How Energy Efficient Are U.S. Homes?

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Abstract

While government policies aim to increase residential energy efficiency, policymakers know little about the efficiency of the U.S. housing stock and improvements in efficiency over time. I estimate the average space heating efficiency of U.S. homes, improvements in residential space heating efficiency over time, and impacts of building energy codes on residential space heating efficiency. Homes built in the 1990s were about 30% more efficient than those built before 1950. Improvements over time in design and construction of new homes can explain about 80% of this difference, and most of the improvement occurred during and after the 1970s. Implementation of building energy codes by states increased home space heating efficiency, accounting for about 30% of the efficiency gains attributable to improvements in design and construction of new homes. Codes saved about 7% of annual residential space heating energy consumption or about 3% of overall annual residential energy consumption and homes saved on average about $60 per year in space heating energy costs. Greater knowledge about home space heating efficiency will enable policymakers to design better policy instruments and to direct resources where they are most needed.

Introduction

Space heating and cooling constitute the largest residential energy end uses, together accounting for 48 percent of all energy used in American homes.[1] In 2013, American homes consumed about 132,000 GWh (0.45 quadrillion Btus) of delivered electricity for space heating and 36 billion therms (3.55 quadrillion Btus) of natural gas for space heating.[2] In the same year, American homes consumed 188,000 GWh (0.64 quadrillion Btus) of delivered electricity for air conditioning. Energy use for space conditioning is also the greatest source of greenhouse (GHG) emissions in the residential sector, responsible for approximately 1,100 million metric tons of carbon dioxide emissions and 38% of residential sector emissions.[3]

In the last several decades, policymakers have sought to reduce energy use and greenhouse gas (GHGs) emissions from residential space conditioning. Policies aimed at increasing residential space conditioning efficiency have included state and local energy efficiency building codes (Aroonruengsawat et. al. 2012, Jacobsen and Kotchen 2013, Kotchen 2015), home weatherization programs for lower income households (Greenstone, Fowlie, and Wolfram, 2014), and utility or public energy-efficiency programs that offer incentives for adoption of high efficiency windows, insulation, and space conditioning equipment (Arimura, Li, Newell, and Powell 2012, Davis, Fuchs, and Gertler, 2014).

While policies intended to increase residential space conditioning efficiency are now widespread, little is known about the current efficiency of the U.S. housing stock as well as improvements in efficiency over time. At the same time, disagreement persists about the impacts and cost-effectiveness of policies intended to increase the energy efficiency of homes (Allcott and Greenstone, 2012; Greenstone, Fowlie, and Wolfram 2014, Levinson, 2014). Better knowledge about the efficiency of U.S. homes and the impacts of efficiency policies would allow policy makers to design better policy instruments and to direct resources where they are most needed.

This paper presents a new approach for estimating the space heating efficiency of U.S. homes and

1 2009 Residential Energy Consumption Survey. See http://www.eia.gov/consumption/residential/.
2 Residential Sector Key Indicators and Consumption. EIA, Annual Energy Outlook, 2015. Series ref2015.d021915a. The average U.S. home uses about 11,000 kWh of electricity annually.
3 Energy-Related Carbon Dioxide Emissions by End Use. EIA, Annual Energy Outlook, 2015. Series ref2015.d021915a.

the impacts of energy efficiency policies on space heating efficiency. The basis for the approach is an econometric model that expresses home space heating energy use in terms of energy lost from both conduction of space heat from the home's interior to the outside and conversion of primary space heating fuel into space heat. The model was derived directly from an engineering model of home space heating and normalizes for differences between homes in size, severity of the heating season, and demand for space heating, enabling comparisons of home space heating efficiency over time and between regions. The model yields estimates of the average efficiency of the exterior walls and attic ceilings, that is, the rate of heat loss intensity per square foot of envelope area per degree of difference between the home's interior temperature and the outside temperature. The rate of heat loss intensity depends on both the thermal resistance of the home's envelope, which includes exterior walls, doors, and windows, and the attic ceiling, as well as the efficiency of space heating equipment in converting the primary heating fuel into useful heat. In the model, the reciprocal of the coefficients represents the product of the efficiency of the space heating unit and the envelope R factor, which is the standard engineering measure of home wall or ceiling resistance to heat loss.

I estimate home space heating energy efficiency using data from the U.S. Department of Energy's Residential Energy Consumption Survey (RECS), a nationally representative survey of energy use of U.S. households, for 2001, 2005, and 2009. It was possible to estimate the average space heating efficiency of U.S. homes because in 2009 the RECS reported for the first time relatively precise information about each home's location, which permitted the mapping of average outside temperature from nearby weather stations to each home. With information about a home's approximate location, characteristics (heated floor space, number of floors, and presence of heated basement), space heating energy use, and typical thermostat heating set point, it was possible to estimate the average efficiency of the attic ceiling and exterior walls of U.S. homes.

Modeling Home Space Heating Efficiency

Home space heating energy use can be expressed in terms of energy loss. Space heat is a form of energy that is transferred across a boundary of a system (e.g., a home) to the outside.[4] Energy may be lost through conduction of heat from the home's interior to the outside, infiltration of outside air, or convection. Energy may also be lost in converting the primary heating fuel into space heat. Space heating energy loss is a function of the heating fuel used (e.g., electricity or natural gas), the efficiency of the space conditioning equipment in converting the fuel to space heat, and the thermal properties of a home's walls, attic ceiling, floors, windows, and doors (collectively, known as the building envelope). A home that uses an old, poorly maintained furnace or that is poorly insulated will use more energy to maintain a given interior temperature than a home that has a high-efficiency furnace (e.g., Energy Star rated) or that is well insulated.

