Smart thermostats in rental housing units: Perspectives from landlords and tenants

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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DEDICATION

I would like to dedicate this work to my wonderful family who have always believed in me.

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NOMENCLATURE

HBI	Human-Building Interaction
HEMS	Home Energy Management Systems
HVAC	Heating, Ventilation, and Air Conditioning
IoT	Internet of Things
L	Landlord
LTR	Long-Term Rental
ST	Smart Thermostat
STR	Short-Term Rental
T	Tenant

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ABSTRACT

Rental properties make up approximately 37% of the U.S. residential building stock and are responsible for 23% of the total energy consumption in this sector. Although this market has great potential for energy efficiency, implementing energy savings measures in this market face numerous challenges. In particular, one of the main challenges cited is the split incentive, limiting the potential motivation of rental property owners and tenants to invest in energy efficient technologies. Smart thermostats have gained substantial interest and adoption in the past decade, and have been the subject of numerous studies in recent years. However, their adoption and use in the context of the rental housing market has not been considered. In this study, reviews posted on an online retailer's website (Amazon.com) were used as an unstructured source of information to evaluate the perspectives of landlords and tenants towards smart thermostats. In total, 31,790 reviews were collected for 14 commercially-available smart thermostats, and from these, 173 reviews were identified to be directly associated with rental units. These selected reviews were then analyzed and categorized based on the unique opportunities and challenges that were expressed. The majority of reviewers focused on usability aspects and expressed an interest in the advanced remote control functions of their purchased devices. Furthermore, our findings indicated that occupancy pattern learning capabilities were not of particular interest among this user group as compared to the non-rental property related reviews. These findings can inform product manufacturers and policymakers in their future interactions with stakeholders in the rental housing market and potentially increase adoption and hence, adoption rate of energy efficiency measures.

CHAPTER 1. INTRODUCTION

Residential energy consumption for space heating and cooling, lighting, appliances, and other energy services is a key driver of energy demand and a major contributor to carbon dioxide emissions worldwide. According to the U.S. Energy Information Administration (EIA), 21% and 37% of the U.S. total energy and electricity consumption in 2019 were attributed to the residential sector, which includes homes that may be owner-occupied or rented by tenants[1]. In the residential rental sector, which makes up approximately 37% of housing units in the U.S., the per unit area energy consumption and expenditures were 134.7 kWh/m^2-yr and 11.9 USD/m^2-yr, respectively. These are considerably higher than the average energy consumption and expenditures in the U.S. residential sector overall (121.1 kWh/m^2-yr and 9.9 USD/m^2-yr respectively) [2]. These higher rates per unit area of living space suggest that the residential sector, in general and the rental sector in particular, present a strong opportunity for accelerating the energy transition to a low-carbon future. However, the rental property market has also proven to be among the most challenging sectors in which to successfully implement energy savings measures [3–5].

Accordingly, the gap between potential and realized energy saving, commonly referred to as the *energy efficiency gap*, is particularly significant with residential rental properties [3]. A commonly discussed cause contributing to this gap is a principal-agent problem best known as the "split incentive" [3,6,7]. Split incentives are defined as when the flow of investments and benefits are not rationed well among stakeholders, impairing investment decisions [8]. In the context of the rental housing market specifically, the split incentive phenomena occurs when neither the homeowner nor the tenant, alone, have the motivation to improve building energy performance [3]. According to [9], split incentive issues can be categorized into two broad types.

First, (1) split incentive problems are most well-known as a split between landlord and tenant. In this situation, a landlord (agent) purchases and supplies all of the components to support an energy-efficient retrofit to a rental property. Their incentive is to supply these at the lowest possible cost (i.e. not the highest efficiency) because they do not pay the energy utility bills. These bills are paid for by the tenant (or principal), who thus has a strong incentive to increase efficiency, but no control over the means to do so since they do not own the property. The second (2) type of split incentive is a temporal split incentive. In this situation, the agent does not know how long they will reside in their current location, thus if they move relatively soon, a high upfront capital cost investment in efficiency is risky. This can occur in rental housing or owner-occupied housing scenarios.

Asymmetric information may also lead to sub-optimal energy efficiency standards in the rental housing market [5,10,11]. In the case of unobservable (i.e. hidden from view) energy-related technologies, such as wall and attic insulation, the market value of a property will not accurately reflect the value of the investment for prospective tenants [5,12]. Even with seemingly observable technologies, such as efficient windows and appliances, the specific thermal and energy consumption information required to form energy and cost expectations may only be available to landlords [5]. Without this information, tenants are unable to make informed decisions when deciding which housing unit to rent. The rental market will, therefore, not provide an economic return on efficiency investments [12]. As [5] discussed, this asymmetric information introduces a 'lemons' problem which refers to the market and pricing effects of information asymmetries between buyers and sellers [13,14]. This can negatively impact the rental market in a region, as prospective tenants searching for a property will assume an average efficiency level across the available properties, and as a result will not choose more energy

efficient properties. Similarly, landlords will not have incentive to invest in energy efficient technologies as this does not result in increased rents.

While previous research projects (e.g. [4,15]) have investigated the opportunities and barriers for higher energy efficiency investments in the rental housing market, emerging Home Energy Management Systems (HEMS) have the potential to unlock new opportunities to increase energy efficiency, as HEMS can provide an unprecedented level of energy use information and insights to inform efficiency investments. These and other emerging smart home technologies may present both opportunities and obstacles for adoption in the rental property market. As these technologies emerge, further research is needed to better understand such obstacles and opportunities.

The focus of this study is on the adoption of smart thermostats, also referred to as intelligent thermostats, self-programming thermostats, neurothermostats, communicating thermostats, or autonomous thermostats, in various literature. Broadly speaking, the definition of a smart thermostat depends on the proposed model and the targeted functionality [16]. Some literature which uses “communicating thermostats”, require the device to be internet-connected and have the ability to be remote-controlled. Others include the ability of the thermostat’s operation to be adjusted in real-time based on input sensor information (occupant presence sensors, meteorological weather station, GPS system, etc.). Others include features that, through learning algorithms, learn the living habits of building occupants to optimize the heating, ventilation, and air conditioning (HVAC) schedule for energy savings and occupant comfort. In essence, unlike the programmable thermostat that adjusts the temperature according to a pre-defined program, a smart thermostat adapts its operation depending on the user [16–18].

Smart thermostats have been commercially available for nearly a decade, with an estimated adoption rate of 13% among the roughly three-quarters of U.S. households who are believed to have broadband service in their home in 2020 [19,20]. Among the various smart technologies on the market today, these are among the most commonly adopted in the residential market. Considering that, depending on the climate zone, approximately 80-100% of U.S. residential buildings are equipped with HVAC systems with thermostats, the proportional share of smart thermostats is relatively low, but is expected to continue to grow [2,21]. While the majority of previous studies (e.g. [22–24]) on smart thermostats have focused on the performance of these devices, the main challenge with translating smart thermostats' energy saving potential to actual savings lies in this relatively low penetration rate of these devices [18,25]. Moreover, even when opportunities and barriers related to further adoption of smart thermostats are studied, the majority of previous research is focused on the owner-occupied units. Such research does not consider the rental housing market which, as previously stated, makes up a large portion of the housing stock (and its associated energy consumption). Accordingly, a study of the adoption of smart thermostats in this rental market can help identify the opportunities and barriers to further adoption in this sector which, to the best of our knowledge, has not been investigated previously.

Accordingly, the objective of this study is to assess the motivation and sentiment of current buyers and users of smart thermostats in rental properties by analyzing reviews of smart thermostats on the online retail website Amazon.com. Fourteen different popular smart thermostats available through this site were selected and the associated reviews for these devices were compiled. The online reviews dataset (N = 31,790) were then divided based on the housing tenure status. Reviews related to the rental units were then both qualitatively and quantitatively

evaluated, including reviewers' sentiments (positive or negative) associated with each of eight pre-defined topics. The use of an online review dataset had a number of advantages over more conventional survey methods used in previous studies. These include the following: (1) online reviews were free and publicly accessible; (2) the sample size was larger than what most laboratory or field test populations are able to achieve; and finally (3) since there was no questionnaire involved in collecting online reviews, the reviewers discussed what they found relevant to share about a device, limiting bias in responses. Accordingly, an online review dataset may help to capture the reality of user perceptions towards smart thermostats without impacting users' responses by asking pre-defined questions. Such advantages have led to the publication of a number of recent related studies which utilize this method of data collection, including indoor environmental quality in short-term rentals, Airbnb market analysis, and user attitudes and perceptions towards smart thermostats [18,26–28].

The results of this study provide insight into the relative interests and cited benefits, both energy and non-energy related, of smart thermostats in the rental housing market. These results also work toward determining the motivational factors for the purchase of these devices by stakeholders in this market. The latter can be used to inform targeted efforts to further encourage adoption of more energy-efficient technologies in rental housing units, and hence increase the overall efficiency of the residential building stock.

CHAPTER 2. METHODOLOGY AND DATA

This section provides details of the different datasets used in the analysis, the data collection and refinement procedures, and the characteristics of each dataset. Online reviews were obtained from the online retailer's website (Amazon.com) and analyzed to measure current users' perceptions of the benefits, risks, and design attributes of smart thermostats, as well as general issues of consumer confidence in smart thermostats among landlords and tenants. Overall, the data collection, refinement, and analysis procedure included the following four general steps: (1) product selection, (2) scraping of online reviews posted for the selected products from the online retailer's website, (3) refinement of the acquired review dataset based on its relevance to the rental housing market, and finally (4) qualitative and quantitative analysis of the reviewers' sentiments towards smart thermostats. In the next sections, each of these steps is described in further detail.

Product Selection

The smart thermostats used for analysis in this study were selected based on the 'Amazon's Top Selected Products and Reviews List' [29]. These products (Table 1) include devices from manufacturers that are identified as dominant market players based on information from the U.S. Department of Energy [30].

