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A Data Analytics Study on Building Characteristics Impacting Energy Consumption in Single-Family Attached Homes

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Abstract

San Antonio, Texas is the seventh largest city in the United States with a population of 1.4 million people, and ranked among the fastest growing cities. To assess the implications of past and present building practices within the residential sector on future energy consumption, the energy utilization of single-family attached homes (SFAH) in Bexar County, Texas is studied. The available dataset includes 3932 SFAH records representing about 33% of the total number of SFAHs within the county. The study is based on pairing and analyzing data at the individual building level from a variety of sources including the buildings' physical characteristics, access to fuels, and monthly energy consumption. The results indicate that the area of conditioned space, presence of swimming pools, number of stories, presence of fireplaces, fuel-type, and number of shared walls are a significant factor on the energy consumption of single-family attached homes. In terms of energy consumption, all-electric two-story homes sharing two walls are the most energy efficient among SFAHs. This study can aid comprehensive master planning efforts for developing sustainable communities by highlighting key features of SFAHs and making the case for higher density housing as a viable and more energy efficient alternative to single-family detached homes (SFDH).

Keywords

Energy Efficiency, Single-Family Attached Homes, Residential Energy Consumption, Building Characteristics, Reference Buildings

1. Introduction

The objective of this study is to better understand the stock of single-family attached homes (SFAH) and associated energy utilization patterns within Bexar County, Texas. A secondary objective is to identify potential implications of current building practices and promote development of more energy-efficient housing alternatives. Pitt [1] studied energy use and greenhouse gas (GHG) emission savings from compact housing. He focused on the impact of sprawl on residential energy use, specifically the opportunity to reduce energy consumption and GHG emissions by emphasizing attached homes and multi-family structures for future residential development rather than more energy-consuming, single-family detached homes (SFDHs). Ewing & Fang [2] in their study on the impact of urban form on US residential energy use also suggested that one way to conserve energy and minimize GHGs is to shift from single-family detached to attached homes. From an architectural standpoint townhouses are individual houses that are built side-by-side, where one or two walls of each house are shared between adjacent homes. Development of attached homes is based on a dense planning pattern with narrow-front and long footprint, which creates sustainable communities by offering higher density housing [3]. Condominiums are typically multifamily construction resembling one or more apartment or townhouse buildings. The major difference between condominiums and townhomes are the type of ownership. In contrast to condominiums in which each homebuyer acquires ownership of an individual unit including the airspace within the walls, each townhome has its own roof, as well as the ground underneath that unit [4].

In a study on the energy efficiency of townhomes, Zoeller *et al.* [5] investigated various housing patterns that can affect energy utilization. Researchers stated that townhomes, as the traditional housing type of New England, could improve energy efficiency due to low ratio of façade to floor area, where façade is a proxy for thermal area. Despite the fact that townhouses are a building typology rooted in earlier centuries, many of their attributes resemble single-family houses and thus make them relevant to current time [3]. In a similar study [6] the effect of housing density on energy efficiency of buildings considering the hot climatic conditions is investigated. The examined row houses configuration offered a reduction in average energy consumption that reaches 28% compared to the rest of examined residential buildings types located in urban situation. On the other hand, bigger houses require more energy than smaller houses because there is more space to heat and cool, and detached houses require more energy than attached houses of the same size due to increased exposed surface area [2].

The energy consumption of homes in cold climates is mostly heating driven while the energy consumption of homes in hot and humid climates, like that of Bexar County, Texas, is mostly cooling driven. Philipsen [7] studied the energy footprint of apartments, row houses and freestanding houses specifically in cold climates. The study looked at some proxies for heating energy consumption such as the exterior surfaces, namely the exterior walls and the roof. The study concluded that in a condition with all other things being equal (window quality, R-value of the walls, R-value of the roof), the row house would be more than twice as efficient for heating as the freestanding house, and the apartment again twice as efficient as the row house [7]. Bexar County, Texas has witnessed an 8.2% increase in population from April 1, 2010 to July 1, 2014 [8], and local building practices rely on construction of SFDHs as the preferred housing alternative. Since downtown revitalization efforts started in 2010, the city has slowly shifted to a more balanced approach in which apartments and condominiums are being built in and around the city core while SFDHs are mostly built in the suburbs where land is still available.