While space heat can be lost to the outside through conduction, infiltration, or convection, by far, the most important source of energy loss is conduction, heat that passes through the building's thermal boundary or envelope—walls, windows, and doors—to the outside (Krigger, 2000). Home thermal efficiency can be measured in terms of conductivity, the rate of heat transfer across a boundary, such as a home exterior wall or attic ceiling. According to Fourier's law of conduction (Borgnakke and Sonntag, 2009), heat transferred through a boundary is proportional to the temperature gradient across the boundary and the boundary area, with the proportional constant equal to the boundary's thermal conductivity. As commonly expressed in engineering models of home heating energy use, Fourier's law of conduction says the rate of conductive heat loss (J) in kBTUs per hour is:

$$J = \text{Area x Heating Degrees x } 1/R \qquad \text{(Equation 1)}$$

4 See Borgnakke and Sonntag (2009), p. 106.

where Area is the area of the home's exterior walls or attic ceiling. Heating degrees (HD) equals Max(F_I – F_O, 0), where F_I is the home's interior temperature and F_O is outside temperature, both measured in °F. R is the envelope's thermal resistance and 1/R is the rate of heat flow in BTUs per hour per square foot of envelope area per heating degree. Space heating energy use depends positively on envelope area and the indoor-outdoor temperature gradient and negatively on the envelope's thermal resistance. Thus, holding heating degrees constant, smaller or more thermally resistant houses will use less heating energy.

Equation 1 only captures heating energy lost through conduction, not any energy lost by the space heating unit in converting the primary fuel (e.g., electricity or natural gas) to space heat. As noted, most electric resistance heating units have efficiencies of close to 100%, that is, all energy used is converted to useful heat. In contrast, most residential gas furnaces, which are in 66% of U.S. single family homes, have efficiencies ranging from 50% to almost 95% (Krigger, 2000). Let *E* be the efficiency of the heating unit. Then given Area, R, and Heating Degrees, total space heating energy loss per hour (J_E) equals

$$J_E = \text{Area x Heating Degrees x } 1/(\text{R x } E) \qquad \text{(Equation 2)}$$

This equation shows that a home with a gas furnace with efficiency of 66% would use 50% more heating energy to maintain the home interior at a particular temperature than an otherwise equivalent home with a fully efficient electric furnace.

To calculate annual space heating energy loss through the envelope area J*, we can restrict attention to hours when the heating system was activated and integrate Equation 2 over time *t*:

$$J^* = \int_{t=0}^{T} \left(\frac{A}{R\ x\ E}\ x \text{ Heating Degrees}_t \text{ x } I_t(\text{HeatOn}=1)\ dt\right) \quad \text{(Equation 3)}$$

Letting j = {1, 2, …, J} denote the different components of the home envelope and summing over the components, home annual space heating energy use equals:

$$J = \sum_{j\ in\ J} \int_{t=0}^{T} \left(\frac{A_j}{R_j\ x\ E}\ x \text{ Heating Degrees}_t \text{ x } I_t(\text{HeatOn} = 1)\ dt\right) \qquad \text{(Equation 4)}$$

In Equation 4, the efficiency of envelope j is measured by $\frac{1}{E\ x\ R_j}$, the *space heating energy use intensity rate*—the energy loss in BTU per hour per square foot of area per heating degree. The home's overall space heating efficiency can be measured by the *space heating energy use rate per heating degree*, calculated as the sum over the envelope components of the product of the envelope space heating energy use intensity rate and the envelope area:

$$\sum_{j\ in\ J} \frac{A_j}{E\ x\ R_j}$$

When comparing overall home space heating efficiencies between different regions or over time, I normalized the efficiency estimates for differences or changes in home sizes by evaluating the above expression using the same values of attic ceiling and exterior wall areas for all regions or time periods.

Finally, the percent of space heating energy lost through envelope j equals:

$$\frac{\frac{A_j}{R_j\ x\ E}}{\sum_{j\ in\ J} \frac{A_j}{E\ x\ R_j}}$$

Note that because the efficiency of the space heating unit cannot be separately estimated, this expression is actually an estimate of the percent of space heating energy *delivered by the space heating unit* lost through envelope j and does not account for losses in converting the primary heating fuel to useful heat.

Data

Data used in this study come from the U.S. Department of Energy's 2001, 2005, and 2009 Residential Energy Consumption Survey (RECS) and the National Climatic Data Center of the National Oceanic and Atmospheric Administration (NOAA).

Approximately every four years, DOE conducts the RECS, a comprehensive survey about home energy use for a nationally-representative sample of U.S. households. DOE surveys households about their annual energy consumption and expenditures for different energy end uses including space conditioning, lighting, water heating, and plug loads (televisions, computers, refrigerators, etc.). It also collects detailed information about each surveyed home's stock of energy-using appliances and the household's utilization of space heating and cooling equipment, including typical thermostat set points during the day (when the home is occupied and unoccupied) and night.

RECS also reports an estimate of each surveyed home's annual space heating energy use. This estimate is based on a DOE statistical model of each home's energy bills, annual HDDs, heating equipment type, thermostat set points, self-reported insulation levels, and information about home characteristics such as floor area and stories. DOE believes the estimates of space heating energy use are accurate and the best available for U.S. homes.

Finally, RECS also reports data on the household such as household size, income, and head age, and housing unit such as home type (e.g., multi-family apartment, single-family home, mobile home, etc.), floor space, number of stories, and year of construction. RECS also provides the approximate location of each home using Building America climate zone and reportable domain, which was either one of 27 U.S. states or a small groups of nearby states. The 2009 RECS, the most recent survey for which household micro-data are available, was the first to report the state of residence for a majority of surveyed households.