Table 1. List of Selected Smart Thermostats Utilized for Online Review Data Collection

#	**Brand**	**Product Name**	**Item Model Number**
1	Google	Nest Learning Thermostat (3rd gen)	T3007ES
2	Honeywell Home	Honeywell Wi-Fi Smart Color Thermostat	RTH9585WF1004/W
3	Ecobee	Ecobee4	EB-STATE4-01
4	Ecobee	Ecobee3 lite Smart Thermostat (4th gen)	EB-STATE3LT-02

Table 1 Continued

#	**Brand**	**Product Name**	**Item Model Number**
5	Emerson	Sensi Wi-Fi Smart Thermostat (2nd gen)	ST55
6	Honeywell	Lyric T5 Thermostat	RCHT8610WF2006/W
7	Emerson	Sensi Touch Wi-Fi Smart Thermostat	ST75
8	Honeywell Home	Honeywell Wi-Fi Smart Touchscreen Thermostat	RTH9580WF1005/W1
9	theSimple	theSimple thermostat	-
10	Honeywell Home	Honeywell Wi-Fi Touch Screen Programmable Thermostat	TH9320WF5003
11	Emerson	Sensi Wi-Fi Smart Thermostat	1F87U-42WF
12	Mysa	Mysa Smart Thermostat for Electric Baseboard Heaters	-
13	Honeywell Home	Honeywell Wi-Fi Color Touch Screen Programmable Thermostat	TH9320WF5003
14	Johnson Controls	GLAS Smart Thermostat	SIO2-10000

All selected thermostats have similar features, including Wi-Fi connectivity, programmable 7-day flexible scheduling, a digital display, and a smart phone application to support remote control, checking of system operations, and facilitating thermostat programming capabilities [30]. In addition, they are generally designed to be used for control of a single zone residential style HVAC system, including a heat pump or air conditioner/furnace combination. These two main systems are the most commonly used type of HVAC system in residential buildings in the U.S. [2]. Some of the selected smart thermostats included additional features, such as occupancy sensing and learning algorithms, geofencing (which provides a signal to a learning algorithm, when a mobile device is within a defined radius of dwelling [31]), alerts for extreme indoor temperatures, touch screens, and the ability to connect to remote temperature sensors placed in different locations within a home. These variations in features and capabilities

were unavoidable given the current smart thermostat market. Generally however, regardless of these variations, all of the selected thermostats can be classified as smart thermostats and have an average rating of at least 3 out of a 5-point scale on the online retailer's website (Table 2).

Review Scraping

In order to analyze users' interests and opinions of smart thermostats, review text and ratings were extracted from *Amazon.com* using the web scraping R package *rvest* in September 2017, February 2018, and August 2019 [32,33]. In total, 31,790 product reviews were collected for the 14 smart thermostat products. Table 2 represents a summary of the collected dataset for the selected smart thermostats, including their list prices, the number of reviews acquired for each, their average overall ratings, and the associated standard deviation at the time of data collection.

Table 2. Summary of the Smart Thermostats Included in the Compiled Online Review Dataset

Product ID	**List Price (2019 USD)**	**Number of Reviews**	**Average Rating (out of 5)**	**Standard Deviation**
Smart Thermostat A	$249.00	18,585	4.59	1.07
Smart Thermostat B	$135.00*	870	4.13	1.42
Smart Thermostat C	$249.00	1,836	3.94	1.47
Smart Thermostat D	$169.00	1,233	4.16	1.40
Smart Thermostat E	$129.99	2,107	4.35	1.28
Smart Thermostat F	$149.99	1,098	3.41	1.70
Smart Thermostat G	$144.39*	1,147	4.41	1.22
Smart Thermostat H	$99.00*	3,160	4.06	1.44
Smart Thermostat I	$134.00*	20	4.15	1.42
Smart Thermostat J	$136.99*	676	4.19	1.38
Smart Thermostat K	$137.01*	62	4.06	1.48

Table 2 Continued

Product ID	List Price (2019 USD)	Number of Reviews	Average Rating (out of 5)	Standard Deviation
Smart Thermostat L	$139.00*	296	4.53	1.02
Smart Thermostat M	$144.17*	594	4.23	1.35
Smart Thermostat N	$249.00	106	3.78	1.44
Total	-	31,790	4.39	1.25

* List Price was not available at the time of data collection, sale price on Amazon.com was recorded instead.

Dataset Cleaning and Refinement

The dataset (n = 31,790) was first cleaned and refined to improve the analysis. The cleaning procedure included the following three steps:

1. Removal of reviews written in non-English languages;
2. Removal of stop words, which often refers to non-meaningful common words such as “the”, “a”, and “my”, and non-meaningful punctuation marks;
3. Removal of irrelevant punctuation marks. This includes punctuation marks such as “!”, and “?” used multiple times in a consecutive manner (as a form of exaggeration), punctuation marks used to construct a pictorial representation of an image (also known as emoticons), and apostrophes used as a form of abbreviation;

The first step was deemed necessary since some users provided reviews in languages other than English. Non-English words cannot be interpreted using the same methodologies followed for English-based text analysis and translating from other languages to English might change the sense and emotions expressed in them [34]. Therefore, non-English reviews were removed from the original dataset of reviews. In the second step, stop words were also removed

from the remaining reviews, since their inclusion in textual analysis provides unnecessary information and clutter in the dataset. This was completed using the *tm* package in R, as also used by [35], and developed by [36]. For the irrelevant punctuation marks (Step 3), while these punctuation marks are a possible means to express a sentiment, they are not used in the text analysis technique used in this work and could be studied further in future efforts. In addition, words with an apostrophe to indicate possession, omission, and pluralization were converted to words without an apostrophe. For example, “didn't” was changed to “did not”.

This cleaned review dataset included reviews written by all users and does not differentiate based on their status of housing tenure (owner-occupied or renter). Therefore, as a final step and in order to exclude any reviews that are not associated with rental housing units, a refinement process was defined and applied to this review dataset (Figure 1).

First, an initial keyword (“rent”) was used in the search process and a limited number of reviews (n = 152) that included this keyword or any of its related forms (Table 3) were selected as the training dataset. Then, a list of all the unique root words in this training dataset was prepared and a complementary set of related keywords (Table 3) was selected from the list to be used in another round of refinement within the complete review dataset. This second round of refinement resulted in the selection of 1,266 additional reviews for analysis. Finally, the two refined datasets were combined (n = 1,418) and reviewed manually to determine if their reviews' contents are related to the topic of study. This step resulted in the exclusion of 1,245 reviews from the refined dataset and generated the “rental-related dataset”, which included 173 reviews in total. While this is a limited number of reviews relative to the larger dataset, such a large number of detailed reviews specifically for rental properties’ use of smart thermostats has not been compiled elsewhere and is thus worthy of investigation.

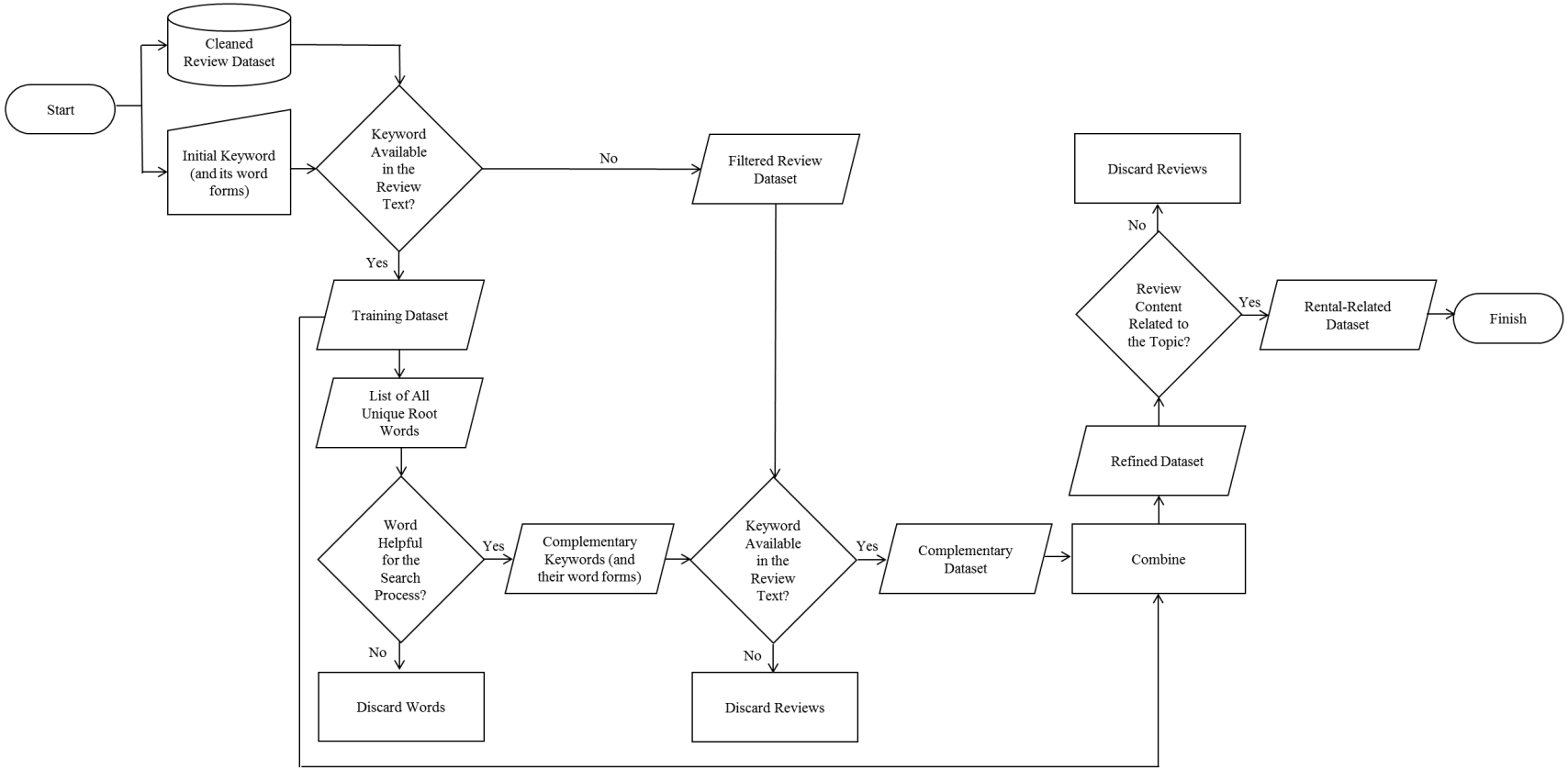

Figure 1. The Refinement Procedure Followed for Identifying the Rental-Related Reviews from the Cleaned Online Reviews Dataset

Table 3. Keywords and Related Word Forms within the Compiled Online Reviews Dataset

PIE Lemma*	**Related Word Forms Available in the Review Dataset**
rente	rent, rental, rentals, rented, renter, renters, renting, rents
aer-	airbnb
com-	condo, condos
ghos-ti-	guest, guests
aik-	homeowner, homeowners, owner, owners
lendh-	landlord, landlords
pro-	property, properties
sed-	resident, residents
sta-	stay, stayed
ten-	tenant, tenants
vac-	vacation

* The related root words were identified with the help of the Online Etymology Dictionary [37].