A study focusing on energy consumption of SFAHs or townhomes will help to better understand the energy utilization patterns of this type of residential building to be considered in city planning. Ewing and Rong [2] in their study on urban form and housing stock stated that people's choice of house type is strongly related to urban form. The odds that a household will live in multifamily housing are seven times greater for compact counties. Households in multifamily housing units, characterized by shared walls and typically smaller floor space, consume less energy for space heating, cooling, and all other purposes than do households in detached single-family homes, when controlling for the age of housing structures as a proxy of construction technology [9]. Kaza [10] studied the factors that affect energy consumption within the residential building stock of a given geographic area and found that size and type are key contributing factors for energy consumption associated with conditioning of living space. In a study analyzing monthly household energy consumption among single-family residences in Texas in 2010 [11] researchers indicate that there is a significant opportunity to reduce household energy consumption by targeting specific types of households within the studied service area because many households are renter-occupied (10%), without central cooling (18%), and have pools (7%). Therefore, the impact of presence of pools on the energy consumption is further studied.

The authors of this manuscript have studied over the past five years the housing stock within the San Antonio, Texas area, which is mainly composed of SFDHs. In [12] Gomez *et al.* calculated energy baselines, using site and source energy index (EI), for approximately 348,000 SFDHs in San Antonio to facilitate adoption of energy efficiency programs offered by the local utility. The authors categorized the homes into four distinct energy index categories, indicating that energy efficiency programs for newer, larger houses should be behavioral or educational in nature while programs for older houses should target the building envelope (e.g., building materials, insulation, windows, roof, foundation) and home systems (e.g., central heating, ventilation, and air-conditioning, domestic water heating, and large appliances). In another study [13], the authors evaluated the influence of fireplaces on winter energy consumption in San Antonio, Texas. The results indicated that there is a significant 31% increase in energy use in homes with fireplaces. Moreover, in another study evaluating the impact of the presence of swimming pools on household electric intensity in San Antonio, Texas [14], the results suggested that on average, San Antonio homes with pools used over 40% more energy than comparable homes without pools. In a related study by a different author [15], statistical analysis indicated that among the urban form factors used, number of shared walls was the most important factor affecting the delivered energy use.

In this study, the authors characterize the SFAHs housing stock of Bexar County and evaluate the impact of key features commonly found in homes in the area (swimming pools, fireplaces) on household energy consumption. This study ascertains that the construction of housing alternatives, such as SFAHs, should be encouraged because of their relatively smaller footprint and increased potential for realizing significant energy savings due to shared walls and floors.

2. Description of Dataset and Methodology

According to the US Census—American Community Survey 5-year estimates, there are about 17,159 SFAHs in Bexar County built as of 2014 [16]. This study is based on an available dataset including information for 5565 SFAHs, equivalent to about 32.6% of all SFAHs. Energy information at the individual household level for the remaining 67% of SFAHs is not available. Furthermore, a large number of SFAHs are located in and around military installations across the county; therefore, the data required to perform the analysis is not readily available. Pairing building data with utility energy data at the individual building level resulted in 3932 records with at least 12 consecutive months of energy consumption and necessary building characteristics. Therefore, analyses conducted and presented in this manuscript represent approximately 23.0% of the SFAHs within Bexar County, Texas.

Researchers were able to obtain complete building information for an additional 3252 SFAH records. Together, the resulting total is now 7184 SFAH, equivalent to approximately 42.0% of the entire SFAH housing stock. The physical characteristics of the homes within the subset of 3252 SFAHs are very similar to the characteristics of homes analyzed for this study. The average vintage is 1983; average size is 1350 sf (125.42 m^2); homes are mostly 1-story; very few homes have a swimming pool or spa; and, about 58% of the homes have a fireplace.

For analysis, the data is further segmented by fuel type. Of the 3932 homes in this study, 1321 are all-electric (33.6%) and 2611 are dual-fuel (66.4%). All-electric homes have only access to electricity while dual-fuel homes have access to electricity and natural gas to satisfy the various end uses of energy within the home. Segmentation using other factors to include vintage and size, number of shared walls, number of stories, and reference versus non-reference homes is also part of this study. The objective of the segmentation approach is to compare energy consumption patterns within similar homes including additional segmentation of the stock based on key features of the home such as presence of swimming pools, fireplaces, number of stories, fuel type, area of conditioned space, and vintage. The analyses in this study are based on the fuel type of the home using source energy as the performance metric, as source energy captures the whole aspects of energy efficiency.

