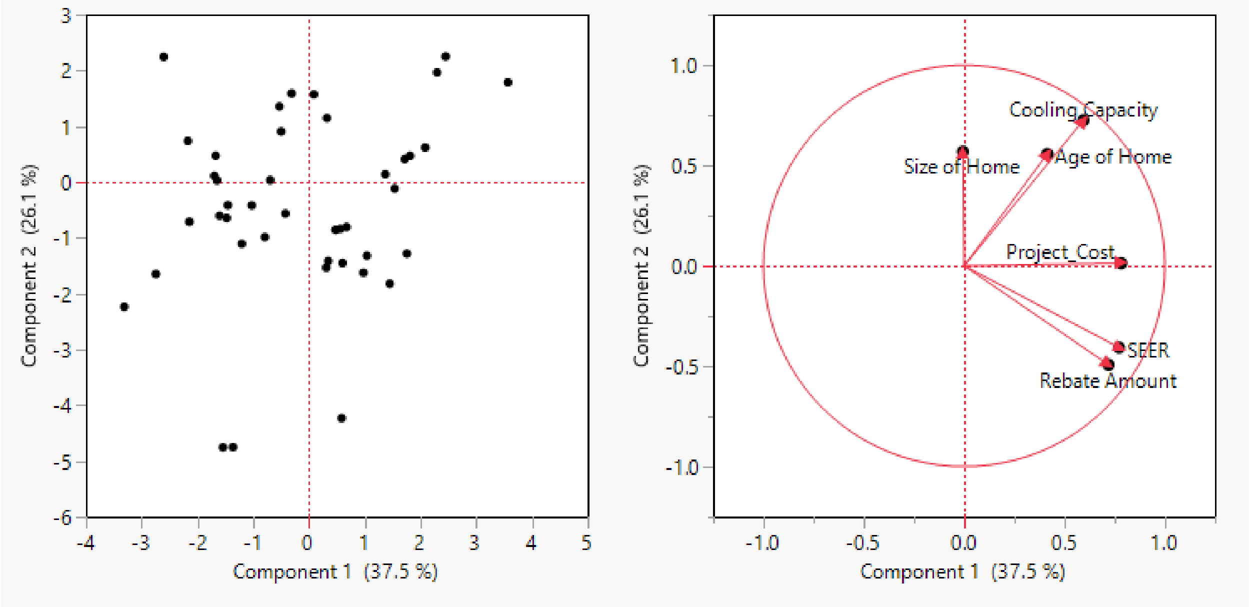


Figure 10**.** Principal Component Analysis (PCA) of air conditioning systems in housing units in lower-income tract: Score plot of dataset scaled (a) on the left, and loading plot of the dataset variable (b) on the right, for Principal Component 1 (PC1), which explain 37.5% of the variance, and Principal Component 2 (PC2) which explain 26.1% of the variance

The correlation between the most significant principal components (PC1 and PC2) and the studied variables is next analyzed and presented in Table 7, to identify the main clusters of housing units in lower-income areas with homogeneous investment behavior patterns, in the sense that their investment behavior pattern is similar. The result shows a strong linear association between PC1 and air condition efficiency (0.77), project cost (0.78), and rebate amount (0.71). That is, when the households in this group invest more in more costly, higher efficiency equipment, they also receive a higher rebate. In addition, there is a strong correlation between PC1 and the air conditioner cooling capacity (0.59), which suggests that this cluster of households also increased the air conditioner cooling capacity when they invested in new air conditioner units. It is also noted that PC1 has a non-important negative correlation with the housing unit size (-0.01) and a weak correlation with age (0.41). These results help to provide a means of understanding the lower-income households' interest in increasing the efficiency of the air conditioners. The findings suggest that these households made larger investments to increase air conditioner efficiency, which also results in them receiving a higher rebate. These households may also have more interest in energy efficiency or are focused on maximizing the rebate amount. Another notable trend is that the air conditioner cooling capacity increased with the housing age, suggesting the larger influence of building age on sizing the air conditioner cooling capacity. This is different from the findings for the higher-income areas.

The correlation study of PC2 demonstrated a strong correlation between PC2 and air condition cooling capacity (0.73), housing size (0.57), and age of home (0.56). This result suggests a higher influence of both housing age and housing size on the air conditioner cooling capacity.

PC2 presents a negative correlation with the air conditioner efficiency (-0.41), and rebate amount (-0.49). This result suggests that these lower-income households invested less in efficient air conditioners, which resulted in a lower rebate.