Sentiment Analysis and Tagging

The review content was first analyzed to determine if the review was specifically related to short-term rental units, which most commonly refers to a rental of fewer than thirty consecutive days [38]. Unlike a lease, which can be classified as a long-term rental, a short-term rental does not involve the grant of an estate in the land being rented [39]. Rather, a short-term rental is a license, which is an agreement which entitles the renter to use the property where the management and control is retained by the owner [40]. While short-term rental of residential property is not a new practice, never before has it been so ubiquitous throughout the U.S. and the world [38,41]. Previous studies (e.g. [38,41]) suggest that the availability of online peer-to-peer home-sharing platforms, such as Airbnb and Vrbo, has helped increase the frequency of this type

of rental. It was important to distinguish if a review was concerned with a short-term rental stay, as the stakeholders in that sector might have had differing motivations and concerns when compared to those dealing with long-term rental agreements.

Next, the reviewers were categorized based on their role, either as a landlord or a tenant (also referred to as renter or guest for short-term rentals). This distinction supported better identification of each stakeholder's sentiment towards smart thermostats and the ability to link their opinions with known characteristics and motivations of their representative group. Lastly, the dataset content was reviewed and eight topic categories were established based on themes of specific features or elements of the thermostats in the dataset. These topic categories included: Aesthetics (X_1), Thermal Comfort (X_2), Controls & Privacy (X_3), Energy & Utility Bill Savings (X_4), Hardware Installation & Compatibility (X_5), Learning Capabilities (X_6), Software Setup & Usability (X_7), and Upfront Cost (X_8). Following the establishment of these topic (aspect) categories, each review was divided into one or more independent clauses. Then each clause was fitted into one of the previously mentioned eight topic categories using MAXQDA v. 2018 [42]. Finally, the sentiment of the review clauses towards the topic it was tagged with was determined to be either positive (P) or negative (N).

CHAPTER 3. RESULTS

This section presents the results by applying sentiment analysis to the dataset of 173 online reviews for smart thermostats. Examples from the data are added to the text for improved clarity. Each referenced review is designated using a smart thermostat device identifier (STa to STn) corresponding to the device designations in Table 2, a review number, a "STR" or "LTR" tag referring to "short-term rental" and "long-term rental" respectively, and an "L" or "T" identifier which determines if the review is written by the "landlord" or "tenant". For example, STe-007006-STR-L is the 7006th online review posted for Smart Thermostat E and is written by a short-term rental housing unit landlord. No edits were made to the reviewers' comments, even when typos were present. First, the quantitative overview of the review dataset is discussed, followed by a qualitative analysis of the content, with the goal of better understanding the motivational factors and sentiments of smart thermostat users in the rental housing market.

Overview of the Review Dataset

In this section, the general characteristics of the dataset that contains those reviews which are identified to be related to the rental units are first compared to the overall dataset of reviews. The former dataset, referred to as the "*rental-related reviews*" dataset, contains 173 reviews posted by landlords or tenants of either short-term or long-term rental housing units. The latter overall dataset contains a total of 31,790 reviews posted for the 14 selected smart thermostats and does not differentiate based on the housing tenure status of the reviewer. Hereafter, this second dataset is referred to as "*all reviews*".

Of the reviews available (Figure 2), the two datasets generally have the same distribution of reviews for each of the 14 selected devices. The small differences between the two datasets in this comparison appeared to be slightly correlated with the price of these devices. As shown in

Figure 3, in the *rental-related reviews* dataset, there is a slightly larger proportion of reviews of devices that fell into the mid-price range ($100-$200), while the devices that fell into the high- (more than $200) and low- (less than $100) price range were comparatively more common with reviewers in the *all reviews* dataset. Previous studies (e.g. [43,44]) suggested that stakeholders in this market, when compared to their counterparts in the owner-occupied group, generally tend to under-invest in energy efficiency technologies. Moreover, even when an investment is made by a stakeholder in this market, it is common for the relative purchase price to be important factor of consideration, which might result in investment inefficiencies in terms of performance [45]. Therefore, this observation aligns with the findings of previous studies and confirms that for the stakeholders in the rental market, the purchase price point is of interest. Another consideration is that the devices that fell into the high-price range have a number of added capabilities that might not be as desirable for users in this group. As discussed in upcoming sections, the *rental-related reviews* appear to be more interested in the remote control and connectivity functions of the thermostats and showed minimal interest in the more advanced features such as geofencing or learning capabilities, given the little number of reviewers that discussed these features. Therefore, investing in high-priced devices might have been less appealing to this group, as their needs were met with the mid-price devices.

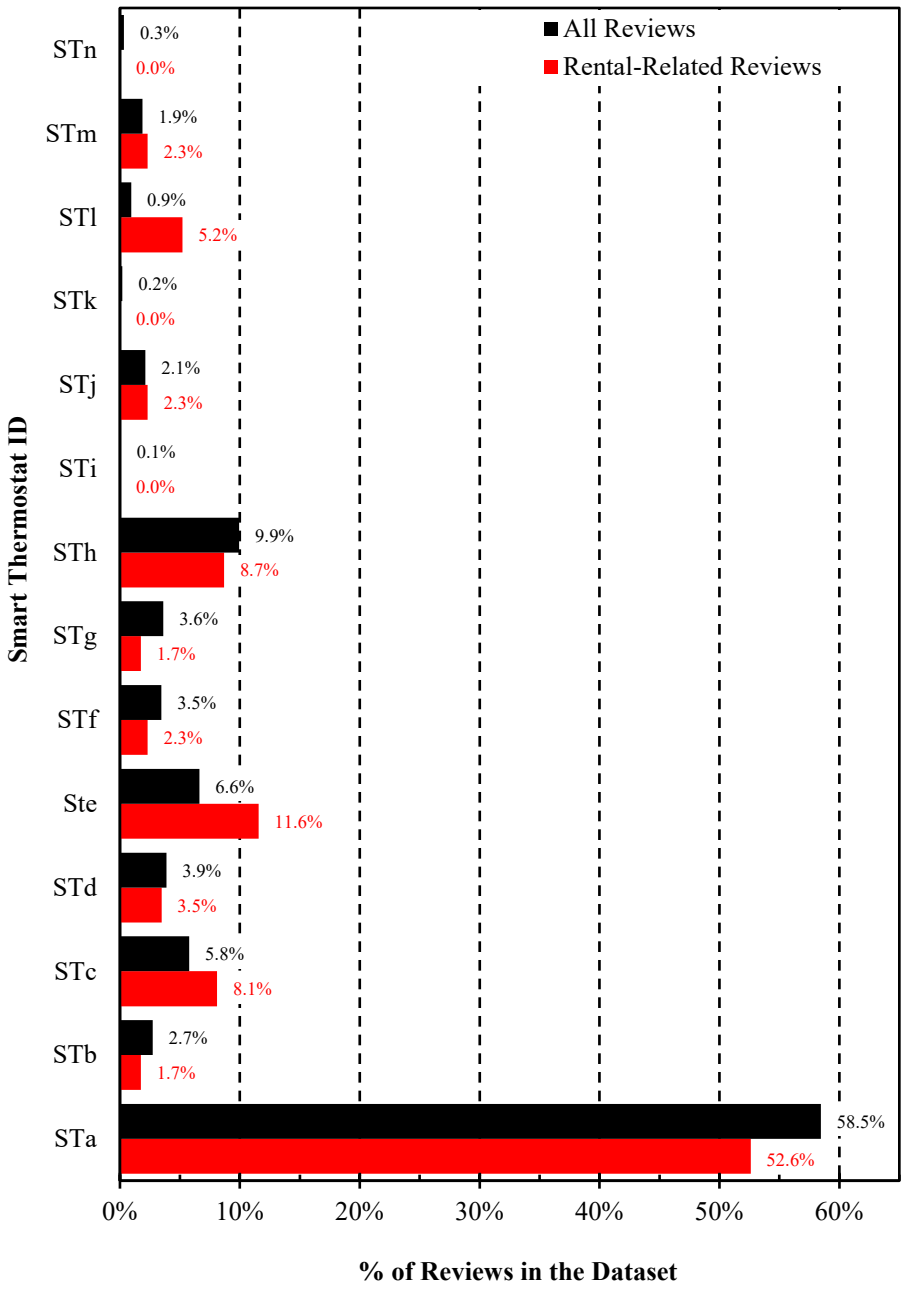

Figure 2. Percentage of Reviews in the Overall and Rental-Related Review Datasets for Each of the Studied Smart Thermostats (Note: STx = Smart Thermostat x, where x is identifier of the specific thermostat)

Figure 3. Percentage of Reviews in the Overall and Rental-Related Review Datasets Divided into Those Associated with Thermostats in Three Price Ranges

Further comparison of the two datasets found that the reviewer ratings generally showed similar characteristics (Figure 4). The numerical star ratings for online customer reviews range from one to five stars. In this rating system, a low rating (one star) indicates an extremely negative view of the product, a high rating (five stars) reflects an extremely positive view, and a three-star rating reflects a moderate view [46]. The star ratings are also a reflection of attitude extremity, that is, the deviation from the midpoint of an attitude scale [47]. Past research has identified two explanations for a midpoint rating, such as three stars out of five [48,49]. A three-star review could (1) reflect a truly moderate review (indifference), or (2) a series of positive and

negative comments that cancel each other out (ambivalence). In either case, a midpoint rating has been shown to be a legitimate measure of a middle-ground attitude [46]. As shown in Figure 4, the majority of the reviews in both datasets (75.3% and 72.3% for the *all reviews* and *rental-related reviews* datasets, respectively) belonged to the 5-star category. This suggests that the majority of the reviewers in both datasets have extreme positive views of the purchased devices. This observation is not surprising, given that the 14 selected products for this study all belong to the 'Amazon's Top Selected Products and Reviews List' and nearly all of them had an average star rating of 4 out of 5 with a relatively low standard deviation between the ratings for each device (Table 2).