Key performance indicators such as annual and seasonal energy consumption are calculated to perform baseline and comparative type of analyses. The vintage and size segmentation methodology is based on categories as described by Gomez *et al.* [12] resulting in 64 unique subgroups. Vintage groups are determined to cover each decade from the 1950s to the present decade. Size categories are established based on 500-square foot (46.45 m^2) increments starting at less than 999 sf (92.81 m^2) to larger than 4000 sf (371.61 m^2).

Monthly energy consumption (both electricity and natural gas) for 2013 was estimated from utility billing information. Comparisons were made across the various SFAH sub groups. For the purposes of this study a constant temperature is assumed across the entire county. Historical weather data was obtained from weather underground [17] for the San Antonio International Airport weather station. Based on the weather data for San Antonio to disaggregate energy consumption between various end uses, the utilized energy through the year is divided into two main groups: weather sensitive (cooling for summer and heating for winter) versus non-weather sensitive (baseload, the minimum amount of energy necessary to operate the home year around). Heating months are January, February and December, representing winter energy consumption. Cooling months are May, June, July, August and September, representing summer energy consumption.

Reference homes were defined as homes that have no swimming pools, no hot tubs, no fireplaces, no solar photovoltaic (PV) ownership, have not participated in utility rebates, and are not certified under the Build San Antonio Green (BSAG) program. Nine parameters are identified for each of the 3932 homes as part of the analyses performed.

- Electric Consumption of 12 months for 2013,
- Gas Consumption of 12 months for 2013,
- Vintage [Year Built],
- Home Size [Living Area],
- Type of Fuel [Dual/Electric Only],
- Number of Shared-Walls [1/2],
- Number of Stories [1/2],
- Presence of Fireplace [Yes/No],
- Presence of Swimming Pool [Yes/No].

Therefore, source energy for every building is calculated based on Equation (1) in 1000 British Thermal Units (kBtu) and Equation (2) in kilowatt hours (kWh), below, to better understand utilization patterns regardless of the fuel utilized by the home. The concept of source energy helped to trace back the heat and electricity requirements to the raw fuel input. Therefore, the losses that usually occur during production, transmission and delivery of the energy to the site are considered in the source energy calculation. A five-year US average ratio is used to convert site to source energy. The ratio for grid electricity is 3.14 and for natural gas is 1.05 [18]. Values presented throughout the paper are in terms of source energy, unless otherwise specified.

Energy use intensity, often referred to as energy index (EI), is calculated based on site energy to compare homes across vintage and size categories. It is based on energy per area of conditioned floor space in kBtu/sf Equation (3) and in kWh/m^2 Equation (4).

$$\text{Source Energy}(\text{kBtu}) = (\text{Annual Electricity}(\text{kBtu}) \times 3.14) + (\text{Annual Gas}(\text{kBtu}) \times 1.05) \quad (1)$$

$$\text{Source Energy}(\text{kWh}) = \text{Source Energy}(\text{kBtu}) \times (1000\ \text{Btu}/1\ \text{kBtu}) \times (1\ \text{kWh}/3413\ \text{Btu}) \quad (2)$$

$$\text{Site Energy Index}(\text{kBtu/sf}) = (\text{Annual Electricity}(\text{kBtu}) + \text{Annual Gas}(\text{kBtu})) / \text{Area of Conditioned Space}(\text{sf}) \quad (3)$$

$$\text{Site Energy Index}(\text{kWh/m}^2) = \text{Energy Index}(\text{kBtu/sf}) \times (1,000\ \text{Btu}/1\ \text{kBtu}) \times (1\ \text{kWh}/3,413\ \text{Btu}) \times (10.7639\ \text{sf}/1\ \text{m}^2) \quad (4)$$

3. Results & Discussion

The homes studied were analyzed with respect to their fuel type (all-electric and dual-fuel) across various other factors to include vintage and size, number of shared walls, number of stories, reference, and non-reference homes. The objective of the segmentation approach, as previously stated, is to compare similar homes as well as to compare energy consumption resulting from the presence of specific home features.

In terms of fuel-type, 66% of SFAHs are dual-fuel homes and 34% are all-electric homes with an average size of 1509 sf (140 m^2) and 1376 sf (128 m^2), respectively. Previous work from [12] on Bexar County's SFDH stock has shown that all-electric houses, on average, are newer and larger in size with lower site and source energy index values than those with access to natural gas. However, **Table 1** indicates that all-electric SFAHs are newer with lower average source energy consumption and average site energy index compared to dual-fuel homes that are older (1978) and larger in size.