I also collected hourly weather data for 2009 from 445 NOAA weather stations across the United States. I used the data to estimate for each home the number of space heating hours and the average outside temperature during heating hours for each RECS home. Estimation of space heating hours was done in a series of steps. First, I estimated the average thermostat set point using self-reported daytime occupancy and daytime and nighttime thermostat set points. Next, for each geographic area defined by a combination of a Building America climate zone and RECS reportable domain, I estimated the population-weighted average of outside temperature for each hour in 2009. Finally, using the location of each home, I calculated the number of hours and the average temperature during the heating season as a function of the home's average thermostat set point and hourly outside temperature. An hour was a heating hour if the difference between the home's average thermostat set point and the outside temperature for that hour was positive. Stewart (2016) tested alternative approaches to estimating heating season hours.

The analysis was limited to 5,471 single-family, detached homes in the continental U.S. that used electricity, natural gas, or fuel oil as a primary heating fuel and that had a furnace or heat pump as their primary heating equipment. Unless otherwise stated, references to U.S. homes in the remainder of this paper refer to this sub-population. Homes in the analysis sample accounted for 49% of U.S. homes and 58% of residential space heating energy use in 2009. Stewart (2016) presents sample summary statistics.

Estimation of Home Space Heating Efficiency

As Equation 6 depends on building characteristics that are not directly observable in RECS, specifically, the attic ceiling area and the exterior wall area, the equation is not directly estimable. However, with some assumptions about the dimensions of homes, we can parameterize and estimate Equation 4.

First, I express Equation 4 in terms of discrete time. Letting h^* in {1, 2, …, H} denote hours when HD>0 and HeatOn=1:

$$J = \sum_{j \ in \ J} \int_{t=0}^{T} (\frac{A_j}{R_j \ x \ E} \ x \ \text{Heating Degrees}_t \ x \ I_t(\text{HeatOn} = 1) \ dt$$

$$\approx \sum_{j \ in \ J} \frac{A_j}{R_j \ x \ E} \text{ x } \overline{HD} \text{ x H} \qquad \text{(Equation 5)}$$

where H is the total number of heating hours and $\overline{HD}$ is average heating degrees during heating hours. Equation 5 is an approximation because the heating system may be switched to on and HD may be greater than zero for parts of some hours.

Next, assume a home with number of heated floors *n* and heated floor space *s* in square feet has a rectangular layout with ratio of length to width equal to *b* and floor-to-ceiling height h. If the home has a heated basement or attic, the basement or attic is included in *n*. Then, the attic ceiling and exterior wall areas are:

$$A_{Ceiling} \approx A_{Floor} \approx {}^{s}/_{n}$$

$$A_{Walls} \approx 2n\sqrt{A_{Ceiling}} \ x \ [h \ x \sqrt{b} + \tfrac{h}{\sqrt{b}}]$$

By expressing heating energy use E in kBTU, dividing both sides of Equation 5 by H, and substituting the expressions for $A_{Ceiling}$ and A_{Wall}, we obtain the following estimating equation:

$$(\text{kBTU/hour})_i = \beta_C \left(\frac{s_i}{n_i}\right) x \ \overline{HD_i} + \beta_W \ 2n_i \ x \sqrt{\left(\frac{s_i}{n_i}\right)} \ x \ [h \ x \sqrt{b} + \tfrac{h}{\sqrt{b}}] \ x \ \overline{HD}_i + \varepsilon_i \qquad \text{(Equation 6)}$$

Comparison to Equation 5 shows that for a given *h* and *b*, the coefficient β_j, j in {Ceiling, Wall}, is the space heating energy use intensity rate per heating degree, that is, the average space heating energy use (kBTU) per square foot of envelope area per hour for each degree of difference between the thermostat set point and the exterior temperature. Also, the inverse of the beta coefficients *x* 1000 is the product of the heating equipment efficiency and the thermal efficiency of the attic ceiling or exterior wall area thermal efficiency.

In order to estimate Equation 6, I made specific assumptions about the dimensions of the average home: the ratio of length to width (*b*) and ceiling to floor height (h). The main analysis assumes b=1.5 and h= 9 feet, that is, homes were 1.5 times long as wide and the floor to ceiling height was 9 feet. However, as part of the analysis below, I tested the sensitivity of the efficiency estimates to different assumptions about home dimensions and show that the estimates were insensitive.

Estimates of average attic ceiling and exterior wall energy use intensity rates will reflect not just effects of wall insulation but also resistance to heat loss provided by interior paneling, exterior sheathing, walls, siding, windows, doors, and, in some attics, uninsulated space. Also, while conduction is the greatest source of heating energy loss in most homes, the exterior wall and attic ceiling efficiency estimates may also reflect other forms of heat loss or gain such as infiltration or solar heating. For example, air infiltration may arise from gaps in the building envelope such as around windows and doors but also from unobserved occupant behaviors such as the frequency of entry and exit.

As Equation 6 was derived from an engineering model of residential space heating energy use, it is important to consider what the model error represents. The largest source of error likely arises from inaccuracies in either the RECS' estimate of home space heating energy use or my estimate of the number of heating days.

Main Results

Table 1 reports average efficiency estimates for home attic ceilings and exterior walls for each climate zone and for the U.S. based on estimation of Equation 6. Space heating energy use intensity rate estimates for the U.S. were obtained as a weighted average of the climate zone estimates, with weights equal to the climate zone shares of space heating energy use. When comparing overall home space heating efficiency between regions or over time, I normalized for differences or changes in home size by evaluating the expression using the mean values of attic ceiling area and exterior wall area of U.S. homes in 2009.