Table 7. Loading matrix between six variables related to air conditioner investments and PC1 and PC2 for housing units in the lower-income tract

	PC1	**PC2**
Age of Home	0.41	**0.56**
Size of Home	-0.01	**0.57**
SEER	**0.77**	-0.41
Project Cost	**0.78**	0.01
Rebate Amount	**0.72**	-0.49
Cooling Capacity	**0.59**	**0.73**

3.2.2 Higher-income tract housing units

The correlation of variables in the higher income tract was calculated using scaled variables (Table 8). We note that there is no strong correlation between the variables, which is distinctly different from that of the lower-income areas. A weak positive linear correlation between the housing unit size and the air conditioner cooling capacity (0.43) is observed. The rebate received also had a weak correlation with the project cost (0.38), which is justified by the weak linear association between the project cost and the air conditioner efficiency (0.43). There is also a weak negative correlation between the cooling capacity and the housing units age (-0.20), and a weak positive correlation between both variables (0.43). The result suggests that higher-income households made fewer investments to increase the air conditioner's efficiency, which resulted in a smaller rebate amount. Compared to housing units in lower-income areas, however, the results suggest that lower-income households made larger investments with higher efficient systems, which resulted in a higher rebate amount. In contrast, the rebate amount may not have been as attractive a feature for the housing units in higher-income areas. In addition, in the higher-income tracts, higher cooling capacity is most closely related to the size of home, while for lower-income tracts, it is the age of home.

Table 8. Correlation analysis between the studied variables for air conditioner investments for housing units in higher-income tracts

	Age of Home	**Size of Home**	**SEER**	**Cooling Capacity**	**Rebate Amount**	**Project Cost**
Age of Home	1.00	**-0.49**	-0.06	-0.20	-0.07	-0.07
Size of Home	**-0.49**	1.00	-0.003	0.43	0.01	0.18
SEER	-0.06	-0.003	1.00	0.01	0.29	0.43
Cooling Capacity	-0.20	0.43	0.01	1.00	0.05	0.17
Rebate Amount	-0.07	0.01	0.29	0.05	1.00	0.38
Project Cost	-0.07	0.17	0.43	0.17	0.38	1.00

The principal component analysis of the variables in the higher-income tracts shows that 58.6% of the variables are explained (Figure 11). In Figure 11a, the 660 sample data are scaled and reduced for the identification of the most influential variables. Figure 11b shows that housing size and project cost are two of the most influential variables, followed by the cooling capacity and efficiency, and finally, rebate amount. All the variables are explained by both of the PCs, with PC1 explaining 32.8% of the variables and the PC2 explaining 25.8%. The unit’s age is in the negative quadrant of PC1 and opposite to the air conditioner cooling capacity and the size of home. This means that any correlation analysis between these three variables with the housing age will be negative. Figure 11 shows that project cost and size of home are orthogonal and have the highest magnitude (over 0.5) amongst the 6 variable studied, meaning, the information from these variables are well captured by both the PCs and their correlation with the PCs is strong. Air conditioner efficiency, on the other hand, shows the smallest magnitude with PC1 compared to PC2. That suggests that this variable is better represented by PC2, and the correlation between them is higher. Cooling capacity and size of home are on the negative quadrant of PC2, such that their correlation is negative with PC2 and when its value increases, the value of the age of home, the rebate amount, project cost, and efficiency decreases. Nevertheless, the age of home is in the negative quadrant of PC1, which means it is negatively correlated with PC1 and in a different direction comparing to the remaining variables. That is when the value of cooling capacity, size of home, efficiency, rebate amount, and project cost increase for PC1, the age of home decreases. Moreover, we also note that the age of home is separated from other variables, i.e., it has a higher degree of freedom as compared to other variables. This means that the rebate amount, efficiency, and project cost tend to adjust in value together, followed by cooling capacity and, finally, the size of home.

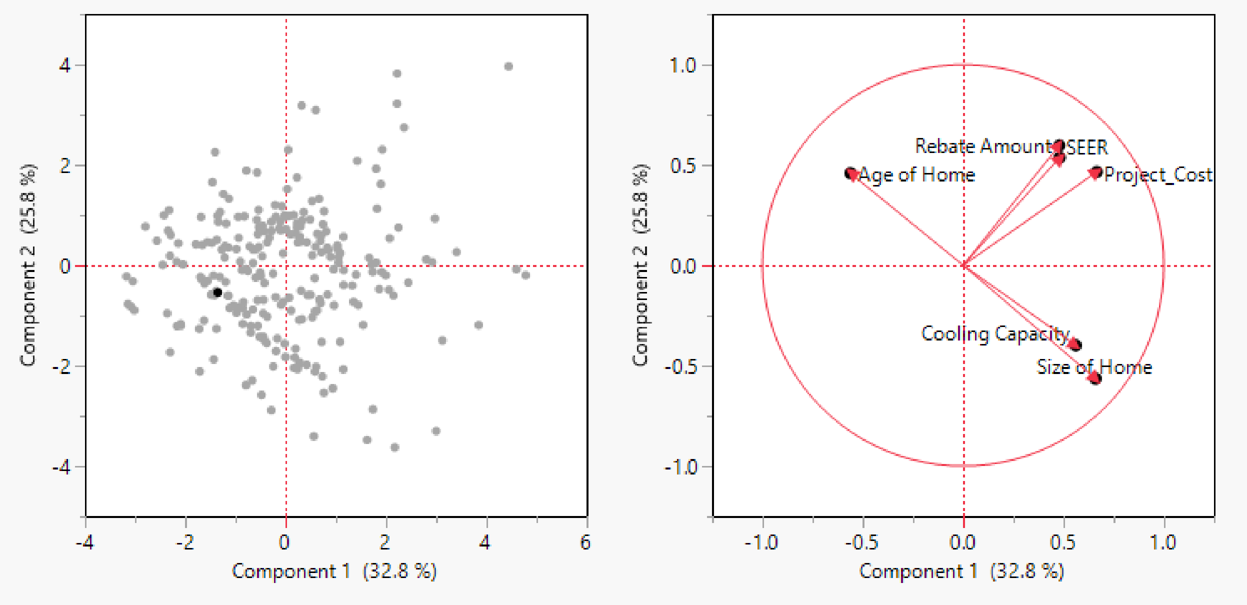


Figure 11**.** Principal Component Analysis (PCA) of air conditioning systems in housing units in highest income tract: Score plot of dataset scaled (a) on the left, and loading plot of the dataset variable (b) on the right, for Principal Component 1 (PC1), which explain 32.8% of the variance, and Principal Component 2 (PC2) which explain 25.8% of the variance