3.1. Size and Vintage

The average size for all SFAHs in this study is 1465 sf (136 m^2). The average size of SFAHs in the resulting subset under analysis has not changed significantly over time. Homes built in the 1960s, are larger in size compared to homes in all other decades and homes built in the 1980s have the smallest average size (**Figure 1**). Since the 1990s the average size of homes has stayed relatively constant and just above the building stock's average. In terms of vintage, the majority of SFAHs are built in the 1970s and 1980s (76%) followed by 1990s and 2010-present (23%). Since 2000, there are more reference homes built than non-reference homes. Larger homes (>2500 sf in size [>232.3 m^2])

Table 1. Average energy consumption of homes based on fuel type.

Category	Average Vintage	2013 Source Energy kBtu (kWh)	Average Site Energy Index kBtu/sf (kWh/m^2)
All Homes	1983	145,532 (42,640)	41.5 (131.4)
All-electric	1994	139,097 (40,755)	33.9 (101.7)
Dual-Fuel	1978	148,787 (43,594)	45.4 (143.4)

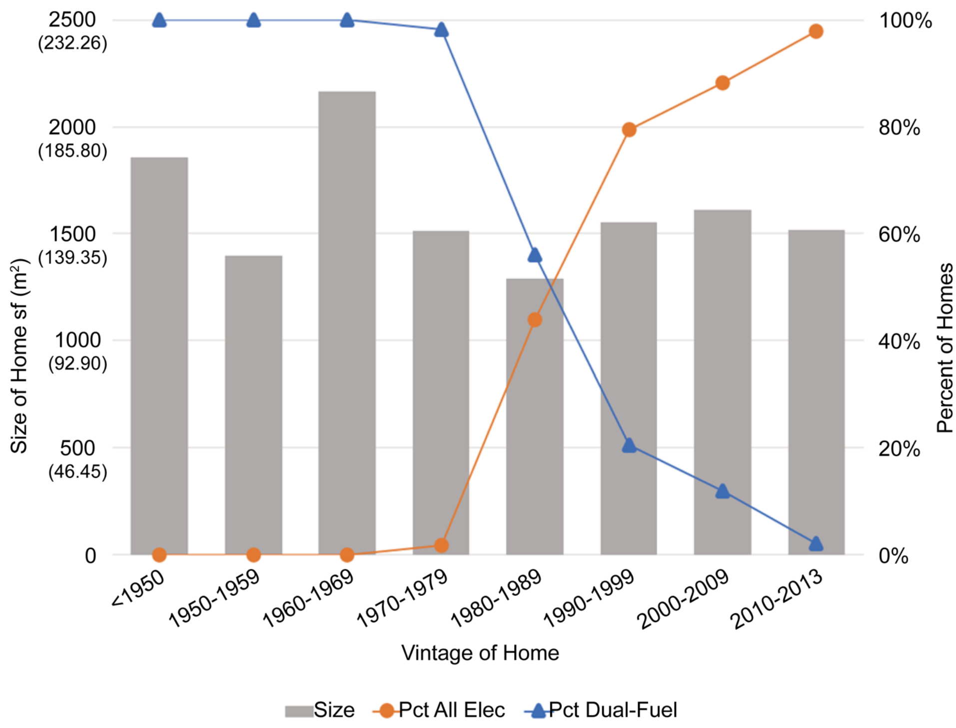

Figure 1. Percent of homes by fuel type based on size and vintage.

are more likely to have fireplaces, swimming pools or both features. Before the 1980s, 98% percent of homes are dual-fuel homes. However, since the 1980s more all-electric homes have been built and the number of dual-fuel homes has experienced a steep decrease, as shown in Figure 1. There are a couple of main reasons for the steep increase in the number of all-electric homes built since the 1980s: 1) the local geology, and, 2) incentives by the local utility. The geology influences development and construction decisions because the soils in the area soils are such that digging and trenching required for installation of natural gas lines is difficult and costly. Local developers and home builders opted to build more all-electric homes, which have lower utility connection and site development costs compared to dual-fuel homes. Cost of mechanical systems is also different for all-electric homes and dual-fuel homes (gas water heaters, gas furnaces, etc). The local electric utility does not control access to natural gas for the entire area within Bexar County. As a consequence, the utility cannot provide natural gas to all of the customers for which it already provides electricity. The resulting effect is a net increase in the number of all-electric homes built in the area.

