

How Much Energy Do Building Energy Codes Save? Evidence from California Houses[†]

By ARIK LEVINSON*

Regulations governing the energy efficiency of new buildings have become a cornerstone of US environmental policy. California enacted the first such codes in 1978 and has tightened them every few years since. I evaluate the resulting energy savings three ways: comparing energy used by houses constructed under different standards, controlling for building and occupant characteristics; examining how energy use varies with outdoor temperatures; and comparing energy used by houses of different vintages in California to that same difference in other states. All three approaches yield estimated energy savings significantly short of those projected when the regulations were enacted. (JEL Q48, Q51, Q52)

In 1978 California began enacting some of the world's first and most ambitious residential building energy codes, aiming "to reduce the electricity and gas now used in typical new buildings by at least 80 percent for new buildings constructed after 1990."¹ This ambitious goal was detailed in analyses published by the California Energy Commission (CEC) and widely cited in the press at the time.² Numerous subsequent revisions to the California codes have projected further savings. The 2008 revisions were designed to reduce electricity used by single-family detached homes for heating, cooling, lighting, and water heating by 23 percent, and the 2013 revisions by another 36 percent.³ Today, some observers claim that the building energy codes are meeting those goals.⁴

Calculating the energy savings from building energy codes requires knowing how much energy would have been used in the absence of the codes, a far more

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¹ California Energy Commission (1979, p. 55).

² Horn et al. (1980) and "Energy Plans for New Homes," *Los Angeles Times*, October 16, 1980, B3.

³ Architectural Energy Corporation (2007) and California Energy Commission (2013).

⁴ See, for example, Thomas Friedman citing Hal Harvey: "New houses in California now use one-fourth of the energy they used 25 years ago," in "Go Ahead, Vladimir, Make My Day," *New York Times*, April 12, 2014, <http://www.nytimes.com/2014/04/13/opinion/sunday/friedman-go-ahead-vladimir-make-my-day.html> (accessed August 12, 2016).

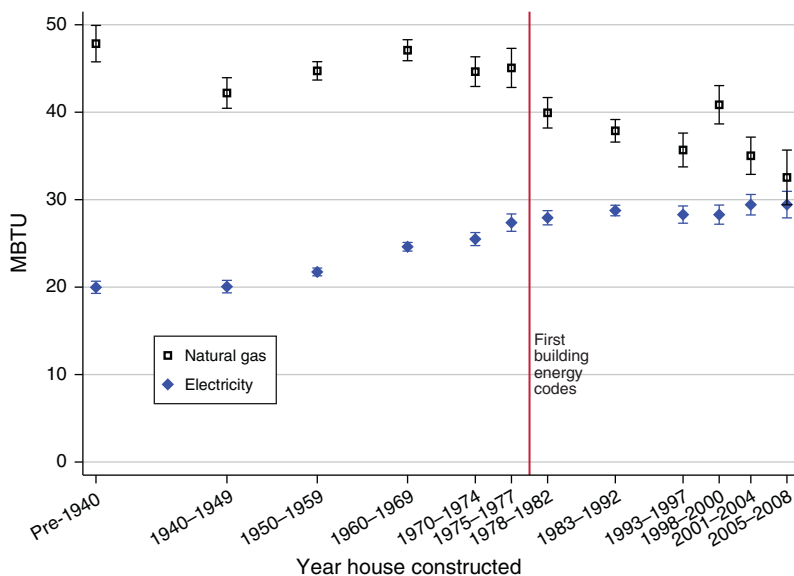


FIGURE 1. AVERAGE ANNUAL HOUSEHOLD ENERGY IN CALIFORNIA, 2003 AND 2009

Note: CEC's (2003, 2009) Residential Appliance Saturation Study (RASS), single-family detached homes without electric heat or hot water

difficult calculation than is sometimes suggested. We cannot just take engineers' ex ante estimates of how much less energy a given building will use because that ignores the ex post response by the building's occupants. We cannot easily compare jurisdictions with more and less strict building codes because those jurisdictions presumably chose to enact the codes based on the energy-using characteristics of their residents. And we cannot simply compare energy use by residents of efficient and inefficient buildings because people with larger energy needs may select energy-efficient homes.