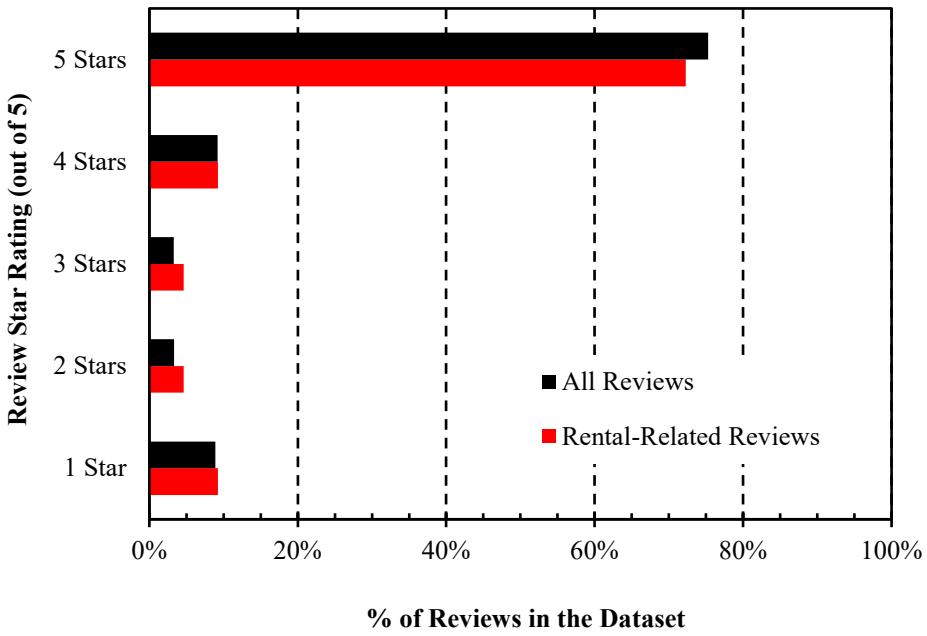

Figure 4. Percentage of Reviews in the Overall and Rental-Related Review Datasets Based on Their Associated Star Ratings

The accumulation of reviews in both datasets also shows a similar trend over time (Figure 5). In the *all reviews* dataset, the first registered reviews were posted in early 2014. Similarly, the first review associated with the rental units (*rental-related reviews*) is also posted in July 2014.

This suggests that the use of these devices in the rental market occurred at a similar time to their adoption in the owner-occupied housing market. The timeline of online news and media material covering the adoption of smart thermostats in rental units further agrees with this assumption [50–52]. For instance, in September of 2014, Nest, one of the major players in the smart thermostats market, partnered with Airbnb to provide selected hosts with free thermostats to install in their apartments and/or homes [52–54]. Media outlets suggested that this partnership was a way for the thermostat provider to reach more customers [52]. This suggests that the major players in the smart thermostats market may already have been aware of the potential of their devices for the rental housing market and interested in expanding their services to the users in this group as early as 2014.

For the first two years of review accumulation past this date, the number of thermostat reviews slowly increased in both owner-occupied and rental user groups (Figure 5). Assuming the number of reviews is a proxy for popularity and thus level of adoption of the devices, their adoption rapidly increased in the third year, and all years thereafter. Since the popularity trend seems to generally follow the same pattern for both user groups, one can generalize the predictions of increased smart thermostat adoption to the rental housing market and expect that the adoption rates will continue to increase in this sector in the future [55].

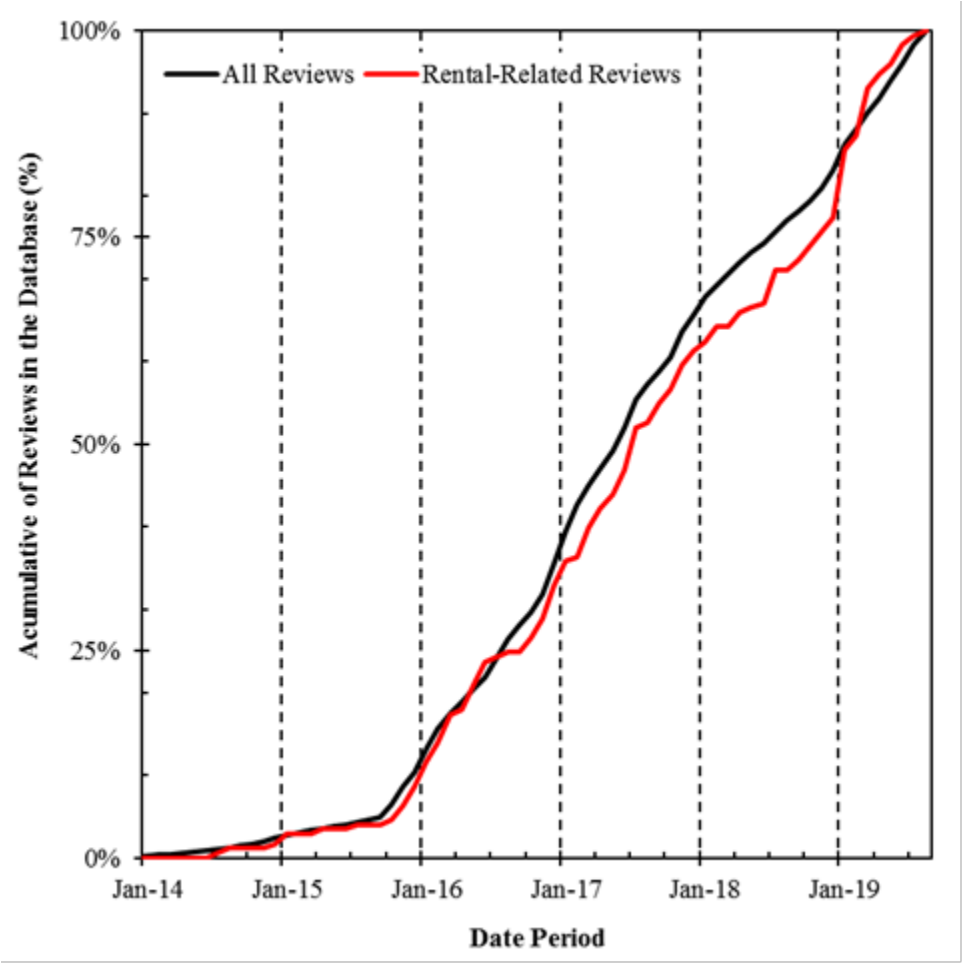

Figure 5. Accumulation of the Cumulative Number of Reviews in the Overall Dataset and the Rental-Related Review Datasets from 2014 to 2019

Content Review

In order to further investigate the opinions and perceptions of stakeholders in the rental market, the 173 reviews in the *rental-related reviews* dataset were next qualitatively analyzed. First the reviewers were categorized based on their role in the rental market. This role was either the "landlord" (or housing unit "owner") or "tenant" (also referred to as "renter" or "guest" in the case of short-term rentals). This distinction helped to analyze each stakeholder's sentiment towards smart thermostats and link their opinions with known characteristics and motivations of their representative user group. Next, the review content was also analyzed to determine if a

review was specifically related to *short-term rental* units. All remaining reviews were tagged as related to *long-term rentals*. This step was crucial as the stakeholders might have differing motivations and concerns according to the type of rental agreement they are involved in.

It is important to note that the role of reviewers identified was solely in relation to their experience with rental units. For example, if a reviewer decided to purchase a smart thermostat device for their own housing unit after a short-term stay as a guest in a rental housing unit, in this analysis they were labeled as a tenant in a short-term rental arrangement. While it can be argued that the current role of the reviewer is an owner in an owner-occupied housing unit, the objective of this study is to investigate the opinions and perceptions of reviewers with regards to the use of smart thermostats in the rental housing market. As such, their other roles are not of interest in this study.

This analysis showed that the review dataset was generally split between the types of rental agreements (short-term or long-term stay). 90 reviews were identified to be related to short-term rental stays (52%), while the other 83 were written about the use of smart thermostats in long-term rental units (48%). However, only 17% of the reviews in the dataset were posted by reviewers who self-identified as tenants. The majority of the reviewers (83%) were considered landlords (Table 4). Since the majority of reviews on Amazon.com are non-incentivized and posted by those who have purchased their devices from this online retailer's platform (i.e. "Verified Purchase" reviews), this sample imbalance in terms of the reviewers' role in the market suggests that the large majority of smart thermostats in the rental housing market are provided by landlords [56,57]. While it is sometimes the case where a tenant reviews a smart thermostat device on Amazon.com, only those who have entered long-term rental agreements might be able to purchase and install a new device in their rental housing unit and in the case of

short-term rental agreements, the tenant is only a temporary user of the space and is thus not generally able to make such upgrades. Therefore, the small number of reviews in the short-term rental tenant subcategory (6% of the number of reviews in the *rental-related reviews* dataset, or 11% of reviews in the short-term rental subcategory) were written by reviewers who wanted to share their experience as a guest in a short-term rental with a smart thermostat device. For instance, STa-004949-STR-T shared their experience as a short-term guest in a rental unit as "*I resisted buying these for our two units for a long time. I swore I would not spend this kind of money on a thermostat. I then stayed in an Airbnb that had one of these and I was sold. I bought two and love them.*"

Table 4. Distribution of Reviewers in the Rental-Related Review Dataset Based on the Reviewers' Roles and Rental Agreement Type

Reviewer's Role	**Rental Agreement Type**	**% of the Reviews in the Dataset**
Landlord (L)	Short-Term Rental (STR)	48%
	Long-Term Rental (LTR)	37%
Tenant (T)	Short-Term Rental (STR)	6%
	Long-Term Rental (LTR)	11%

The reviews were then each divided into one or more independent clauses. Each clause was then fitted into one or more of the following eight topic categories: *Aesthetics (X1)*, *Thermal Comfort (X2), Controls & Privacy (X3), Energy & Utility Bill Savings (X4), Hardware Installation & Compatibility (X5), Learning Capabilities (X6), Software Setup & Usability (X7),* and *Upfront Cost (X8).* These topic categories are described further within this section. We note that some clauses were tagged with more than one topic category, as they included information that was related to multiple categories. Next, the sentiment polarity of the clauses towards the

topic category they were matched with was determined to be either positive (P) or negative (N). Figure 6 shows the frequency and sentiment polarity of these clause tags in the smart thermostat reviews by topic category.