3.2. Reference vs Non-Reference Homes

In general, reference SFAHs in the San Antonio area tend to be smaller in size than non-reference homes with an average size of 1311 sf (122 m^2) and built in the 1980s. Figure 2 shows the source energy for reference homes and non-reference homes in 2013. Residential energy consumption per unit of conditioned space, also referred to as energy index, is 9.5% lower for reference homes compared to non-reference homes.

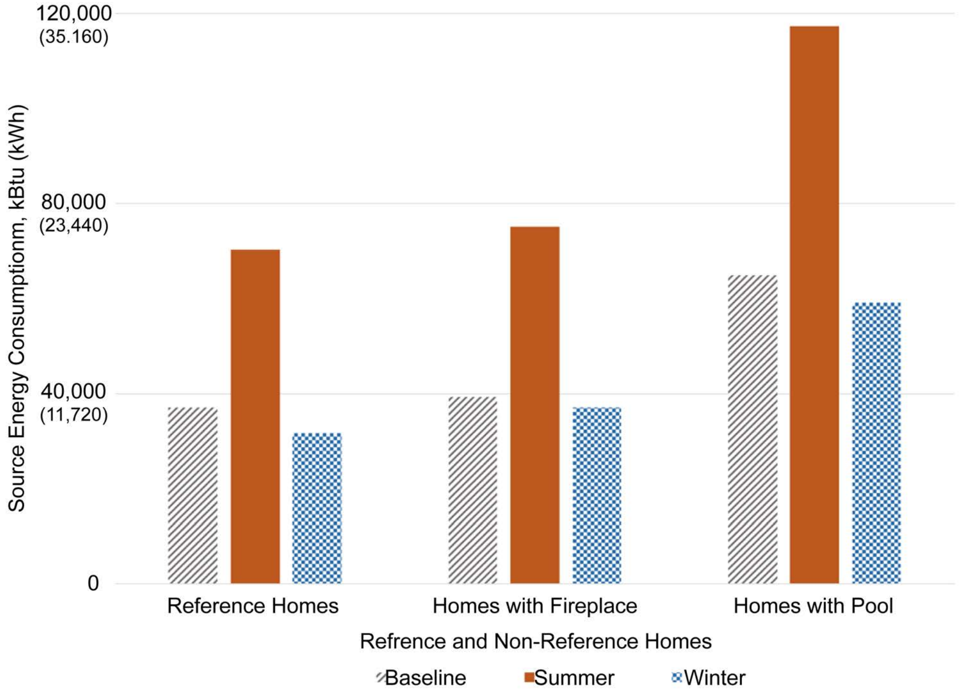

Figure 2. Average Source energy of reference homes vs non-reference homes.

The non-reference homes are bigger in size and therefore consume more energy compared to reference homes [19].

In terms of source energy reference homes consume significantly (9.2%) less energy compared to non-reference homes (p-value < 0.05, df = 3855) and are mostly built in the 1970s and 1980s. There is also a significant difference (p-value < 0.05, df = 3848) in the baseload source energy consumption of reference homes when compared to non-reference homes. In addition, non-reference homes include homes with fireplaces and/or swimming pools, which have been shown to increase seasonal energy consumption.

The homes with a pool and/or spa, consume significantly (47.9%) more source energy in the summer on average 13,279 kBtu (3892 kWh) compared to homes without pools and/or spas (p-value < 0.05, df = 77). Additionally, the impact of the presence of fireplaces on winter source energy consumption of homes was also studied. Homes with fireplaces, consume significantly (15.4%) more source energy in winter by the average of 5304 kBtu (1554 kWh) compared to homes without fireplaces (p-value < 0.05, df = 3735). Results from this study are aligned with previously published work by the authors studying the impact of fireplaces on energy consumption in SFDHs [13] that indicated homes with fireplaces consume approximately 31% more heating energy than homes without fireplaces, regardless of fuel type.

As shown in Figure 2, homes with pools consume on average 74% more energy in all seasons than reference homes. It can be said, there is a positive correlation between swimming pool presence and overall household energy consumption. The presence of pool is also the indicator of other household structural, behavioral, and demographical features that are associated with higher energy consumption. Compared to reference homes, homes with fireplaces consume more energy in the winter. Based on our dataset, homes with swimming pools consume, on average, 67% more energy during the summer months when compared to reference homes. Similarly, homes with fireplaces consume, on average, 17.2% more energy during winter months compared to reference homes. Results from this study are aligned with previously published work by the authors studying the impact of swimming pools on household electric intensity in San Antonio, Texas [14] that indicated homes with pools used over 40% more energy than comparable homes without pools.