Table 1. Estimates of Residential Average Space Heating Efficiency

	N	Attic Ceiling - Space Heating Energy Loss Intensity Rate	Exterior Wall - Space Heating Energy Loss Intensity Rate	Attic Ceiling Thermal Efficiency	Exterior Wall Thermal Efficiency	Rate of home space heating energy loss per heating degree (kBTU/hr)	% of Space Heating Energy Lost through Exterior Walls
Hot-Dry/Mixed-Dry	753	0.000054	0.000116	18.5	8.6	0.29	70.3%
		(0.000016)	(0.000015)			(0.01)	
Hot-Humid	1155	0.000042	0.000096	23.9	10.5	0.24	70.4%
		(0.000013)	(0.000013)			(0.01)	
Marine	274	0.000115	0.000078	8.7	12.8	0.3	47.8%
		(0.000038)	(0.000026)			(0.02)	
Mixed-Humid	1698	0.00004	0.000145	25.2	6.9	0.33	83.3%
		(0.000011)	(0.000009)			(0.01)	
Very Cold/Cold	1591	0.000036	0.000174	27.7	5.8	0.36	88.3%
		(0.000013)	(0.000008)			(0.01)	
United States	5471	0.000042	0.000153	23.8	6.5	0.34	82.9%
		(0.000008)	(0.000005)			0	

Notes: Models estimated by weighted least squares. Dependent variables is home average hourly space heating energy use and observations were weighted by RECS sampling weight. Heteroscedasticity-robust standard errors in parentheses. Attic ceiling space heating energy loss intensity rate and exterior wall space heating energy loss intensity rate are measured in kBTU per square foot of attic ceiling area per hour per heating degree. Attic ceiling thermal efficiency is the product of attic ceiling R value and heating equipment efficiency. Exterior wall thermal efficiency defined analogously.% of space heating lost through exterior walls is percent of space heating energy delivered by the space heating equipment that was lost through exterior walls.

For the United States, the average space heating energy use intensity rate for the attic ceiling was 0.000042 kBTU per hour per square foot per heating degree. The average energy use intensity rate for the exterior walls was 0.000153 kBTU per square foot per hour per heating degree, about four times as large. Both estimates were statistically significant at the 1% level. These estimates imply average effective thermal resistance of the attic ceiling and exterior walls of 23.8 and 6.5, respectively, where I used *effective* to emphasize that the estimate measures the combined efficiency of the envelope and space heating unit. For point of reference, EPA recommends that home attics be insulated with materials rated between R30 and R60 depending on the climate zone.[5] If the average efficiency of heating equipment in the United States were 80%, this would imply an attic ceiling R value of about 30 (≈23.8/0.8). U.S. homes used an average of 0.34 kBTU of space heating energy per hour per heating degree. This amount of energy is equivalent to about 1.15 kWh or about the amount of electricity required to power eleven 100 Watt light bulbs for an hour. On average, about 83% of space heating energy was lost through the home's exterior walls.

The remaining rows of Table 1 report estimates of average space heating efficiency for homes in each climate zone. While homes in the Hot-Humid and Hot-Dry/Mixed-Dry climate zones had the highest space heating efficiency, those in the Mixed-Humid and Very Cold/Cold climate zones were least efficient. Homes in the Very Cold/Cold climate zone used an average of 0.37 kBTU per hour per heating degree, 58% higher than that of homes in the Hot-Humid climate zone. Nonetheless, homes in the Very Cold/Cold climate zone had the most efficient attic ceilings, with average effective thermal resistance of 28. This was offset by low exterior wall average thermal resistance of just 5.6. Because the exterior walls had low average thermal resistance, about 88% of space heating energy was lost through home exterior walls.

Stewart (2016) shows the attic ceiling and exterior wall efficiency estimates were robust to changes in the approach for estimating exterior wall and attic ceiling areas and the number of heating

5 http://www.energystar.gov/index.cfm?c=home_sealing.hm_improvement_insulation_table

hours as well as relaxation of the assumption that the home interior temperature equaled the thermostat average set point. Stewart (2016) also shows that differences in proportion of homes using electricity as a heating fuel can explain all of the difference in space heating efficiency between the Very Cold/Cold and Hot-Humid climate zones.

Effect of Building Vintage on Space Heating Efficiency

A factor that may explain climate zone differences in average space heating efficiency was differences in the average age of homes. Homes in the Very Cold/Cold climate zone were oldest on average, having been built 10 years before those in the Marine climate zone and 16 years before those in the Hot-Humid climate zone. The average year of construction of homes was 1982 in the Hot-Humid climate zone and 1965 in the Very Cold/Cold climate zone. Newer homes could take advantage of advances in building design and materials and the increased efficiency of heating systems. In addition, newer homes in many states were required to meet increasingly stringent energy efficiency standards. Finally, older homes may have experienced greater degradation of the building envelope since construction, further worsening thermal efficiency relative to new homes. All of these factors could have contributed to differences in space heating efficiencies between homes of different vintages and climate zones.

Figure 1 shows for each climate zone and the United States estimates of home average energy use per hour per heating degree by decade of construction.