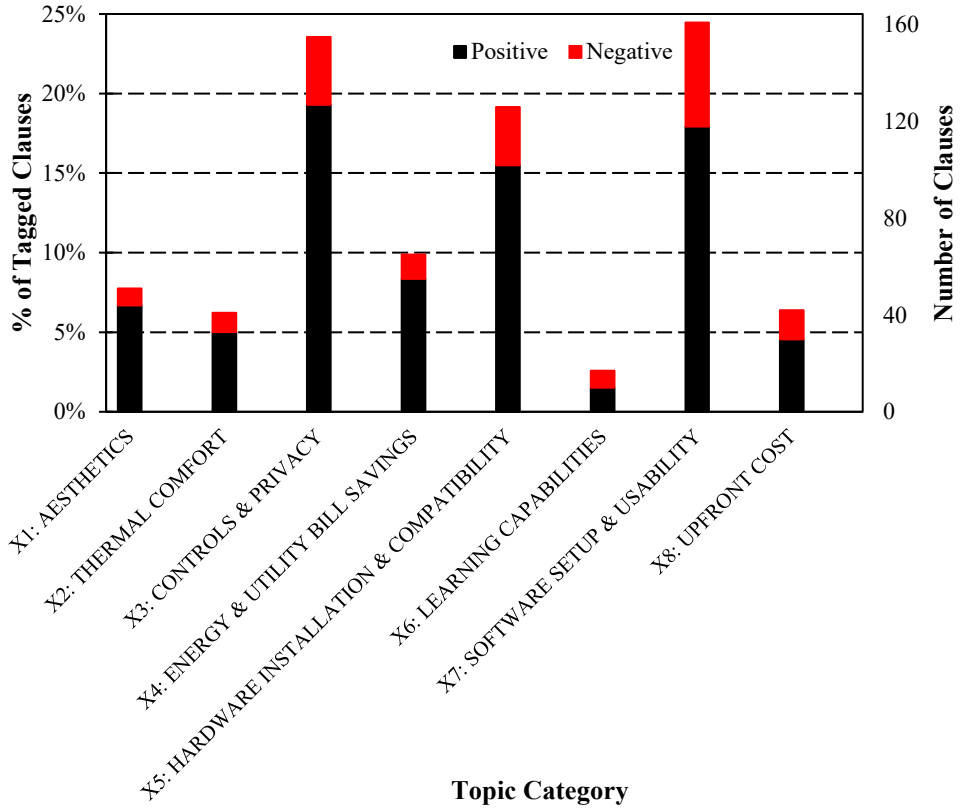

Figure 6. Sentiment Tag Frequency per Topic Category for Smart Thermostat Reviews Related to Rental Units, Including Those Considered to Be Positive (Black) and Negative (Red)

Software Setup & Usability

Overall, the *Software Setup & Usability* topic category was one of the most common topics, amounting to 24.5% of total categorized clauses. This suggests that users in the rental market typically found this aspect of their devices note-worthy and that the related capabilities might have been a determining factor for their purchase decision. Previous research has also repeatedly highlighted the importance of usability for the adoption of smart home technologies [58–60]. Earlier studies (e.g. [58,59]) had identified this aspect as a major challenge for

widespread adoption. However, building on the idea that human-building interaction (HBI) interfaces are critical to smart housing and could greatly affect the perception of the users, more recent studies (e.g. [18,61]) found that a combination of higher technological literacy and better interface design may have contributed to reduced concerns and negative commentary on the usability issues that early users had expressed [62–65].

Similarly, in this topic category, the majority of the clauses in the dataset were tagged as positive (73.3%), indicating an overall positive experience with the user interfaces of the selected devices. For instance, STa-014064-LTR-L expressed their positive experience with the thermostat's usability: "*I installed this in a rental property. [X Brand] account and interface is well thought and allows me to access and give my tenants access to observe and control online but not access to my other [X Brand] devices in my home. This is a mature IoT device.*" However, it is important to note that the majority of these positive views were expressed by primary users (device owners), and some concerns about the ease of use were expressed in the comments with regards to the secondary users. A good example of this issue can be seen in the frustration that a short-term guest (STa-005032-STR-T) had expressed in the following review: "*I have been staying at an Airbnb for 3 weeks and the house has one of these awful devices. I hate this thermostat with a passion and would love nothing more than to rip it out of the wall and hit it with a sledgehammer. It is always doing something and is very hard to fiddle with all the settings to get it to do what I want. I'm in Georgia and for the past three weeks, every time I have come home, it has been over 80 degrees inside. Why? Because this piece of junk has an Eco setting that detects motion and if it thinks nobody is here it allows the temperature to rise. I never come home to a comfortable house and I'm really tired of trying to fiddle with settings to make that happen. What an annoying piece of junk.*"

Another set of criticisms in this topic category were related to the shared access of the data and control via the related online platforms. Such privacy concerns and data sharing agreements have been an ongoing area of research in the field of the Internet of Things (IoT) [60,66–68]. These concerns are further heightened in instances where shared use of a device is practiced. For instance, STa-016459-STR-L stated that "*... I wish the [X Brand] app would allow you to give a guest access to a specific thermostat without giving them access to all thermostats. Or authorizing a guest to use the app for only a specific period of time."* This set of noted issues seem to be mostly related to the user interface design and accessibility. Accordingly, previous studies have suggested that a secondary-user dashboard might be a good response to this challenge [67,68]. However, further investigation is needed to determine what relevant information and permissions should be shared with such users.

Controls & Privacy

Another closely related and highly discussed topic category in the obtained reviews was *Controls & Privacy* (23.6%). Based on the percent of reviews discussing this topic area, the landlord group was specifically highly interested in the controls related capabilities of smart thermostats. They commonly expressed having more and better control as their main purchase motivation. A good example of this is the review posted by a short-term rental unit owner (STh-001267-STR-L) that stated, "*My main reason for purchase was to be able to remotely monitor and control the temp. It works perfectly in this regard. Now I know if the rental guests leave the temp on high after they leave and I can also tell if someone is in my place when I don't expect them to be. ...*" The remote-control functions were particularly identified to be crucial for owners who managed either distant properties or multiple properties at the same time. For short-term rentals specifically, the challenge of making sure the house rules are followed and doing routine

remote checks when the property was unoccupied were also frequently brought up in the review comments.

While owners were generally pleased with having more control over their properties and "locking out" the tenants either completely or partially, the guests had some complaints related to the limited control access they were given during their stay. A secondary-user platform and advanced control sharing options could resolve this issue. One thing to consider in designing such a software and hardware platform is that users' control and/or automation preferences are diverse. Therefore, it may be beneficial for the devices' control mechanisms to reflect this diversity in users' desires and provide a range of options for users to choose from.

Hardware Installation & Compatibility

Hardware Installation & Compatibility related clauses made up for nearly 20% of the tagged clauses in the *rental-related reviews* dataset. Similar to the first two topic categories, the majority of the associated clauses in this topic category were also tagged as positive (81%), which indicates a generally positive experience with the installation process. The smaller number of negative reviews in this category (19%) were related to either defective or incompatible devices. For instance, STf-000953-LTR-T stated that "*Product looks great, however nowhere in the description does this say it requires a specific number of conductors on the page. Bought this product to find out that a 4 conductor thermostat wire isnt sufficient. ...*" Accordingly, a possible resolution is for manufacturers and retailers to offer a thorough system-compatibility check to potential buyers to avoid such issues and also provide a reasonable return period for defected or incompatible devices.

The compatibility of the device with the existing wiring and HVAC system without the need for substantial alternations was found to be critical for the tenant group, which typically have limited flexibility in making such changes as compared to landlords. Some tenant

purchasers expressed that they plan to take the device with them when they relocate after their lease term is over and would like to put the old thermostat back in place. This means that any changes to the existing wiring or system need to be minimal. For example, STe-001260-LTR-T stated that "*this product was my first step into the smart home space. As a renter, I was looking for a smart thermostat that I could install and uninstall it easily without having to worry about damaging the property. I'm decent with electronics but have never put in this type of equipment, and with the instructions that were included it took me about 10 minutes to have thermostat installed and functional. ...*"

While some Amazon.com reviewers expressed that they sought professional help for device installation, it appeared that most purchased and installed their device themselves. The reviewers often mentioned their overall limited technical skills and were pleasantly surprised that they were able to install their devices on their own successfully. Frequently mentioned resources that were useful for the installation included real-time technical support from the manufacturers in the form of customer service phone calls and online chats, the installation documentation that was included in the device package, and online videos both on the manufacturers' websites and in other video-sharing platform.

Energy & Utility Bill Savings

Approximately 10% of the comments focused on *Energy & Utility Bill Savings*. The reviewers often associated their smart devices with energy savings and, in some cases, mentioned such savings as an important motive for their purchase. Their view on this topic category, however, seemed to be highly affected by their personal belief system towards the environment and energy-related issues. STa-007629-LTR-T mentioned that "*Great way to cut costs and be environmentally conscious about energy consumption. As a young adult who rents a place with electric heat, this is a great way to save money and do right when it comes to cutting*

down on fossil fuels." Such observations are consistent with the findings of previous studies, which suggested that a strong link exists between the purchasing decisions of energy-efficient products and measures of environmental consciousness [69,70].

Overall, the energy savings were usually discussed parallel to monetary issues. These included utility expenditures or the up-front investment needed for purchasing a device. The discussed energy savings generally seemed to be achieved as a consequence of modifying the non-responsible choices of short-term and/or long-term renters. These choices included setting the heating or cooling set points too high and too low, respectively, or leaving the property for extended periods of time and keeping it at comfortable levels for the period of absence. These issues seemed to be more critical in short-term rentals and harsher climates, as the possibility of such neglects happening or potential savings was deemed higher in those specific settings. For instance, STa-000894-STR-L expresses their expectations of utility bill savings as a result of more control over his short-term rental property as "*... Too early to tell if I'm saving on my energy bill. I had too many guests jacking up the thermostat to 80 in the middle of winter so it's nice to be able to lock it down.*"

However, it should be noted that almost all of the reviews in this category were related to the rental agreements where the reviewer was directly paying for the utilities. Literature associated with split incentives has shown that when a building occupant is not responsible for paying for utilities directly (commonly referred to as "utilities-included" rental agreements), their energy-related behavior tends to be less efficient when compared to those who are responsible to do so [71,72]. STe-002043-STR-L explains this phenomenon as "*... We expressly wanted this to use in a second home used as a seasonal rental. Condos are rented as hotel rooms through a third party on-site management company. The rent is charged by the day and includes water,*

heat, electric, etc, . If you own a "Cond-Hotel," or really any rental property that includes utilities, you already know that some renters behave differently than they would if they owned the place. Theyre the ones that turn on every light when they enter and pretty much leave them on the entire time. At their own homes, they keep the thermostat at a frugal setting. In the Condo-Hotel room, they have no qualms cranking it to the coldest or hottest possible, depending on the season. With a wi-fi thermostat, we could turn the temp down to a reasonable 75F degrees if we determined the occupants were [running] the heater 24-7 at the max even while gone. ..."

Aesthetics

The topic of *Aesthetics* (7.8% of categorized clauses) was also discussed in some reviews. Both owners and tenants expressed an interest in the "modern" look of the smart devices, especially when compared to other non-smart thermostats. Some reviewers also mentioned that the size of smart thermostats might be different than the thermostat that is being replaced, and some additional paintwork may be required upon installation. STh-001267-STR-L explains that "*... It is a bit smaller than expected and smaller than most programmable thermostats, so you may have a little touch-up painting to do once you remove the old thermostat, but it is really beautiful on the wall and I like the continuous display of the ambient temp. ...*" This may specifically be an issue for long-term renters as they explicitly expressed a need to avoid any permanent alteration to their housing units.

Also of interest was that while most short-time tenants seemed to be locked out of the remote functionalities of the devices, as discussed, their mostly physical and non-smart interaction with the device during their stay persuaded them to purchase one for their own homes. For instance, STa-003204-STR-T states that "*We used one of these in a vacation house we rented and I immediately ordered one for my home. I love the modern look and the*

functionality. Easy installation, too!" This may suggest that the purchase motivation of potential buyers is strongly related to the physical design of the device and its interface.