All-electric homes consume 6.7% less source energy compared to dual-fuel homes (p-value < 0.05, df = 3156). In **Figure 3** the average winter source energy of homes with fireplaces is studied. Results indicate that winter source energy consumption for reference dual-fuel homes is less than dual-fuel homes with fireplaces by 18%. The average vintage of dual-fuel reference homes and dual-fuel homes with fireplaces is approximately the same (1978); however, dual-fuel homes with fireplaces are approximately 420 sf (39 m^2) larger than dual-fuel reference homes.

Reference all-electric homes consume 9% less winter source energy compared to all-electric homes with fireplaces. The average size of all-electric reference homes and all-electric homes with fireplaces is approximately the same; however, all-electric homes with fireplaces are 12 years older (1988) on average than reference homes (2000).

3.3. Number of Shared Walls

By definition, SFAHs share one or two walls, a factor that affects energy consumption.

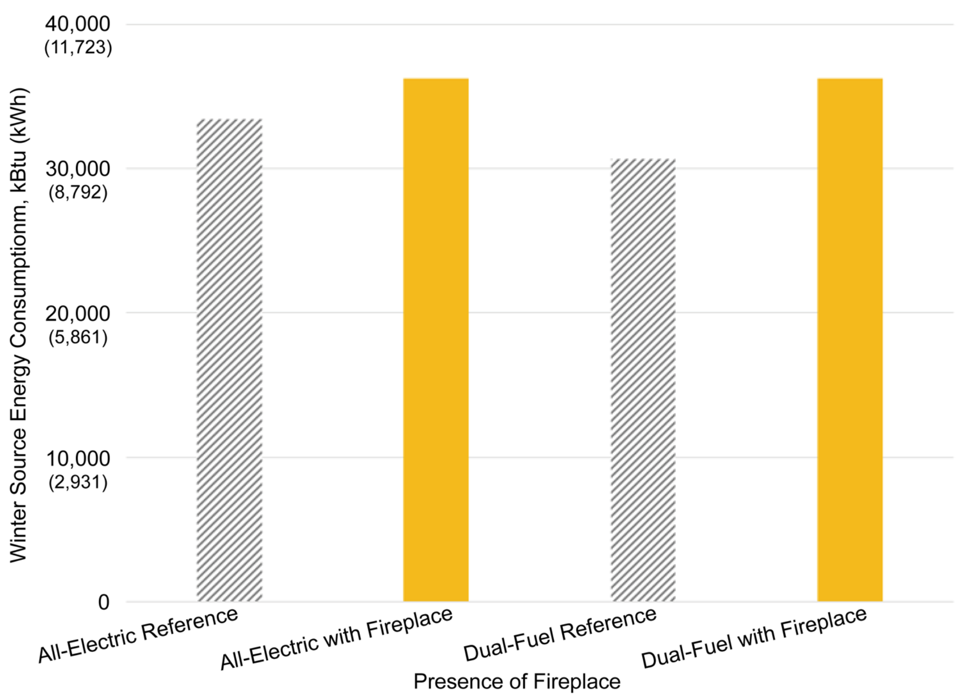

Figure 3. 2013 source energy consumption for homes with fireplaces by fuel type.

In the data set, 169 records out of 3932 homes did not have data on the number of shared walls and are therefore excluded from further analysis. 58% of the SFAHs share one wall and the rest (42%) share two walls. **Table 2** indicates the source energy consumption in one- and two-walls shared all-electric and dual-fuel homes. The number of homes with one-shared wall in both all-electric and dual-fuel categories is higher than the number of homes with two-shared walls. The all-electric homes with two-shared walls consume significantly (6.85%) (p-value < 0.05, df = 576) less energy than homes sharing one wall. However, the source energy consumption of dual-fuel homes with one- or two-shared walls is not significantly different (p-value > 0.05, df = 2511). This result is aligned with previous related studies on the effects of household and building characteristics on the annual energy consumption of US residential buildings by [10] [15] [20] and [21].

Within both fuel type categories, homes with one-shared wall are smaller in size and consume more energy compared to homes with two-shared walls. Sharing more than one wall will help to minimize the surface of the building that is exposed to outside temperature and conditions. The results indicate that the number of shared walls is a factor on the energy consumption of the homes, due to the reduction in exposure to sun, wind, and other climatic features.

3.4. Number of Stories

The results from a study [22] on the urban energy consumption at neighborhood scale support the results of this study. Researchers indicated that the most effective urban factor besides other physical factors such as parcel size and setback on energy consumption is the number of floors or stories (building height).