Next, the correlation between the principal components and the most influential variables is studied. As shown in Table 9, there is a strong linear association between PC1 and the project cost (0.67), housing size (0.66), and air conditioner cooling capacity (0.56). This suggests that increased cooling capacity for housing units in the higher income tract is highly influenced by the size of home. In comparison to the lower-income area where the age of home was found to have a strong influence, for the higher-income area, age is not shown to be impactful. Interestingly, there is a negative linear correlation between PC1 and the age of home (-0.56), which suggests that the younger housing units tend to be larger in size. Thus, households made more investments in air conditioners with higher cooling capacity. The results also show a weak correlation with the air conditioner efficiency (0.48) and the rebate amount (0.48). These results differ strongly compared to the lower-income area where the PC1 represents a cluster of households with larger investments in equipment with higher efficiencies (0.77), which also provided them with a higher rebate (0.72). Comparing PC1 from the lower and higher - income tracts, we notice that PC1 from the lower-income tracts purchased air conditioners with higher efficiency and cooling capacity was also higher while investment from PC1 from-higher income tracts more strongly related to cooling capacity.

PC2 indicates a strong positive linear association between PC2 and air conditioner efficiency (0.60) and a strong positive association with the rebate amount (0.54). We also note that PC2 has a strong negative correlation with the size of home (-0.56) and a week correlation with the cooling capacity (0.40). This may indicate that these housing units within PC2 are smaller. However, here the age of homes is not found to influence the cooling capacity, which makes sense since the smaller housing units require less cooling capacity than the bigger units, as found for PC1. PC2 from the higher-income housing units invested mostly in air conditioners with higher efficiency (0.60) compared to those in lower-income housing units (-0.41), resulting in a higher rebate. These results differ from the lower-income tract, where the households in PC2 made larger investments in air conditioners with a higher cooling capacity (0.73). The equipment cooling capacity for housing units in the lower-income tract is highly influenced by both the housing age and size, while in the higher-income housing units, the age of homes has the biggest influence.

The results show that the cooling capacity of both PCs in the lower-income housing units and PC2 in the higher-income housing units may have been influenced by the age of home.

Table 9. Loading matrix between six variables related to air conditioner investments and PC1 and PC2 for housing units in the higher income tract

	PC1	**PC2**
Age of Home	**-0.56**	0.46
Size of Home	**0.66**	**-0.56**
SEER	0.48	**0.60**
Cooling Capacity	**0.56**	-0.40
Rebate Amount	0.48	**0.54**
Project Cost	**0.67**	0.47

3.3 Stage 3 – Housing Unit Characteristics in High and Low-income Tracts

Stage 3 includes analysis of 12 housing units in the lowest and highest income tracts. The size of home and their age were used as criteria to limit and chose the sample data, such that the housing units studied in both the high- and low-income areas are similar. This includes housing units between 50 to 60 years in age and 102 to 185 square meters.

3.3.1 Stage 3 – Lowest income tract housing units

The linear association between the four variables is first analyzed for the lower-income tract (Table 10). The result shows a very strong association between project cost and efficiency (0.78), meaning the amount invested by these housing units increases as the air conditioner efficiency increases. There is, however, a weak positive correlation between the air conditioner efficiency and the rebate amount (0.48). The results imply that these households may have received a high rebate, but they did not always invest in high efficient air conditioners.

Table 10. Correlation analysis between the studied variables for air conditioner investments for housing units in lower income tracts (Stage 3)

	SEER	**Cooling Capacity**	**Rebate Amount**	**Project Cost**
SEER	**1.00**	0.12	0.48	**0.78**
Cooling Capacity	0.12	**1.00**	0.22	0.44
Rebate Amount	0.48	0.22	**1.00**	0.46
Project Cost	**0.78**	0.44	0.46	**1.00**

In Figure 12 the most influential variables among the 12 units in the lower-income tract are shown. In total, 80.7% of the variables are explained by PC1 (58%) and PC2 (22.7%), as shown in Figure 12a and b, respectively. Figure 12a presents the score plot of the 12 lower-income sample data. In Figure 12b the most influential variables are shown. As can be seen, the project cost and efficiency have the highest magnitudes compared to the rebate amount that has the smallest magnitude. The figure also shows that rebate amount, project cost, and efficiency are positively strongly related to PC1. These variables tend to vary together, i.e., they have a strong influence over each other in PC1. However, such factors are poorly described by PC2. The cooling capacity, however, is better captured by PC2. That suggests that cooling capacity is the only variable well explained by PC2.