Upfront Cost

The *Upfront Cost* category was among the least-discussed topics (6.4%). While most reviewers admitted that they considered their selected devices somewhat expensive, most did not see this as a negative issue. This may be impacted by the origin of the data being from only those that had already purchased a thermostat, and did not include those who considered it but did not. Many justified this up-front investment by referring to the rebate programs they had qualified for and used as well as the savings they had achieved (or were at least expecting to achieve) by the devices. STa-005814-LTR-L stated that "*We put this in our rental unit to monitor/control HVAC usage in a nice way... The stylish & very readable function lights up when approached so it makes users aware/conscientious, and when better to use optional Evaporative Cooler instead of AC. Being able to check/control from mobile device when necessary & away is a real cost-saver. While onset it is spendy, the electric co rebate & readability functions made us take the leap. So glad... just got our first bill and despite crazy record heat our usage was so much less than we expected. Exceeded our expectations, learning more ways to conserve energy that well put one in our own house!*" However, most utility rebate programs target owner-occupied units and have a limitation on the number of devices one customer can purchase. Such a limit would be problematic for rental property managers with multiple units. Thus, further research is needed to ensure that rebate policies are in line with the needs of this specific user group.

Lastly, some landlords appeared to see the purchase of a smart thermostat as a marketing opportunity for the younger and/or more tech-savvy renters. STa-011753-LTR-L explains this interest as "… *This would be my 5th purchase... Ive installed [X Brand] for my rental properties and tenants love it! Yes, youre paying a few extra dollars, but residents dig high tech gadgets*

these days! …" Product manufacturers appear to be informed about this motivational factor for purchase and have used it in their marketing materials to attract potential buyers in this market [73].

Thermal Comfort

Another less-discussed topic was *Thermal Comfort (6.2%)*. Most reviewers who discussed comfort-related issues expressed a generally positive view towards comfort associated with the use of the thermostats. For those operating short-term vacation rental units specifically, the remote control feature enabled the ability to adjust the indoor temperature just prior to their guests' arrival and then return to a more energy-saving mode after their departure. STl-000092-STR-L explains this matter as "*We are using the [X Brand] for our vacation home in the mountains. By using the app, we can turn the heat on before our guests arrive so the house is warm and make sure the heat is turned off when they leave to save energy.*" However, for some guests, the automation of the devices kept them from experiencing their most desired comfort levels. They expressed frustration while trying to manage the systems by interacting with the device on the wall as it kept overriding their commands based on the settings set up by the device owner in the online platform. This following from STa-000866-STR-L's review explains an experience of such: "*A mind of its own. I was 1300 miles away and had someone staying at the house and he was not able to adjust the temperature to a comfortable level as the [X Brand] kept setting the temperature back up picking up that I was away. Obviously, this becomes a real pain in the butt if you ever want to allow others to be in your house when you are away. My guest tried to unlock the system but even with my password he was unable. He had to physically take off the [X Brand] and reinstall my old manual thermostat to get the place comfortable again. ...*"

Learning Capabilities

Finally, the least discussed topic among the reviewers was determined to be *Learning Capabilities,* with 2.6% of tagged clauses. While *learning capabilities* are a defining feature of several of the smart thermostats considered, this feature was not often mentioned by reviewers. Some reviewers also indicated that this feature was unnecessary for use in rental units. STh-001267-STR-L's following review is a good example of such views: "*... I debated between this and the [X Brand], but since this is a vacation home with periodic rentals, I really didnt need to focus on the pattern ""learning"" capabilities that the [X Brand] seems to offer. ... My main reason for purchase was to be able to remotely monitor and control the temp. It works perfectly in this regard. ...*"

Another closely-related subject discussed by reviewers is the ease of overriding or modifying the devices' auto-generated schedules. Reviewers suggested that users need to be able to make schedule and control changes easily and quickly. One example of such comments is STa-009608-LTR-T's review, which states, "*Sometimes you have to tweak the automatically generated schedule to match your taste, but at least its easily done in the app…"* The previously known issue of exception flagging was also discussed by some reviewers, which is the flagging of situations in which the occupant behavior and associated thermostat settings should not be used as a part of the training data for the thermostat's control algorithm learning capacities [24]. Such concerns, also studied by [24,74], can be addressed with flagging techniques that allow user input to be collected and used for learning, but also allow users to identify, or flag, exceptional inputs (i.e., inputs that should not be used for learning). Using such flags, the learning algorithm would ignore such inputs.

Topic Correlation

It is also important to note that the majority of the reviews discussed more than one topic (Table 5), which might suggest that individual users' perceptions are shaped by more than one set of product features. This is consistent with the findings of previous studies on the mental models of smart home devices. These studies have suggested that such mental models are highly complicated and shaped by a variety of different factors [75–77].

Table 5. Number of Topic Categories Discussed in Individual Reviews in the Rental-Related Review Dataset

Number of Topics Discussed*	**% of the Reviews in the Dataset**
1	16.1%
2	25.6%
3	28.0%
4	16.7%
5	7.7%
6	4.8%
7	1.2%

*The number of topics discussed here do not account for sentiment polarity towards the topic.

Figure 7 is a map of how different product features and sentiments were correlated in the obtained dataset of reviews for rental housing units. In this map, all sentiment tags that co-appeared in the dataset of reviews more than 4 times are shown and correlated. The numbers on the correlation lines shown reflect the number of instances when such co-appearances occurred, taking the sentiment polarity (positive or negative) of the topic tags into consideration. It can be seen that positive sentiment towards the *control & privacy* features of the devices was often closely linked to positive impressions of *Software Setup & Usability* (N = 20) and *Thermal*

Comfort (N = 13). This is not surprising, given that a common goal of the smart thermostats controls is to provide thermal comfort for occupant(s). *Software Setup & Usability* tags were also frequently mentioned with *Hardware Installation & Compatibility* (N = 11). This is likely because most reviewers discussed the ease of the installation process in a comprehensive manner, including comments about both hardware installation and software setup simultaneously. Another closely linked topic was the positive comments regarding *Aesthetics* (N = 6). Reviewers suggested they were impressed with the design of the user interface and commented on it frequently. As for the positive comments on *Energy & Utility Bill Savings*, such comments were often discussed in parallel with *Upfront Cost* (N = 6) and advanced *control & privacy*-related features (N = 11) that supported the discussed savings. Lastly, when reviewers were not pleased with the *Controls & Privacy* and/or *software setup &usability* of their devices (N = 7), they tended to express their negative sentiment towards both subjects in parallel.

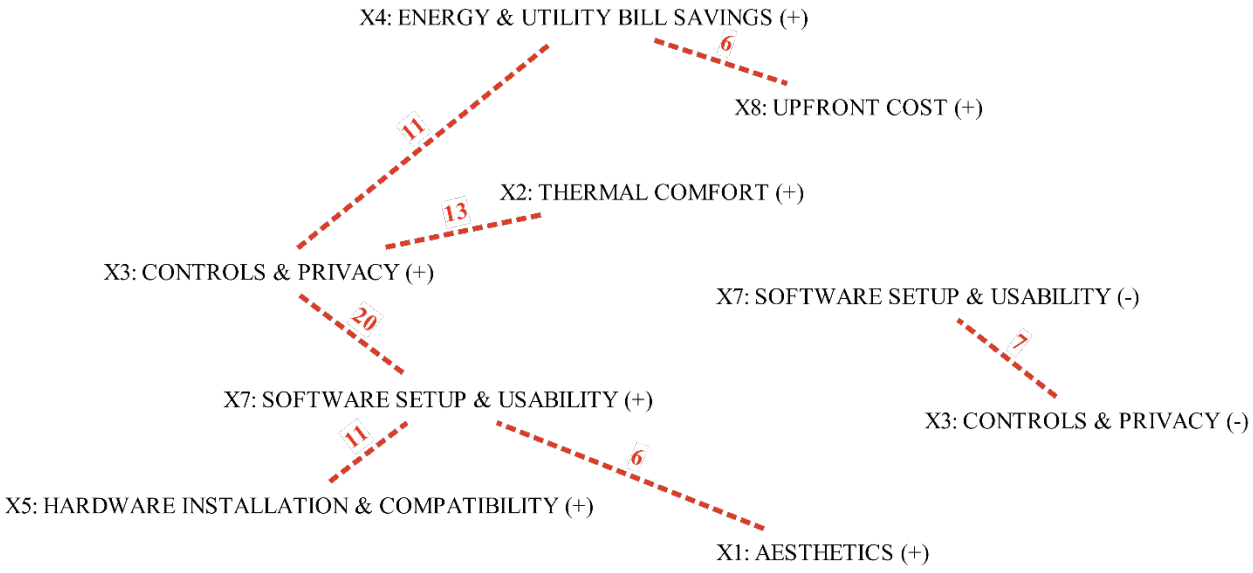

Figure 7. Map of the Co-Appearance of Sentiment Tags in the Dataset of Reviews Related to Rental Units

CHAPTER 4. DISCUSSION

Based on the discussed results, there are several themes that emerge, which are discussed as follows.

Improved Intuitive Usability for Secondary Users Is Needed

Research suggests that the usability of thermostats, in general, has been a long-standing issue for realizing the possible levels of energy efficiency [78]. Earlier studies on smart thermostats (e.g. [59,79,80]) expressed concerns regarding the usability of the devices for the "average" user. More recent studies (e.g. [18]) have suggested that such concerns are no longer as significant due to improvements in interface designs and higher technological literacy among users. The findings in this work, however, suggest that the same cannot be said for secondary users of these devices. The reviews in this study frequently expressed concerns with non-primary users' interactions with the devices and suggested they were not satisfied with the interface for such users. As such, while more widespread adoption of such devices across the residential building stock might provide greater technological literacy for the average user in the future, it is recommended that the user interface should be improved to be more intuitive and user-friendly keeping in mind the variety of possible primary and secondary user types. This would help gain potential users' confidence in the usability of the devices for their intended use and hence, increase adoption in this market.

The Rental Market Is Interested in a Platform Dedicated to Secondary Users

Another set of frequently mentioned concerns discussed shared access of the data and controls of the smart thermostats. Nearly all reviewers suggested the need for a better way to share control for rental property scenarios. Some, however, expressed concerns with regard to the privacy implications of shared access. Such comments suggest the need for a secondary

platform with limited access to controls and data that could be used by non-primary users of a space [67,68]. This platform would give the primary users the flexibility to choose the specific controls their tenants have access to and the extent to which they allow changes to their pre-defined settings. Another important consideration is the duration of shared access by secondary users. This would likely depend on the length of the rental agreement as well as the preferences of the space owner. However, further research is needed to determine the needs and preferences of all users and establish the extent to which data and controls could be shared and the flexibility of such settings.