The number of stories of a home, which is an indicator of the exposed surface area of the home, is considered to have an effect on the energy consumption of the building. In a study on efficient design of residential buildings [23], results indicated that a smaller façade resulted in 26.67% reduction in energy consumption.

As illustrated in **Figure 4**, energy consumption of all-electric and dual-fuel homes is analyzed based on number of stories and size. Two-story dual-fuel homes sized 1000 - 1499 sf (93 - 139 m^2) [size category 2] and two-story all-electric homes sized 1500 -

Table 2. Source energy consumption in homes with one and two-shared walls.

	All-Electric Homes		Dual-Fuel Homes	
	One-shared wall	Two-shared wall	One-shared wall	Two-shared wall
Average Vintage	1993	1997	1979	1979
Average Size sf (m^2)	1309 (122)	1558 (145)	1455 (135)	1566 (145)
Source Energy Consumption kBtu (kWh)	141,604 (41,490)	132,526 (38,830)	150,386 (44,063)	147,199 (43,129)
Average Site Energy Index kBtu/sf (kWh/m^2)	36.3 (114.8)	27.7 (87.9)	47.2 (149.6)	43.3 (137)

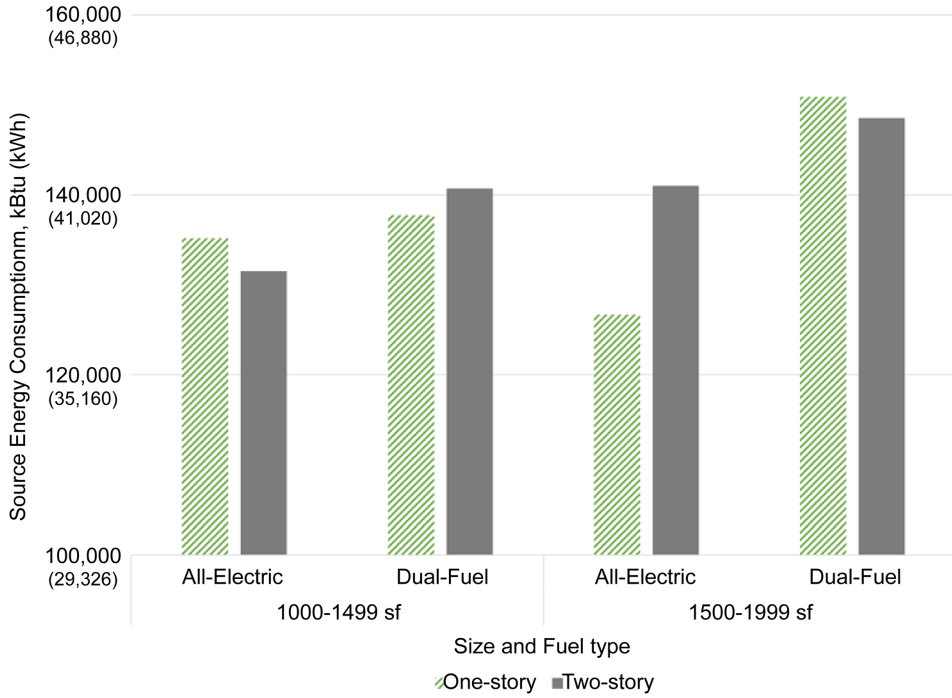

Figure 4. Average source energy consumption of all-electric and dual-fuel homes based on number of stories and size.

1999 sf (139 - 186 m^2) [size category 3] consume more energy than the one-story counterparts.

The two-story all-electric homes sized 1500 - 1999 sf (139 - 186 m^2) [size category 3] consume 11.34% (p-value < 0.05, df = 85) more energy throughout the year compared to one-story homes. The reason is further investigated, and it appeared that average vintage of homes is similar and both one-story and two-story homes do not have swimming pools. However, the 2-story homes have greater number of fireplaces and more are sharing two-walls. That said, neither of these factors adequately explains the 11.34% increase in source energy consumption.

On the other hand, although two-story dual-fuel homes sized 1000 - 1499 sf (93 - 139 m^2) [size category 2], consume 2.15% more energy throughout the year compared to one-story homes, the difference in source energy consumption is not significant (p-value > 0.05, df = 213).

Interestingly, an insignificant decrease (2.80%) is seen in source energy consumption (p-value > 0.05, df = 669) from one- to two-story homes when looking at all-electric homes sized 1000 - 1499 sf (93 - 139 m^2) [size category 2]. Within this size category there is a larger presence of fireplaces and two shared-walls in one-story homes compared to two-story homes.