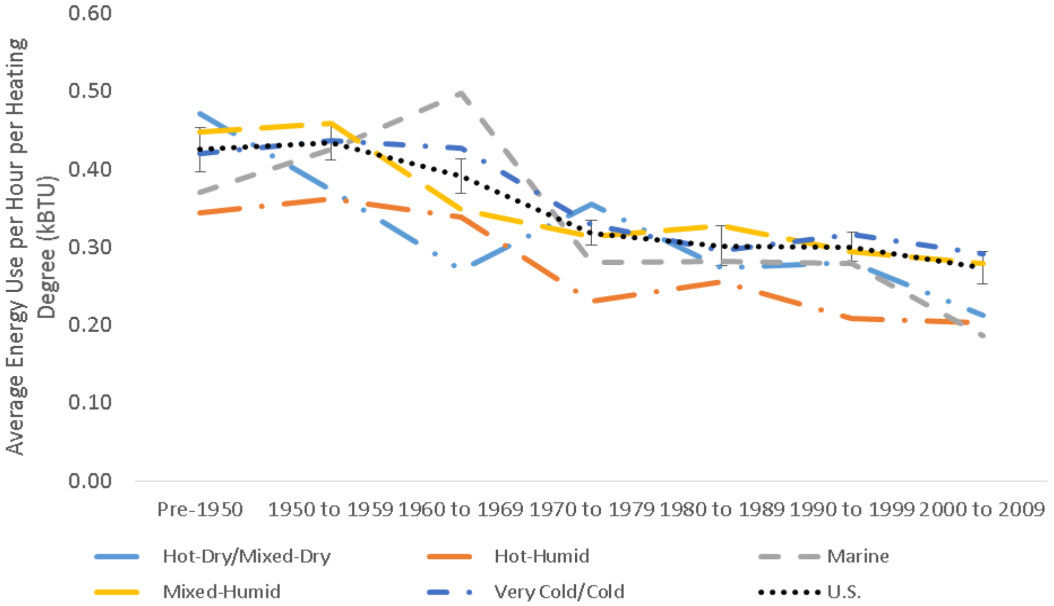

Figure 1. Home Space Heating Efficiency by Decade of Construction

These climate zone estimates of overall home space heating efficiency by decade were obtained from the following regression:

$$\text{kBTU per hour}_i = EW\_HD_i * (\sum_d \gamma_{W,d} I(D=d)_i) + AC\_HD_i * (\sum_d \theta_{A,d} I(D=d)_i) + \varepsilon_i \qquad \text{(Equation 7)}$$

where d indexes the decade during which the house was constructed, d in {Pre-1950s, 1960s, 1970s, 1980s, 1990s, 2000s}; EW_HD is the product of the exterior wall area and average heating degrees for home i, AC_HD is the product of the attic ceiling area and heating degrees for home i, and I(•) is an indicator variable for decade D=d.

Newer homes were significantly more efficient than older homes in 2009. Across the United States, homes built in the 1950s had an average energy use rate of 0.43 kBTU per heating degree while those built in the 2000s had an average energy use rate of 0.27 kBTU per heating degree, a difference of 37%. Homes built in the 1990s were 31% more efficient than those built in the 1950s. A similar relationship held between newer and older homes in 2009 in each climate zone. As **Error! Reference source not found.** shows, differences in space heating efficiency between homes built in the 1990s or 2000s and those built before or during the 1950s were greatest in the Marine, Hot-Humid, and Hot-Dry/Mixed-Dry climate zones.

Panel Regression Analysis

The *age* efficiency effect reflecting degradation of or improvement to the home envelope or space heating equipment since construction is distinct from the *vintage* efficiency effect reflecting the efficiency of home design and construction. Generally, in a cross-sectional analysis in which homes of a particular vintage are observed at only one point in time, it is impossible to identify both effects separately. For example, in the 2009 RECS, all homes constructed in 1984 were also built 25 years ago. This means in Figure 1 that the greater average thermal efficiency of more recently built homes could reflect the gradual but steady degradation of existing homes, not that new homes were built more efficiently than old ones.

To estimate the vintage effect on home efficiency, I collected and analyzed data on U.S. homes from multiple RECS surveys, an approach also employed by Levinson (2014). In the panel, homes built before 2001 are observed at three points in time, in 2001, 2005, and 2009. (Note, however, that this is not a true panel, as the RECS surveyed different homes in each year.) For example, in 2005 and 2009, homes constructed in 1984 can be observed at 21 and 24 years of age. With data on homes of the same vintage in different survey years, it is possible to identify the efficiency effects of both building vintage and age.

I ran the panel regression analysis using RECS homes located in California, Florida, New York, or Texas. The sample was limited geographically because the 2001 RECS and 2005 RECS only reported the state of residence for homes located in one of these states. Also, I excluded homes constructed after 2000 from the analysis sample because most of these homes would not have been observed in the 2005 survey and very few would have been observed in the 2001 survey. In Stewart (2016), I show that homes in California, Florida, New York, and Texas in the 2009 RECS exhibited a similar relationship between average space heating efficiency and decade of construction as homes in the rest of the United States. In these "big states," homes built in the 1990s (0.26 kBTU per hour per heating degree) had average space heating efficiency about 40% lower than that of homes built before the 1950s (0.43 kBTU per hour per heating degree).

In the panel regressions, two-way interaction variables between AC_HD_i or EW_HD_i and decade of construction captured the effect of home vintage on space heating efficiency, and three-way interaction variables between AC_HD_i or EW_HD_i, decade of construction, and indicator variables for survey year captured effects of age. I used three-way interactions to control for building age instead of actual building age in the survey year because the 2001 and 2005 RECS only reported the decade of home construction, not the construction year.

$$\text{kBTU per hour}_i = EW\_HD_i *(\gamma + \sum_d \gamma_d I(D=d)_i + \sum_{d^*} [\gamma_{2001}^d RECS2001_i*I(D=d)_i + \gamma_{2005}^d RECS2005_i*I(D=d)_i]) + AC\_HD_i * (\theta + \sum_d \theta_d I(D=d)_i + \sum_{d^*} [\theta_{2001} RECS2001_i*I(D=d)_i + \theta_{2005} RECS2005_i)*I(D=d)_i]) + \varepsilon_i \qquad \text{(Equation 8)}$$

EW_HD_i and AC_HD_i are defined as before; d and d^* index the decade during which the house was constructed, d in {1950s, 1960s, 1970s, 1980s, 1990s}; d* in {pre-1950s, 1950s, 1960s, 1970s, 1980s, 1990s}; RECS2001 and $RECS2005_i$ are, respectively, indicators that the home was surveyed in 2001 or 2005. The omitted survey year was 2009. The γ and θ coefficients indicate the average energy use intensity rate per heating degree for, respectively, the exterior wall and the attic ceiling of homes built before 1950. The coefficients on the two-way interaction variables indicate the vintage effects. The γ_d

and θ_d coefficients indicate the average energy use intensity rate per heating degree for, respectively, the exterior wall and the attic ceiling of homes constructed during decade *d* relative to the energy use intensity rate of homes built before 1950. The coefficients γ_d^{2001}, γ_d^{2005}, θ_d^{2001}, and θ_d^{2005} indicate the average energy use intensity rate per heating degree of, respectively, the exterior wall and attic ceiling of homes built during decade *d* and surveyed in 2001 or 2005 relative to homes built before 1950 and surveyed in 2009.