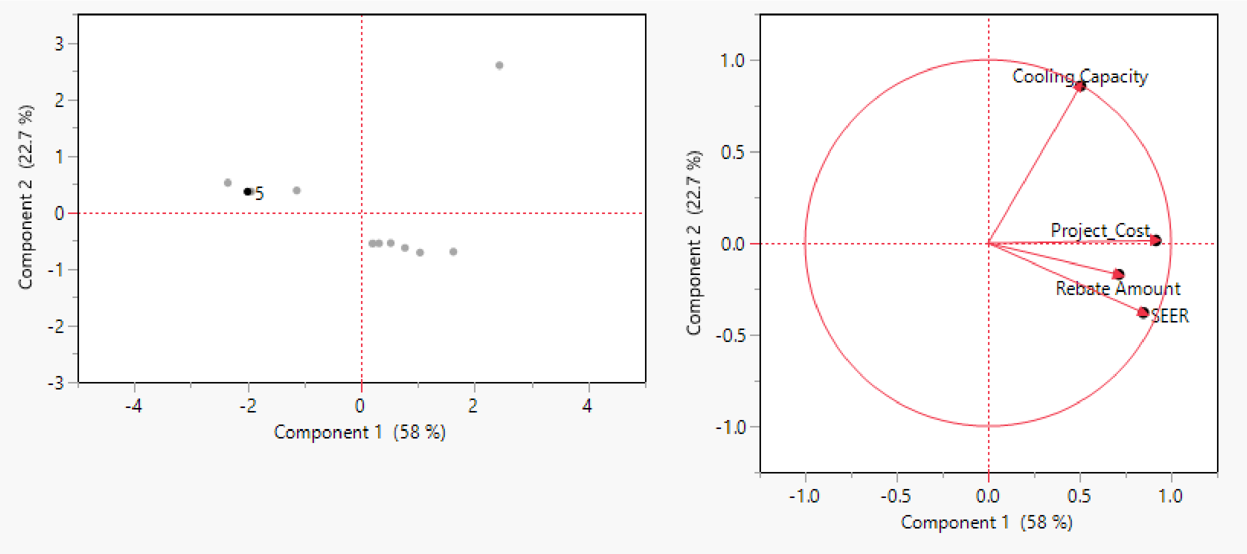


Figure 12**.** Lower-income stage 3: Principal component analysis: Score plot of households scaled on the left (a); loading plot on the right (b), for principal components one, with 58% of the variance explained and principal component two, with 22.7% of the variance

In Table 11 the correlation between the principal components and the most influential variables is calculated. In the correlation comparison, there is a strong positive correlation between PC1 and project cost (0.92), air condition efficiency (0.85), and rebate amount (0.71). This suggests that whenever those housing units increased their investments, they purchased air conditioners with higher cooling capacity and higher efficiency, and that resulted in a higher rebate. The fact that this PC1 is strongly correlated with air conditioners efficiency, project cost, and rebate amount suggests that this PC measure a cluster of household's investments in air conditioners with high efficiency. The PC2, on the other hand, shows no significant result in this analysis. That is, the most important information is explained by PC1.

Table 11. Lower-income housing units stage 3: Loading matrix between the variables of investments in air conditioners and the PC

	PC1	**PC2**
SEER	**0.85**	-0.38
Cooling Capacity	**0.50**	**0.86**
Rebate Amount	**0.71**	-0.17
Project Cost	**0.92**	0.01

3.3.2 Stage 3 - Highest-income tract housing units

In Table 12, the dataset of the 12 housing units in the higher income area is studied through correlation analyses. The strong correlation between efficiency and the air conditioner cooling capacity (0.77), and between project cost (0.60), and rebate amount (0.53) suggests that these households made high investments in air conditioners with high capacity and efficiency, which resulted in a higher rebate. The correlation between cooling capacity and efficiency (0.77) is higher from the 12 housing units from the lower-income housing (0.12). This implies that the efficiency of the air conditioning units purchased by households from higher-income housing was more proportional to their efficiency.

Table 12. Higher-income housing units (Stage 3): Result of the correlation analysis between the studied variables that describe the investments in air condition

	SEER	**Cooling Capacity**	**Rebate Amount**	**Project Cost**
SEER	**1.00**	**0.77**	**0.53**	**0.60**
Cooling Capacity	**0.77**	**1.00**	0.17	0.42
Rebate Amount	**0.53**	0.17	**1.00**	0.42
Project Cost	**0.60**	0.42	0.42	1.00

Figure 13 shows the results of the PCA for the 12 higher-income housing units and the variables for this study. The principal component analysis of the 12 highest income units shows a total of 83.4% of the variables explained by PC1 (62.1%) and PC2 (21.3%) (Figure 13 a and b). In Figure 13a, the 12 highest-income sample data scaled are presented. Figure 13b shows that efficiency, cooling capacity, and project cost have the highest magnitude. That is, the information from these variables is very well described by PC1. The PC2, on the other hand, shows no significant result in this analysis. That is, the most important information is explained by PC1.