In addition, an insignificant decrease (1.58%) is seen in source energy consumption (p-value > 0.05, df = 919) from one- to two-story homes when looking at dual-fuel homes sized 1500 - 1999 sf (139 - 186 m^2) [size category 3]. Within this size category there is a larger presence of pools in one-story homes compared to two-story homes.

4. Conclusions and Policy Implications

This study investigated source energy consumption for approximately 33% of SFAHs in Bexar County, Texas. The objective of this study was to better understand the stock of SFAHs and associated energy utilization patterns. A secondary objective was to identify potential implications of current building practices and promote development of more energy-efficient housing alternatives. Results indicate that the size of SFAHs has been relatively stable over time. The homes are relatively efficient, with an average energy index of less than 50 kBtu/sf (157.5 kWh/m^2). Reference SFAHs in the area are smaller in size (average size of 1311 sf [122 m^2]), were built in the 1980s, and consume less energy compared to non-reference SFAHs. Newer single-family attached homes tend to consume less energy on an annual basis and have lower energy index values.

The study shows that home size is the driving factor in energy consumption. Smaller homes with pool and/or spa or fireplace consume more energy than larger homes, which have none of the mentioned features. Therefore, as shown in **Figure 5**, the major drivers of energy consumption for SFAHs in the area are: 1) home size or area of conditioned space, 2) presence of swimming pools, 3) number of bedrooms, 4) number of stories, 5) presence of fireplace, 6) home vintage, 7) fuel-type, and 8) lot size.

The results of this study also show that in terms of energy consumption, all-electric two-story homes that are sharing two walls are the most energy efficient among SFAHs. Therefore, to promote energy-efficient housing alternatives, it would be helpful to build smaller reference SFAHs. Finally, the researchers recommend further investigation using modelling programs and experimental methods to highlight the effect of housing

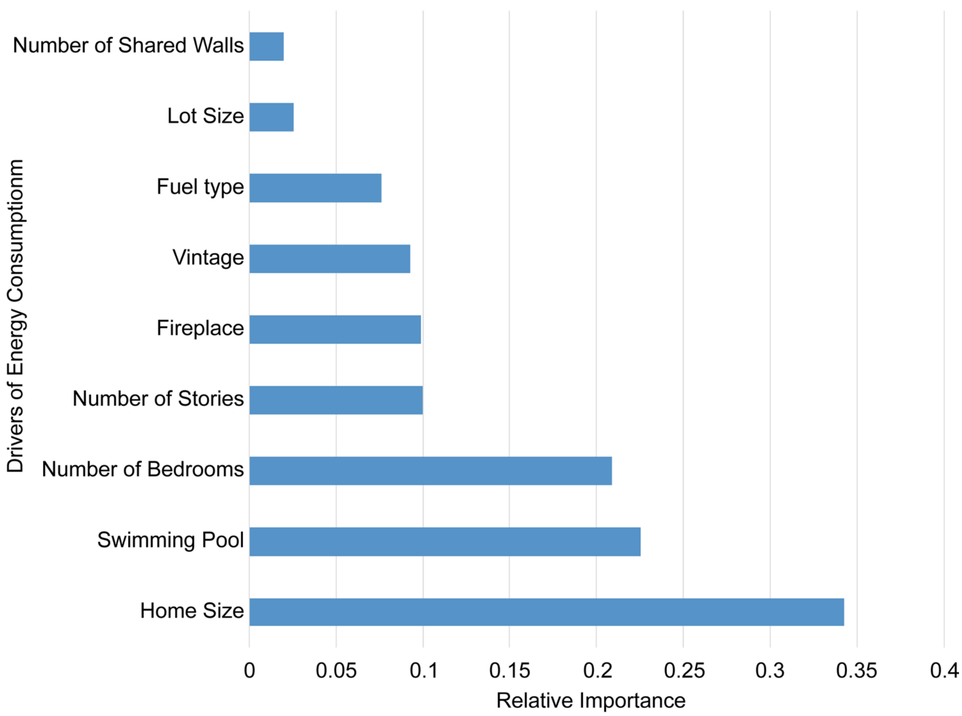

Figure 5. Drivers of energy consumption in single family attached homes.

characteristics on energy consumption considering more detailed climatic conditions, and to implement the findings as part of a housing strategy that promotes energy efficiency in building design and long-term urban planning.

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