Figure 2 shows estimates of the vintage effects for each decade as a percentage of the average energy use rate per heating degree for homes built before the 1950s.

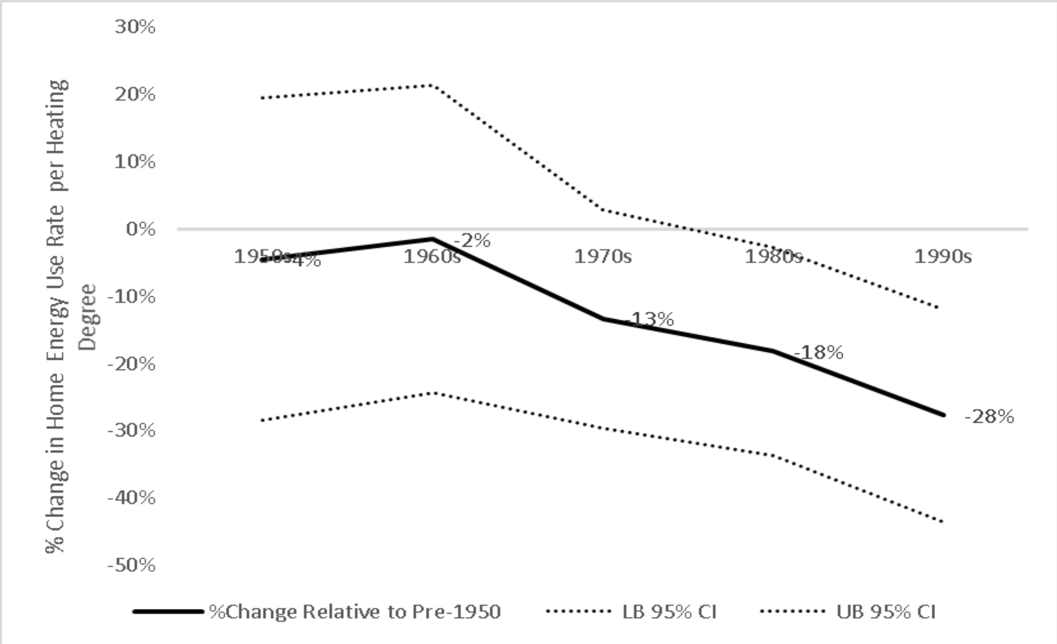

Figure 2. Estimates of Home Vintage Efficiency Effects

The estimates were obtained from estimation of Equation 8 with the addition of interaction variables between AC_HD_i or EW_HD_i and indicators for each of the four states. After controlling for building age, I found that homes of more recent vintage had greater average space heating efficiency, although the rate of improvement was not uniform. Homes constructed in the 1950s or 1960s were no more efficient than those built before 1950. The effect of home construction during the 1950s or 1960s was small and not statistically significant. However, homes constructed during and after the 1970s had significantly greater efficiency than homes built during previous decades. The effect of home construction during the 1970s was to reduce energy use in 2009 by 0.05 kBTU per hour per heating degree relative to that of new homes built before or during the 1950s. Space heating efficiency was even greater for homes built during the 1980s and 1990s. After controlling for building age, homes built in the 1990s used an average of 0.11 kBTU per hour per heating degree less energy than homes built before 1950. Relative to homes built before the 1950s, homes constructed in the 1990s were 28% more efficient.

How much of the difference in average space heating efficiency between homes constructed during different decades can the vintage effect account for? In 2009, the difference in the average energy use rate per heating degree between homes built before the 1950s and those built during the 1990s was about 0.14 kBTU. The space heating efficiency improvement of 0.11 kBTU per hour per heating degree attributable to vintage effects can therefore explain 78% of the difference in average energy use rate between homes built before the 1950 and those built in the 1990s. The remainder can be attributed to different rates of either degradation or improvement in heating efficiency of existing homes of different vintages. For example, the efficiency of old homes may have degraded faster than that of new homes.

Stewart (2016) reports estimates of additional models to demonstrate the robustness of the vintage space heating efficiency impacts. Stewart (2016) also shows that differences between RECS surveys in methodology for estimating space heating energy consumption or in random sampling of homes do not affect the vintage efficiency impact estimates.

Impact of Building Energy Codes on Space Heating Efficiency

A potential explanation for improvements in space heating efficiency of newly constructed homes was implementation by U.S. states of residential building energy codes. Beginning in the 1970s, many states implemented building energy codes to address rising energy costs as well as to reduce the nation's reliance on foreign sources of energy.

Previous research about energy savings from residential building energy codes has compared energy use of homes built before and after code adoption.[6] A challenge of this approach is that there were changes in how households consumed energy while states implemented building energy codes, making it difficult to identify the effect of building energy codes. For example, since states started implementing residential building energy codes in the 1970s, residential energy use patterns have changed in response to changing demographics, increasing penetration of central air conditioning, and adoption of home electronics and other kinds of plug loads. Many of these changes affected newer homes, which were more likely subject to codes, differently than older homes.