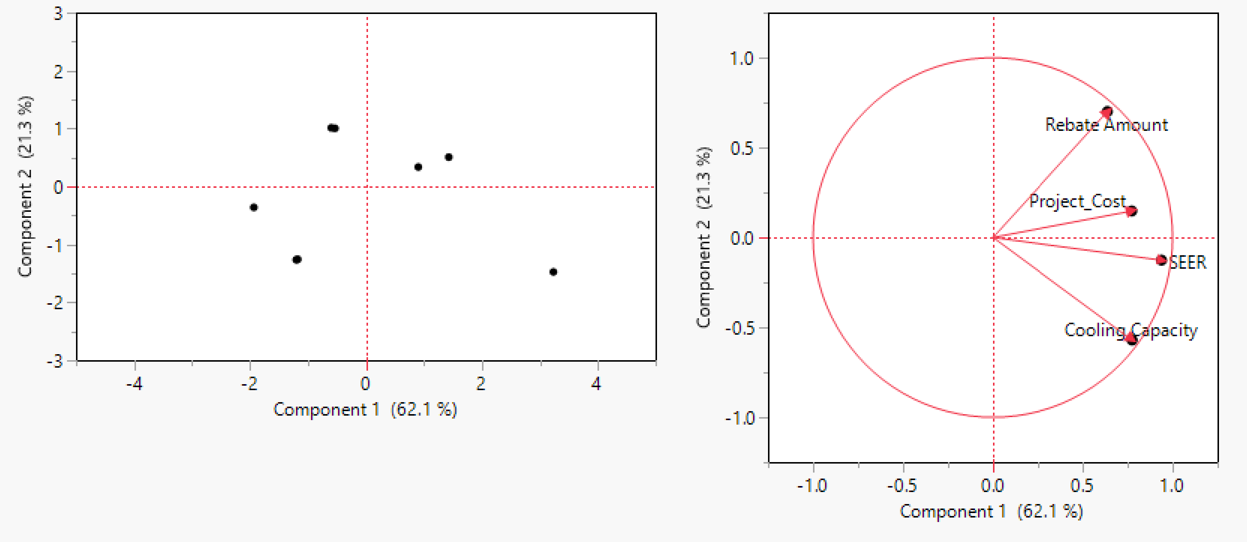


Figure 13**.** Higher-income (Stage 3): Principal component analysis: Score plot of households scaled on the left (a); loading plot on the right (b), for principal components one, with 62.1% of the variance explained and principal component two, with 21.3% of the variance
Note: The dots overlap, so only 8 can be seem

In Table 13, the correlation between the principal components and the variables influence is studied. The correlation result shows a very strong positive correlation between the PC1 and efficiency (0.94), and total cooling capacity (0.77), project cost (0.77), and the rebate amount (0.64). The increase in the value of one of these variables will also cause others to increase. That suggests that within this PC, households invest air conditioning systems with high efficiency, which also results in a higher rebate amount. Similar to PC1 from the lower-income region, housing units in this PC1 invest in air conditioning with high efficiency, which provides them with a higher rebate.

The correlation study for the PC2 shows a very strong positive correlation between the PC and the rebate amount (0.70) and a strong negative correlation with the cooling capacity (-0.57). Nevertheless, this result presents no significant findings, meaning most of the samples from the variables are best explained by PC1.

Table 13. Highest-income housing units stage 3: Loading matrix between the variables of investments in AC and the PC

	PC1	**PC2**
SEER	**0.94**	-0.13
Cooling Capacity	**0.77**	**-0.57**
Rebate Amount	**0.64**	**0.70**
Project Cost	**0.77**	0.15

CHAPTER 4. CONCLUSIONS

In this research, a combination of utility energy efficiency investment data and U.S. Census data is used to compare the energy-efficient technology investment behaviors of households located in Cedar Falls, Iowa. This includes 3,327 investments in insulation, air conditioners, furnaces, and efficient lighting made by 1,819 households from January 2013 to December 2016. The data is analyzed in three stages. These include, (Stage 1) a general analysis of investments in Cedar Falls, Iowa; (Stage 2) comparative analysis between the investments of the housing units in the lower- and higher-income tracts; and finally (Stage 3) a comparison of the investments of 12 households in the lower- and higher-income tracts with similar building characteristics. The findings suggest the following conclusions for each stage.

Stage 1: The overall dataset is studied. The goal at this stage was to understand the frequency households made investments, the type of technology they invested in most, and for heating and cooling, which may have impacted the decision to invest in a new, more efficient cooling system. The findings from the overall analysis of the Cedar Falls region include the following:

- Overall, efficient lighting accounts for 37% of all the rebate filled, followed by air conditioners (29%), furnaces (29%), and insulation (15%). Thus, when studying investments individually, lighting is the most popular technology for investments. However, when considering air conditioners and furnaces are both HVAC system components, combined HVAC system technologies are the most common investment.
- Of the four studied technologies, HVAC systems (air conditioners and furnaces) are the most expensive appliances to invest in and with the lowest rebate yet are the most common investment among those studied. The most common efficiency rating purchased ranged from 14-16 SEER, despite the availability of higher efficiency systems. This is not

surprising given that the incremental increase in SEER rating corresponded to a significant increase in costs with minimal increase in rebate. If higher SEER systems are the goal, this points to a potential need to more strongly incentivize higher SEER systems.