Learning Capabilities Are Not of Highly Discussed Among Rental Housing Reviewers

The vast majority of the reviewers expressed little to no interest in the learning capabilities of their smart thermostats. This lack of interest is closely linked to the limited ability of currently utilized learning algorithms in smart thermostats to consider exceptional flagging [81]. Variation in occupants and occupant behavior, including one-time or short-term occurrences of behaviors and/or settings, are common in rental settings. Such concerns could be addressed with techniques that allow implicit user input to be collected and used for learning, while also allowing users to identify, or flag, exceptional inputs (i.e., inputs that should not be learned), triggering the system to ignore such inputs when building models and making predictions [24,82]. However, the inclusion of such techniques in the thermostats' learning algorithms would require the user to regularly review and identify such occurrences. This might be too demanding if required to be done manually. However, if linked to a calendar or other application with rental schedules, this could help to distinguish between user types and associated data. A possible resolution could be to have specialized versions and/or add on features of smart thermostats specifically for this user group. Such features could focus on the remote control and shared access of the devices, as these appear to be most valued by the studied

rental property stakeholders. Such features do not necessarily need to incorporate learning capabilities, unless more extensive considerations can be made to distinguish between user (occupant) types.

Connection Reliability Is Important for Remote Control of Properties

A common requirement for smart home technologies, like other types of IoT devices, is a reliable internet connection [60,83]. In the case of landlords who intend to use smart thermostats in either distant vacation properties or multiple properties simultaneously, connection reliability is of heightened importance. Some reviewers discussed concerns with regards to the sudden loss of connection due to either a power outage, loss of the internet connection, or other loss of functionality of their thermostats. Such connection losses risk monetary damages to the properties (e.g. frozen pipes), complaints from the tenants who may experience thermally uncomfortable conditions, and/or loss of trust in the devices by the device owners and/or renters. Such relative importance of connectivity suggests a need for enhanced reliability, in terms of connection and also privacy. A possible solution might be to add a backup cellular networks' device to the coordinator while keeping the proper security and cost precautions in mind [84,85]. Moreover, the landlords expressed a need to be notified of any lost connections immediately to prevent negative consequences. Therefore, it is recommended that the devices should always be accompanied by a comprehensive alert/notification system in the case of any possible failures.

CHAPTER 5. CONCLUSIONS

In this study, online reviews were used to evaluate users' perceptions and attitudes towards the use of smart thermostats in rental housing units. For this purpose, 31,790 reviews posted on an online retailer's website (Amazon.com) were collected for 14 commercially available smart thermostats. These reviews were then refined based on their context and from these, 173 reviews were identified to be directly associated with rental units. The selected reviews were first analyzed to understand the characteristics of this market compared to that of the owner-occupied group. The findings indicated that the adoption of smart thermostats in the rental market has occurred in parallel with the owner-occupied housing market and that the popularity trends seem to generally follow the same pattern for both groups. The reviewers in the rental group seemed to be slightly more interested in the devices that fell into the mid-price range while the devices that fell into the high- and low-price range were relatively more popular with the owner-occupied group.

The reviews were also analyzed based on their content, where each review was divided into one or more independent clauses then fitted into one of the eight previously-defined topic categories. The sentiment of the review clauses towards the topics it was tagged with was also determined to be either *positive (P)* or *negative (N).* This analysis showed that the majority of reviewers in the rental group were focused on usability aspects and expressed an interest in the advanced remote control functions of their purchased devices. Nearly all of the users asked for more flexible mechanisms of sharing control between the landlords and tenants and some expressed concerns with regards to the privacy implications of this shared access. This suggests the need for a secondary platform with limited access to controls and data that could be used by non-primary users of the space. However, further research is needed to determine the needs and

preferences of all stakeholders in this market and establish the extent to which data and controls should be made possible to share between different parties involved. Our findings also indicated that learning capabilities were not of particular interest among this user group as compared to the non-rental property related reviews. It is thus recommended that tailored devices for this user group should focus mostly on the remote control and shared access of the devices.

Overall, by evaluating rental users' perceptions and attitudes towards smart thermostats, the findings of this study may be beneficial to manufacturers of smart thermostats who may be interested in better understanding a subset of their customer and user base and their associated sentiments and opinions about thermostat products. This may also be of interest to those that design and execute energy efficiency rebate programs, including those with smart thermostats, to understand what features are of interest and associated with positive sentiment to potential customers interested in participating in such programs. Generally, energy efficiency rebate programs are not designed for this user group, as they usually only apply to owner-occupied units. Thus, further research is needed to ensure that rebate policies are in line with the needs of this specific user group.

Limitations of this work are related to the exclusion of input data from potential buyers from the dataset used for analysis. Given that those that do not purchase thermostats do not write online reviews which could be used in this dataset, it is unlikely that a parallel dataset of potential users' reviews of thermostats exists. Future work would benefit from a comparative side-by-side analysis of both current and potential users in the rental market.

REFERENCES

[1] U.S. Energy Information Administration (EIA), Residential Energy Consumption Survey (RECS) Terminology, (2020). https://www.eia.gov/consumption/residential/terminology.php (accessed July 27, 2020).

[2] U.S. Energy Information Administration (EIA), 2015 Residential Energy Consumption Survey (RECS) Survey Data, 2015. https://www.eia.gov/consumption/residential/data/2015/.

[3] J. Im, Y. Seo, K.S. Cetin, J. Singh, Energy efficiency in US residential rental housing: Adoption rates and impact on rent, Appl. Energy. 205 (2017) 1021–1033.

[4] A.J. Hope, A. Booth, Attitudes and behaviours of private sector landlords towards the energy efficiency of tenanted homes, Energy Policy. 75 (2014) 369–378.

[5] J. Carroll, C. Aravena, E. Denny, Low energy efficiency in rental properties: Asymmetric information or low willingness-to-pay?, Energy Policy. 96 (2016) 617–629.

[6] K. Gillingham, M. Harding, D. Rapson, Split Incentives in Residential Energy Consumption, Energy J. 33 (2012) 37–62.

[7] S. Bird, D. Hernández, Policy options for the split incentive: Increasing energy efficiency for low-income renters, Energy Policy. 48 (2012) 506–514.

[8] California Sustainability Alliance, Green Leases Toolkit - Glossary, (2020). http://sustainca.org/green_leases_toolkit/glossary (accessed July 27, 2020).

[9] D. Hernández, S. Bird, Energy burden and the need for integrated low-income housing and energy policy, Poverty & Public Policy. 2 (2010) 5–25.

[10] International Energy Agency (IEA), Mind the Gap: Quantifying Principal-agent Problems in Energy Efficiency, 2007. doi:10.1787/9789264038950-en.

[11] E. Myers, Asymmetric information in residential rental markets: Implications for the energy efficiency gap, Energy Inst. Haas Work. Pap. 246 (2015).

[12] Y. Phillips, Landlords versus tenants: Information asymmetry and mismatched preferences for home energy efficiency, Energy Policy. 45 (2012) 112–121.

[13] G.A. Akerlof, The market for “lemons”: Quality uncertainty and the market mechanism, in: Uncertain. Econ., Elsevier, 1978: pp. 235–251.

[14] F. Fuerst, G. Warren-Myers, Does voluntary disclosure create a green lemon problem? Energy-efficiency ratings and house prices, Energy Econ. 74 (2018) 1–12.

[15] A.R. Ambrose, Improving energy efficiency in private rented housing: Why don't landlords act?, Indoor Built Environ. 24 (2015) 913–924.

[16] A. Nacer, B. Marhic, L. Delahoche, Smart Home, Smart HEMS, Smart heating: An overview of the latest products and trends, in: 2017 6th Int. Conf. Syst. Control, IEEE, 2017: pp. 90–95.

[17] M. Zeifman, K. Roth, B. Urban, Communicating thermostats as a tool for home energy performance assessment, in: 2017 IEEE Int. Conf. Consum. Electron., IEEE, 2017: pp. 192–193.

[18] D. Malekpour Koupaei, T. Song, K. Cetin, J. Im, An Assessment of Opinions and Perceptions of Smart Thermostats using Aspect-Based Sentiment Analysis of Online Reviews, Build. Environ. 170 (2020). doi:10.1016/j.buildenv.2019.106603.

[19] Parks Associates, Twenty-nine percent of US broadband households plan to purchase a smart thermostat in 2020, (2020). http://www.parksassociates.com/blog/article/pr-02042020 (accessed July 27, 2020).

[20] Pew Research Center, Internet/Broadband Fact Sheet, 2019. https://www.pewresearch.org/internet/fact-sheet/internet-broadband/.

[21] Statista Digital Market Outlook, SMART HOME REPORT 2020 - ENERGY MANAGEMENT, 2020. https://www.statista.com/outlook/284/109/energy-management/united-states.

[22] G. Gao, K. Whitehouse, The self-programming thermostat: optimizing setback schedules based on home occupancy patterns, in: Proc. First ACM Work. Embed. Sens. Syst. Energy-Efficiency Build., 2009: pp. 67–72.

[23] J. Lu, T. Sookoor, V. Srinivasan, G. Gao, B. Holben, J. Stankovic, E. Field, K. Whitehouse, The smart thermostat: using occupancy sensors to save energy in homes, in: Proc. 8th ACM Conf. Embed. Networked Sens. Syst., 2010: pp. 211–224.

[24] R. Yang, M.W. Newman, Learning from a learning thermostat: lessons for intelligent systems for the home, in: Proc. 2013 ACM Int. Jt. Conf. Pervasive Ubiquitous Comput., 2013: pp. 93–102.

[25] J. King, Energy impacts of smart home technologies, Rep. A1801. (2018).

[26] J. Yua, K.-Y. Wangb, Online Evaluation and Tourist Purchase Behaviours for Urban Homestay Selection, (2020).

[27] H. Villeneuve, W. O'Brien, Listen to the guests: Text-mining Airbnb reviews to explore indoor environmental quality, Build. Environ. 169 (2020) 106555.

[28] Q. Ke, Sharing means renting? An entire-marketplace analysis of Airbnb, in: Proc. 2017 ACM Web Sci. Conf., 2017: pp. 131–139.

[29] Amazon.com, Smart Thermostat: Top Selected Products and Reviews, (2020). https://www.amazon.com/slp/smart-thermostat/aufno5u2j85b8pv (accessed August 1, 2019).

[30] U.S. Department of Energy (DOE), Overview of Existing and Future Residential Use Cases for Connected Thermostats, 2016. https://www.energy.gov/sites/prod/files/2016/12/f34/Overview of Existing Future Residential Use Cases for CT_2016-12-16.pdf.