Rather than estimating efficiency code impacts on residential energy use, I estimate their impacts on home space heating efficiency. Using difference-in-differences analysis, I compared home space heating efficiency before and after implementation of state building energy codes with changes in efficiency over the same period in states that did not implement such codes.

This approach has several advantages. First, by focusing on improvements in home space heating efficiency, it measures impacts on a primary objective of residential building energy codes. Second, by analyzing space heating energy use as opposed to home energy use, the approach reduces scope for omitted variable bias. As noted already, there are fewer potential confounding variables. Third, the estimates account for any "take-back" in space heating use because homes built to code were more energy efficient. Because the analysis used thermostat set points to control for the household's utilization of the space heating system, the estimates are net of any increase in space heating energy use.

The analysis sample was limited to homes in 17 states in the 2009 RECS for which it was possible to identify the exact state of residence of the home and the year that the state first implemented residential building energy codes. The analysis sample accounted for 61% of U.S. single-family homes and 58% of space heating energy use in single-family homes in 2009. Most states in the analysis sample first implemented residential energy efficiency building codes in three decades, the 1970s (N=12), the 2000s (N=3), or 2010s (N=1).[7] . It is worth pointing out that implementation of building codes during the 1970s coincided with the beginning of sustained efficiency improvements in home design and construction in California, Florida, New York, and Texas, as suggested by the estimated vintage effects estimated in Figure 2.

As the data are a cross-section of U.S. homes in 2009, the analysis of home space heating efficiency cannot control explicitly for age effects, i.e., improvements to or degradation of the home envelope since construction. As a consequence, an important assumption is that homes in code implementing and non-implementing states experienced similar rates of natural change in space heating efficiency. If this parallel trends assumption does not hold, the code impact estimates may be biased. For example, if residents of states that implemented building codes were more likely to make efficiency improvements to existing homes, estimates of building code impacts on home thermal efficiency would be biased upwards.

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6 See Aroonruengsawat, Auffhammer, and Sanstad (2009), Jacobsen and Kotchen (2013), and Kotchen (2015).
7 Missouri has yet to implement residential building energy codes. The other states include Arizona, California, Colorado, Florida, Georgia, Illinois, Indiana, Michigan, Missouri, New Jersey, New York, Ohio, Pennsylvania, Tennessee, Texas, Virginia, and Wisconsin. The implementation year data were collected from Aroonruengsawat et al. (2009) and http://energycodesocean.org/code-status-residential.

Stewart (2016) plots estimates of the average energy use rate per heating degree by decade of construction for homes in states that implemented residential efficiency codes during the 1970s ("early implementers") and homes in states that implemented codes in the 2000s ("late implementers") and shows that in early and late implementing states homes built before the 1970s exhibited similar relationships between construction decade and average space heating efficiency, suggesting that during this period early and late implementing states followed similar efficiency trends.

To test the impacts of residential building energy codes, I estimated a regression model of home average space heating energy use per hour on indicators for implementation of state building codes, decade of home construction, and climate zone:

$$\text{kBTU per hour}_i = EW\_HD_i*(\gamma + \delta^{EW}Code_i + \sum_d \gamma_d I(D=d)_i + \sum_j \mu^{EW}{}_j C_{ij}) + AC\_HD_i*(\theta + \delta^{AC}Code_i + \sum_d \theta_{,d} I(D=d)_i + \sum_j \mu_{AC,j}C_{ij}) + \varepsilon_i \quad \text{(Equation 9)}$$

kBTU per $hour_i$ is space heating energy use per heating hour in 2009. The variable $Code_i$ indicates whether home *i* was constructed when a state residential building energy efficiency code was in effect (=1 if code was in effect and =0, otherwise); and C_{ij} is an indicator variable for home *i* having been located in climate zone *j*, *j* in {Hot-Dry/Mixed-Dry, Hot-Humid, Marine, Mixed-Humid, Very Cold/Cold}. All of the other variables are defined as in Equation 7.

The coefficients δ^{EW} and δ^{AC} represent the average effect of residential energy efficiency building codes on exterior wall and attic ceiling efficiency in 2009. If residential building codes improved home space heating efficiency, the combined estimated effects of any changes in attic ceiling or exterior wall efficiencies should have been negative. The model also includes decade-built variables to control for naturally-occurring changes in efficiency as well as climate zone indicator variables to account for differences between climate zones in average efficiency of the housing stock.

I estimated several models using different sets of controls, as shown in Table 2. Model 1 only included AC_dT_i and EW_dT_i and interactions of these variables with $Code_i$ as explanatory variables. Model 2 allowed home space heating energy use to depend on the home's climate zone but was otherwise the same as Model 1. Model 3 allowed space heating energy efficiency to depend on the decade of home construction. This variable controlled for changes over time in naturally-occurring efficiency and differences in levels of home construction between early and late implementing states. Early implementing states such as California, Florida, and Georgia had relatively high levels of home construction after the 1970s, so even in absence of efficiency codes their housing stocks would have been newer and more efficient than those of late implementing states such as Missouri, Illinois, and Pennsylvania. Model 4 included climate zone and decade of home construction variables and therefore controlled for differences both over time and between regions in naturally-occurring space heating efficiency.

According to Model 4, which controls for both decade of construction and climate zone location, building energy codes reduced the average exterior wall space heating loss by 0.000025 kBTU/sq. ft/hour per heating degree. This effect was statistically significant at the 5% level and amounted to a reduction of between 13% and 26% in average energy use intensity rate, depending on the climate zone and decade of construction chosen for the baseline. Overall, codes reduced the average hourly space heating energy use rate per heating degree by a 0.034 kBTU. Assuming the 17 U.S. states experienced improvements in space heating efficiency of new homes over time as the four most populous states, implementation of state building energy codes can account for about 30% (0.034/0.11) of this improvement. The remaining 70% can be attributed to naturally occurring changes in home design and construction.[8]

8 This estimate would understate the effect of residential building energy efficiency codes if improvements in building design and construction in code implementing states spilled over into non-implementing states.