- Approximately 80% of all households invested in only one energy efficiency technology of the four studied. For these households, HVAC (air conditioners and furnaces) accounted for 74% (37% each) of technologies, and are thus most common. This is followed by LED lighting (18%) and insulation (10%).
- The HVAC system investments appear to be the most common “gateway” for households towards awareness of energy-efficient technologies and associated rebates supporting such investments. This is likely motivated by the requirement that HVAC systems be replaced when they break since most housing units in the U.S. are not designed to operate without a heating and cooling system comfortably, particularly in extreme heat and cold occurring in this region of the country. In 69% of cases, the HVAC systems being replaced with the energy-efficient systems were broken, thus even though HVAC systems are costly to replace, such systems are nearly mandatory. Therefore even though the rebate amounts are relatively low compared to the cost of the systems, for such high-cost systems, any amount of rebate appears to be beneficial.
- Efficient lighting was among the most common investments, and also represents nearly 100% of housing units that make more than six investments. However, only approximately 19% of the housing units with one investment purchased lighting as their first energy-efficient technology. Efficient lighting is inexpensive, easy to install, and does not require a contractor. In addition, the rebate was approximately 50% of the amount spent. It is also an investment that can be made multiple times, given the number of lighting fixtures

present in most housing units. These advantages may make an investment in efficient lighting attractive to households, thus supporting the commonality of this investment.

Stage 2: At this stage, the lower-income tract in the studied area, with 195 investments made by 97 units, and the higher-income tract, with 1,189 investment made by 660 units, were analyzed. We focused on understanding which technologies the lower and higher-income housing invested in most frequently, and the associated investment behavior. The analysis of the lower and higher income tracts within the studied area demonstrated a number of differences in investment behavior. These are as follows:

- The most common investment for housing units in the lower-income tract was HVAC systems (air conditioners and furnaces) at 61%, followed by insulation (32%) then lighting (29%). For higher-income tracts, the most common investments are in HVAC (air conditioners and furnaces) and light, followed by insulation. Housing units in the lower-income area were older (74 years) and smaller (147 m^2), thus given their age, their existing insulation may not be as efficient as the newer housing units located in the higher-income areas. This suggests insulation investments may be more common for housing units in lower-income areas because they more strongly benefit from this relatively inexpensive investment for energy savings and comfort compared to the overall newer housing units elsewhere.
- The correlation analyses between efficiency and rebate amount (0.67) suggest that lower incomes households invested in higher efficiency air conditioners and received a higher rebate amount compared to the higher-income area. The housing units' age appears to also contribute more strongly to an increase in air conditioning cooling capacity in lower-income housing units. This is not surprising giving that lower-income housing is older.

- The principal component analysis of housing units in the lower-income tract presents two different clusters of households.
- PC1 represents households that invested in equipment with high efficiency and cooling capacity and thus received a high rebate amount. These households also purchased air conditioners with higher cooling capacity, likely due in part of the age and thus inefficiency of the housing units.
- For PC2, the findings suggest lower-income housing units where both size and age may have contributed to the purchase of air conditioners with higher cooling capacity. These housing units' investments show no focus on the efficiency of the air conditioner, which resulted in low rebate amounts. These results may be justified by the high out of pocket investment incurred by the households to increase air conditioning efficiency. In addition, the Cedar Falls area experiences severe warm and cold weather yearly, so older housing units might perform poorly in isolating the indoor thermal comfort from the outdoor due to no or poor insulation. These may also have influenced the sizing of these units.
- The higher-income housing units correlation study suggests that these housing units may have invested in air conditioners with higher cooling capacity due to larger housing size. This may be justified by the fact that housing units in this tract are younger and larger than those in the lower-income tract.
- The main cluster of higher-income housing units, PC1, suggests that for these housing units, efficiency may not have been a priority. In addition, air conditioner cooling capacity and size of home show a strong correlation with PC1, meaning the size of home had the most influence on the cooling capacity. Compared to PC1 in the lower-income area, these households invested less in equipment with higher efficiency.

- The strong correlation of PC2 indicates that these households in the higher income area invested more in air conditioners with high efficiency, which also increased the rebate amount. The results also show that, contrary to PC1 in these higher-income tracts, the cooling capacity is not as influenced by the size of home. Instead, it is more influenced by the age of home, similar to PC1 from the overall lower-income tract. This similarity may suggest that these housing units are older.

Stage 3: In this stage, 12 housing units between 50 to 60 years old and 102 to 185 square meters in the lowest and higher-income tracts are compared. The main purpose was to study the investments in efficiency while limiting the impacts of both housing age and size. The overall findings are as follows:

- The analysis of the 12 homes in the lower-income tract shows that the investment households made are strongly correlated with efficiency. This may indicate that these households care about the efficiency of the equipment, or they used it as the means to increase the rebate amount or both. The weak correlation between the cooling capacity and the project cost suggests that when households purchased new equipment, they typically purchased air conditioners that had higher cooling capacity.
- The findings for PC1 in this stage suggest these lower-income households made larger investments in air conditioners with higher efficiency, and thus received a higher rebate amount. In the analysis of these 12 lower-income housing units, the investment pattern associated with the four studied variables is mostly explained by the PC1, and not PC2.
- For the 12 housing units in the higher-income area, the results present a strong correlation between air conditioners cooling capacity and efficiency, and between project cost and efficiency. That is, the higher the efficiency of the equipment they purchased, the higher

the cooling capacity it also typically had. Compared to the 12 housing in the lower-income area, however, the results show a higher correlation between the project cost and efficiency in the lower-income tract. This suggests that lower-income housing units may have spent more to increase the efficiency of the air conditioners. A comparison of the housing in the main cluster (PC1) of the overall datasets in the higher and lower-income areas also shows that PC1 from the lower-income housing invested more inefficiency. In addition, similar to the result of PC2 from the lower-income tract, there is not much information captured by PC2.