[31] K.J. Lomas, S. Oliveira, P. Warren, V.J. Haines, T. Chatterton, A. Beizaee, E. Prestwood, B. Gething, Do domestic heating controls save energy? A review of the evidence, Renew. Sustain. Energy Rev. 93 (2018) 52–75.

[32] H. Wickham, M.H. Wickham, Package 'rvest,' URL Https//Cran. r-Project. Org/Web/Packages/Rvest/Rvest. Pdf. (2016).

[33] R Core Team, R: A language and environment for statistical computing, (2013).

[34] A. Yadollahi, A.G. Shahraki, O.R. Zaiane, Current state of text sentiment analysis from opinion to emotion mining, ACM Comput. Surv. 50 (2017) 1–33.

[35] J. Im, T. Song, Y. Lee, J. Kim, Confirmatory aspect-based opinion mining processes, ArXiv Prepr. ArXiv1907.12850. (2019).

[36] I. Feinerer, Introduction to the tm Package Text Mining in R, Access. En Ligne Http//Cran. r-Project. Org/Web/Packages/Tm/Vignettes/Tm. Pdf. (2013).

[37] D. Harper, Online Etymology Dictionary, (2001). https://www.etymonline.com/ (accessed August 1, 2019).

[38] C. Roman, Making a Business of Residential Use: The Short-Term-Rental Dilemma in Common-Interest Communities, Emory LJ. 68 (2018) 801.

[39] D. McAdam, The Rights, Duties, Remedies, and Incidents Belonging to and Growing out of the Relation of Landlord and Tenant, Remick, Schilling & Company, 1900.

[40] R.A.N. Harrington, Vacation rentals: Commercial activity butting heads with CC&Rs, Cal. WL Rev. 51 (2014) 187.

[41] S.L. Griffiths, Where Home Meets Hotel: Regulating tourist accommodations in the age of Airbnb, (2017).

[42] Verbi Software, MAXQDA 2018, [Computer Software]. (2017). https://www.maxqda.com/.

[43] K. Gillingham, R.G. Newell, K. Palmer, Energy efficiency economics and policy, Annu. Rev. Resour. Econ. 1 (2009) 597–620.

[44] J. Melvin, The split incentives energy efficiency problem: Evidence of underinvestment by landlords, Energy Policy. 115 (2018) 342–352.

[45] H. Allcott, M. Greenstone, Is there an energy efficiency gap?, J. Econ. Perspect. 26 (2012) 3–28.

[46] S.M. Mudambi, D. Schuff, Research note: What makes a helpful online review? A study of customer reviews on Amazon. com, MIS Q. (2010) 185–200.

[47] J.A. Krosnick, D.S. Boninger, Y.C. Chuang, M.K. Berent, C.G. Carnot, Attitude strength: One construct or many related constructs?, J. Pers. Soc. Psychol. 65 (1993) 1132.

[48] K.J. Kaplan, On the ambivalence-indifference problem in attitude theory and measurement: A suggested modification of the semantic differential technique., Psychol. Bull. 77 (1972) 361.

[49] S. Presser, H. Schuman, The measurement of a middle position in attitude surveys, Public Opin. Q. 44 (1980) 70–85.

[50] K. Hill, How Your Airbnb Host Can Use Nest For Surveillance, Forbes Media. (2013). https://www.forbes.com/sites/kashmirhill/2013/11/04/how-your-airbnb-host-can-use-nest-for-surveillance/#56672da1931c (accessed August 14, 2019).

[51] S. Higginbotham, Renters rejoice! This company is testing “smart” apartments, Fortune Media. (2015). https://fortune.com/2015/08/24/nwp-smart-apartments/.

[52] S. Lacey, Nest’s New Partnership With Airbnb Is About More Than Energy Savings, Greentech Media. (2014). https://www.greentechmedia.com/articles/read/nests-new-partnership-with-airbnb-is-about-much-more-than-energy-savings (accessed August 14, 2019).

[53] D. Reisinger, Nest to give free thermostats to some Airbnb hosts, Yahoo News Netw. (2014). https://news.yahoo.com/nest-free-thermostats-airbnb-hosts-143852096.html.

[54] Airbnb, Airbnb Partners with Nest to Help Community Continue to Save Energy, Airbnb. (2020). https://www.airbnb.com/press/news/airbnb-partners-with-nest-to-help-community-continue-to-save-energy.

[55] Frost & Sullivan, Global Smart Thermostats Market, Forecast to 2025, 2019. https://www.reportlinker.com/p05808196/Global-Smart-Thermostats-Market-Forecast-to.html.

[56] ReviewMeta, Analysis of 7 million Amazon reviews: customers who receive free or discounted item much more likely to write positive review, (2016). https://reviewmeta.com/blog/analysis-of-7-million-amazon-reviews-customers-who-receive-free-or-discounted-item-much-more-likely-to-write-positive-review/.

[57] Amazon.com, About Amazon Verified Purchase Reviews, (2020). https://www.amazon.com/gp/help/customer/display.html?nodeId=202076110.

[58] W.K. Edwards, R.E. Grinter, At home with ubiquitous computing: Seven challenges, in: Int. Conf. Ubiquitous Comput., Springer, 2001: pp. 256–272.

[59] L.C.R. de Oliveira, A. May, V. Mitchell, M. Coleman, T. Kane, S. Firth, Pre-installation challenges: classifying barriers to the introduction of smart home technology, in: EnviroInfo ICT Sustain. 2015, Atlantis Press, 2015.

[60] D. Marikyan, S. Papagiannidis, E. Alamanos, A systematic review of the smart home literature: A user perspective, Technol. Forecast. Soc. Change. 138 (2019) 139–154.

[61] J. Shin, Y. Park, D. Lee, Who will be smart home users? An analysis of adoption and diffusion of smart homes, Technol. Forecast. Soc. Change. 134 (2018) 246–253.

[62] J.K. Day, C. McIlvennie, C. Brackley, M. Tarantini, C. Piselli, J. Hahn, W. O'Brien, V.S. Rajus, M. De Simone, M.B. Kjærgaard, A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort, Build. Environ. (2020) 106920.

[63] P. Agee, X. Gao, F. Paige, A. McCoy, B. Kleiner, A human-centred approach to smart housing, Build. Res. Inf. (2020) 1–16.

[64] W. O'Brien, A. Wagner, M. Schweiker, A. Mahdavi, J. Day, M.B. Kjærgaard, S. Carlucci, B. Dong, F. Tahmasebi, D. Yan, Introducing IEA EBC Annex 79: Key challenges and opportunities in the field of occupant-centric building design and operation, Build. Environ. (2020) 106738.

[65] D. Schäuble, A. Marian, L. Cremonese, Conditions for a cost-effective application of smart thermostat systems in residential buildings, Appl. Energy. 262 (2020) 114526.

[66] S. Zheng, N. Apthorpe, M. Chetty, N. Feamster, User perceptions of smart home IoT privacy, Proc. ACM Human-Computer Interact. 2 (2018) 1–20.

[67] S. Mare, F. Roesner, T. Kohno, Smart Devices in Airbnbs: Considering Privacy and Security for both Guests and Hosts, Proc. Priv. Enhancing Technol. 2020 (2020) 436–458.

[68] C. Geeng, F. Roesner, Who's In Control? Interactions In Multi-User Smart Homes, in: Proc. 2019 CHI Conf. Hum. Factors Comput. Syst., 2019: pp. 1–13.

[69] M. Laroche, J. Bergeron, G. Barbaro-Forleo, Targeting consumers who are willing to pay more for environmentally friendly products, J. Consum. Mark. (2001).

[70] B.B. Schlegelmilch, G.M. Bohlen, A. Diamantopoulos, The link between green purchasing decisions and measures of environmental consciousness, Eur. J. Mark. (1996).

[71] A. Levinson, S. Niemann, Energy use by apartment tenants when landlords pay for utilities, Resour. Energy Econ. 26 (2004) 51–75.

[72] L. Maruejols, D. Young, Split incentives and energy efficiency in Canadian multi-family dwellings, Energy Policy. 39 (2011) 3655–3668.

[73] L. Bourland, Why Airbnb Owners Need a Smart Thermostat, Mysa Smart Thermostats. (2019). https://getmysa.com/blog/thermostat-talk/why-airbnb-owners-need-a-smart-thermostat/.

[74] R. Yang, M.W. Newman, Living with an intelligent thermostat: advanced control for heating and cooling systems, in: Proc. 2012 ACM Conf. Ubiquitous Comput., 2012: pp. 1102–1107.

[75] V. Zimmermann, M. Bennighof, M. Edel, O. Hofmann, J. Jung, M. von Wick, 'Home, Smart Home'–Exploring End Users' Mental Models of Smart Homes, Mensch Und Comput. 2018-Workshopband. (2018).

[76] K. Gram-Hanssen, S.J. Darby, "Home is where the smart is"? Evaluating smart home research and approaches against the concept of home, Energy Res. Soc. Sci. 37 (2018) 94–101.

[77] S.J. Darby, Smart technology in the home: time for more clarity, Build. Res. Inf. 46 (2018) 140–147.

[78] T. Peffer, D. Perry, M. Pritoni, C. Aragon, A. Meier, Facilitating energy savings with programmable thermostats: evaluation and guidelines for the thermostat user interface, Ergonomics. 56 (2013) 463–479.

[79] T. Hargreaves, C. Wilson, R. Hauxwell-Baldwin, Learning to live in a smart home, Build. Res. Inf. 46 (2018) 127–139.

[80] P. Ponce, T. Peffer, A. Molina, Framework for communicating with consumers using an expectation interface in smart thermostats, Energy Build. 145 (2017) 44–56.

[81] R. Yang, Supporting User Understanding and Engagement in Designing Intelligent Systems for the Home., (2016).

[82] R. Anuradha, P. Linde, Where is the interface?–Appropriating Interaction with IoT in the Smart Home, EAI Endorsed Trans. Creat. Technol. 6 (2019).

[83] J. Bugeja, A. Jacobsson, P. Davidsson, Smart connected homes, Internet Things A to Z Technol. Appl. (2018) 359–384.

[84] S.-M. Kazempour-Radi, M.-H. Rafiei-Sakhaei, A utilization of wireless sensor network in smart homes, reviewing its combination with modern cellular networks, in: 2011 Int. Conf. Commun. Ind. Appl., IEEE, 2011: pp. 1–5.

[85] M. Lee, What role will cellular connectivity play in the future of IoT and M2M connections?, InterDigital. (2019). https://iottechnews.com/news/2019/aug/02/what-role-will-cellular-connectivity-play-future-iot-and-m2m-connections/.