Table 2. Energy Savings from Residential Energy Efficiency Code Implementation

Model	Additional Control variables	Space Heating Energy Savings (kBTU)	Space Heating Energy Cost Savings (millions of $)	Average Space Heating Energy Savings per Home (kBTU)	Average Space Heating Energy Cost Savings per Home Built ($)	% Energy Savings
Model 1	None	138,044,010,841	2,410	10,768	188	20%
		(19,709,943,819)	(354)	(1537)	(28)	
Model 2	Climate Zone	124,596,433,298	2,186	9,719	171	18%
		(18,069,234,186)	(320)	(1409)	(25)	
Model 3	Decade of home construction	41,271,332,207	695	3,219	54	6.8%
		(10,968,149,719)	(204)	(856)	(16)	
Model 4	Climate Zone, Decade of Home Construction	44,757,678,563	771	3,491	60	7.4%
		(18,005,596,961)	(342)	(1404)	(27)	

Notes: Savings estimates based on energy efficiency building code regression models. See Table 7. Standard errors in parentheses. All cost savings in 2009 dollars.

I conducted several robustness checks of the results, which can be found in Stewart (2016), showing that none of the five late adopting states (Arizona, Illinois, Missouri, Pennsylvania, and Texas) was driving the findings; that the results hold when homes built during the 2000s are excluded from the analysis sample so that all variation in residential energy efficiency code implementation after the 1970s came from between early and late implementing states, and that the results do not change if homes constructed a year or less after implementation of building efficiency codes were assumed to have been permitted before the code went into effect and therefore not subject to codes.

Why did energy efficiency building codes increase the average efficiency of home exterior walls but not attic ceilings in new homes? It is likely that codes increased the efficiency of both attic ceiling and exterior walls in the short run, but impacts on attic ceiling efficiency were short-lived and therefore impossible to measure in this analysis of energy use in 2009. Owners of existing homes not regulated by building energy codes could have undertaken relatively inexpensive efficiency improvements to bring their attic ceilings up to code requirement levels. In contrast, home owners could only undertake improvement to exterior walls at much greater cost and were therefore much less likely to have done them. Therefore, these estimates represent long-run efficiency effects of building energy codes, which take into account the ability of owners of existing homes to make efficiency improvements. Building energy code impacts were likely greater in the first few years after implementation when efficiency differences between new and existing homes were greatest.

Energy Savings from Residential Building Energy Codes

Using the results from the preceding regression analysis, I estimated the annual space heating energy savings and energy cost savings in 2009 from efficiency improvements attributable to implementation of residential building energy codes. Energy savings were the amount of additional energy that would have been used to heat a home to the *same* temperature if building energy codes had not been implemented. Energy cost savings equaled the product of energy savings and the average cost per kBTU for space heating energy paid by the household in 2009. The estimates do not account for demand substitution and income effects on space heating energy use from households facing higher marginal costs of space heating (Borenstein, 2013). Some households may have reduced space heating in response to having less efficient homes.

Stewart (2016) reports energy savings estimates from implementation of building energy codes. Total energy savings were estimated for 15 U.S. states in the analysis sample that had implemented residential efficiency codes before 2009. Using the results of Model 4, I estimated that implementation of building efficiency codes resulted in efficiency savings of approximately 7.4% of space heating energy use in 2009 or 45 billion kBTU (± 35 billion kBTU at the 95% confidence level). The average U.S. single-family home used approximately 41,000 kBTU for space heating in 2009, so space heating energy savings from efficiency improvements would have been enough to heat about 1.1 million or 3.3% of single-family homes in implementing states. The heating energy cost savings from code adoption in implementing states in 2009 was $771 million (± 671 million kBTU at the 95% confidence level). The average energy savings per home for homes subject to building energy codes were 3,491 kBTU. These energy savings translated to average annual energy cost savings per home of about $60.

To assess the potential effects of behavioral responses to changes in space heating efficiency (Borenstein, 2013), I re-estimated the energy savings under different behavioral response assumptions. First, if households in homes subject to building energy codes at construction would have increased the interior temperature by an average of 0.65°F, as in Greenstone, Fowlie, and Wolfram (2015), in response to occupying a more efficient home, such an adjustment would have increased space heating energy use by about 1,262 kBTU. Average energy savings per home from implementation of building energy codes would have decreased by 36% from 3,491 kBTU to 2,228 kBTU or from 7% to 5% of home space heating energy use. An increase in thermostat average set point of 1°F would have reduced energy savings from residential energy codes to 1,548 kBTU or 3.4% of home space heating energy use. While households occupying homes regulated by energy codes may have increased their thermostat set points, savings from building energy codes still would have been substantial even with this rebound.

Conclusions

Residential space heating efficiency increased over time because of both naturally-occurring market changes as well as implementation of energy efficiency building codes. Most of the improvement occurred during and after the 1970s. Implementation of building energy codes could account for about 30% of the improvement in space heating efficiency of U.S, homes. Single family homes subject to building energy codes at construction had space heating energy use that was about 7% less and home energy use that was about 3% less than homes not subject to code, assuming no rebound in energy use. In 2009, the average single-family home subject to efficiency codes saved about $60 in space heating energy costs.

The paper has several implications for energy efficiency policy. First, it provides additional evidence that residential building energy codes saved energy and reduced GHG emissions. Second, the paper suggests that policymakers may want to research the cost-effectiveness of directing more efficiency resources towards improving the efficiency of exterior walls of existing homes. Finally, this paper presents a new way of evaluating energy savings from residential building energy codes.

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