Of interest to note in these findings is the implications for the implementation, specifically, of energy efficient HVAC rebate programs, targeted at improving overall efficiency by replacing lower SEER, older HVAC units, with higher SEER newer units. The findings of this work indicate that, particular for the lower income areas, the age of the homes have a higher impact on the sizing of the new cooling system, compared to higher-income homes. These housing units are older, typically with higher infiltration rates, making them less energy efficient and thus requiring additional cooling and heating energy to operate at the same setpoint temperatures as more tightly constructed homes. By improving only the efficiency of air conditioner and/or heating systems, and in many cases increasing the cooling capacity, this does not necessarily result in making the homes more energy efficient. A larger system requires more power to operate, thus increasing energy use and operation costs. This highlights the importance of weatherization of homes prior to or during the replacement of the HVAC system in the older, typically more leaky homes. Completing both the replacement of the HVAC and weatherization would support the use of a new HVAC system of the same or smaller size, which could operate more efficiently under tighter conditions. Since the lower-income households may not be financially capable of paying for such additional costs, consideration of low-cost weatherization efforts when completing other energy efficiency retrofits may be beneficial to consider to benefit both the utility and the homeowner.

4.1 Limitation and Future Work

The findings of this research are subject to limitations that could help better understand households' investment behaviors and help improving energy efficiency policies and energy efficiency rebate programs. The results are based on statistical analysis from data collected in Cedar Falls, IA. However, further data collection on households' preferences could be performed to help validate some of the findings in this work, as well as to better understand the motivations for such trends. In addition, the households' sentiments about energy efficiency, in comparison with other opportunities, could also be important to study.

The dataset used in this research includes information collected for 4 years. However, appliances considered in this study can last for ten or more years, according to manufacturers. Future research could be beneficial to support a long period of data and a larger dataset. In addition, future research could analyze the households' expectations versus the realized energy-saving and how it impacts their motivation for new investments. We found a high percentage of households that changed the system only after it was broken (65%). Understanding the implication of these results on households' decisions to retrofit the cooling system may help to better design energy-efficient policies and suggest the right time to change air conditioning systems.

REFERENCES

Attari, S. Z., M. L. Dekay, C. I. Davidson, and W. Bruine De Bruin (2010). "Public Perceptions of Energy Consumption and Savings." *Proceedings of the National Academy of Sciences* 107, no. 37: 16054–59. https://doi.org/10.1073/pnas.1001509107.

Brown, Rich, Sam Borgeson, Jon Koomey, and Peter Biermayer. "U.S. Building-Sector Energy Efficiency Potential," 2008. https://doi.org/10.2172/941430.

Cetin, K.s., P.c. Tabares-Velasco, and A. Novoselac. (2014) "Appliance Daily Energy Use in New Residential Buildings: Use Profiles and Variation in Time-of-Use." *Energy and Buildings* 84: 716–26. https://doi.org/10.1016/j.enbuild.2014.07.045.

Clinch, J. Peter, and John D. Healy. "Cost-Benefit Analysis of Domestic Energy Efficiency." *Energy Policy*, vol. 29, no. 2, 2001, pp. 113–124., doi:10.1016/s0301-4215(00)00110-5

Dietz, T., G. T. Gardner, J. Gilligan, P. C. Stern, and M. P. Vandenbergh. (2009) "Household Actions Can Provide a Behavioral Wedge to Rapidly Reduce US Carbon Emissions." *Proceedings of the National Academy of Sciences* 106, no. 44: 18452–56. https://doi.org/10.1073/pnas.0908738106.

Enteria, N., Mizutani, K. "The role of the thermally activated desiccant cooling technologies in the issue of energy and environment." *Renew Sustain Energy*. May 2011 https://doi.org/10.1016/j.rser.2011.01.013

Frederiks, E. R., Karen S., and Elizabeth V. H. (2015). "Household Energy Use: Ap-plying Behavioural Economics to Understand Consumer Decision-Making and Behaviour." *Renewable and Sustainable Energy Reviews* 41: 1385–94. https://doi.org/10.1016/j.rser.2014.09.026.

Gillingham, K., Newell, R.G., Palmer, K., 2009. Energy efficiency economics and policy. Annual Reviews of Resources Economics 1, 597–619.

Ha H., and Swinder J., (2012) "Predicting Consumer Intentions to Purchase Energy-Efficient Products." *Journal of Consumer Marketing* 29, no. 7: 461–69. https://doi.org/10.1108/07363761211274974.

Ian T. J. and Jorge C. "Principal component analysis: a review and recent developments" 13 April 2016 https://doi.org/10.1098/rsta.2015.0202

Jaffe, Adam B., Richard G. Newell, and Robert N. Stavins. "Economics of Energy Efficiency." *Encyclopedia of Energy*, 2004, 79–90. https://doi.org/10.1016/b0-12-176480-x/00228-x.v

Jaffe, Adam B., and Robert N. Stavins. "The Energy-Efficiency Gap What Does It Mean?" *Energy Policy* 22, no. 10 (1994): 804–10. https://doi.org/10.1016/0301-4215(94)90138-4.

Jessel, Sonal, Samantha Sawyer, and Diana Hernández. “Energy, Poverty, and Health in Climate Change: A Comprehensive Review of an Emerging Literature.” *Frontiers in Public Health* 7 (2019). https://doi.org/10.3389/fpubh.2019.00357.

Kontokosta, Constantine E., Reina Vicente, Bonczak Bartosz. “Energy Cost Burdens for Low-Income and Minority Households in Six U.S. Cities: Evidence from Energy Benchmarking and Audit Data.” *SSRN Electronic Journal*, 2018. https://doi.org/10.2139/ssrn.3295367.

Lopes, M., Antunes, C., & Martins, N. (2012). Energy behaviors as promoters of energy efficiency: A 21st century review. *Renewable and Sustainable Energy Re-views, 16*(6), 4095-4104. doi:10.1016/j.rser.2012.03.034

Nielsen, L. (1993) "How to Get the Birds in the Bush into Your Hand." *Energy Policy* 21, no. 11: 1133–44. https://doi.org/10.1016/0301-4215(93)90263-f.

Poortinga, Wouter, Shiyu Jiang, Charlotte Grey, and Chris Tweed. “Impacts of Energy-Efficiency Investments on Internal Conditions in Low-Income Households.” *Building Research & Information* 46, no. 6 (2017): 653–67. https://doi.org/10.1080/09613218.2017.1314641.

"""ResStock - NREL""." Accessed June 16, 2020. https://resstock.nrel.gov/. Retrieved from https://resstock.nrel.gov/dataviewer/efs_v2_base#building-characteristics.

Santamouris, M, N Papanikolaou, I Livada, I Koronakis, C Georgakis, A Argiriou, and D.n Assimakopoulos. "On the Impact of Urban Climate on the Energy Consumption of Buildings." *Solar Energy* 70, no. 3 (2001): 201–16. https://doi.org/10.1016/s0038-092x(00)00095-5.

Steg, L. (2008). Promoting household energy conservation. Energy Policy, 36(12), 4449-4453. doi:10.1016/j.enpol.2008.09.027.

The National academies press. "Americas Energy Future: Technology and Transformation." *Choice Reviews Online*, vol. 47, no. 12, Jan. 2009, doi:10.5860/choice.47-6818. https://www.nap.edu/read/12091/chapter/8

US Census Bureau. """"American Community Survey (ACS""")." The United States Census Bureau, May 11, 2020. Retrieved from https://www.census.gov/programs-surveys/ahs/data.html_00_PY_D1&tid=ACSST1Y2013.S1101&cid=S0101_C01_001E&y=2013

US Dept. of Energy, (2019). "Annual Energy Outlook". United States Energy Information Administration, Washington, DC, USA, DOE/EIA-0383,.

US Dept. of Energy. (2010). "Customer incentives for energy efficiency through program offerings". A resource of the National Action Plan for Energy Efficiency. Washington DC.

U.S. Energy Information Administration. "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis," 2015. Accessed June 22, 2020. Retrieved from https://www.eia.gov/consumption/residential/data/2015/hc/php/hc10.1.php.

U.S. Energy Information Administration. "U.S. Energy Information Administration - EIA - Consumption & Efficiency - U.S. Energy Information Administration (EIA). Accessed June 22, 2020. Retrieved from https://www.eia.gov/consumption/residential/data/2015/c.

U.S. Energy Information Administration, Annual Energy Outlook DOE/EIA-0383, US Department of Energy, Washington, DC, USA, 2019.

Vigneau, E, et al. "Segmentation of a Panel of Consumers Using Clustering of Variables around Latent Directions of Preference." *Food Quality and Preference*, vol. 12, no. 5-7, 2001, pp. 359–363., doi:10.1016/s0950-3293(01)00025-8.

Vigneau, E, et al. "Segmentation of a Panel of Consumers Using Clustering of Variables around Latent Directions of Preference." *Food Quality and Preference*, vol. 12, no. 5-7, 2001, doi:10.1016/s0950-3293(01)00025-8.

Wilson, E., Craig, C., Scott, H., Joseph R., and Jeff M. "Electric End-Use Energy Efficiency Potential in the U.S. Single-Family Housing Stock." National Renewable Energy Laboratory, January 2017. https://doi.org/10.2172/1339938.

Zhao, T., Bell, L., Horner, M. W., Sulik, J., & Zhang, J. (2012). Consumer responses towards home energy financial incentives: A survey-based study. Energy Policy, 47, 291-297. doi:10.1016/j.enpol.2012.04.070