Figure 1 illustrates that challenge. It shows the current average annual household electricity and natural gas used by California houses according to when they were constructed, both measured in thousands of British thermal units (MBTU) of energy.⁵ Houses built recently are not using dramatically less energy than older houses built under less strict building energy codes. Newer houses use a third less natural gas but 50 percent more electricity. The comparison is not fair, of course, because houses built more recently are larger, have more occupants, and are in less temperate parts of the state, and because both patterns start before the first building codes in 1978. Controlling for those home features, time trends, and the selection of people with high energy demand into recently-built homes, is the objective here.

The stakes are far higher than whether one state's building energy codes have worked as promised. Energy efficiency policies like California's are held up as a model for other states and countries and have become central to US climate policy. These include appliance standards, building weatherization incentives, and other

⁵One kilowatt hour of electricity is the equivalent of 3.412 MBTU; one therm of natural gas is 100 MBTU (www.eia.gov).

efficiency-related regulations. More than one-third of the greenhouse gas emissions reductions targeted by Massachusetts in its Global Warming Solutions Act of 2008 were projected to come from energy efficiency improvements to buildings and appliances. Nearly 20 percent of the reductions in California's 2006 Global Warming Solutions Act were projected to come from new energy efficiency standards for buildings and utilities.⁶ And half of the projected carbon reductions from the US Environmental Protection Agency's Clean Power Plan for existing electric power plants are expected to come from demand-side energy efficiency improvements, including building energy codes. The United States is putting much of its climate effort into this one policy.

Americans now have four decades of experience with energy efficiency standards. But most attempts to measure the energy savings fail to address the empirical challenges of behavioral responses, policy endogeneity, and selection by occupants. I address those problems in three ways. First, I use the CEC's (2003, 2009) Residential Appliance Saturation Study (RASS) to estimate annual energy use as a function of resident demographics, building characteristics, and year of construction. If building codes save energy, otherwise similar houses built more recently under stricter standards should use less energy. Though this first approach still ignores the potential selection of tenants into buildings, I control for a richer set of occupant and house characteristics than has been possible before.

The second approach focuses on the sensitivity of energy use to outdoor temperature changes. I match the monthly utility bills from the California RASS data with monthly temperatures in the households' zip codes. If building codes work as promised, during months that are hotter than usual, electricity use for air conditioning should increase less steeply in buildings constructed under more stringent standards. And similarly, in months that are colder than usual, natural gas use for heating should increase less steeply.

Finally, the third approach compares California with the rest of the United States. California established the nation's first and most stringent building energy efficiency standards and today still appears at the top of rankings of state energy efficiency regulations.⁷ If the building codes have been as effective as suggested, new houses in California should use less energy than older houses, and that gap should be larger in California than in other states. For this third approach I need data on non-California houses, and so I turn to a nationwide data source, the US Energy Information Administration's (1993–2009) Residential Energy Consumption Survey (RECS).

With two energy sources—electricity and natural gas—and three empirical strategies, I generate six basic findings. For electricity, after controlling for building and occupant characteristics, houses constructed after about 1990 are using 10 to 15 percent less electricity than those built before California's building codes were enacted in 1978. But that difference between newer and older houses is no different in California than in other US states with less strict building codes, and the newer houses in California do not increase their electricity use less when the weather is hot. For natural gas, after controlling for building and occupant characteristics,

⁶Massachusetts Office of Energy and Environmental Affairs (2010, p. ES-6); and California Air Resources Board (2008, p. 17).

⁷American Council for an Energy Efficient Economy (ACEEE), www.aceee.org.

houses built after 1990 are using up to 25 percent less energy than those built before 1978, and the newer houses do increase gas use by less when outside temperatures fall. But again, that difference between houses built at different times is no different in California than in the rest of the country. Although the findings vary by energy source and empirical approach, all six estimates fall significantly short of the savings anticipated when the building codes were established.

Because results like these can be controversial, let me be clear about what this paper does not say. Nothing here should be interpreted as a general critique of building energy codes. The codes are part of construction standards that prohibit homebuilders from cutting corners on hidden costs like fire safety, electric wiring, plumbing, and also insulation and appliance quality. Plus, new and old buildings might use similar amounts of energy today because residents of efficient houses respond to the lowered cost of lighting, air conditioning, and heating by using more: the so-called “rebound” effect. In that case, the codes may make homeowners warmer in winter and cooler in summer but not save as much energy as promised.

Nor should anything here be taken as evidence that energy efficiency technologies themselves don’t work as promised, only that mandated *new* building codes alone, in the absence of other public policies, haven’t delivered as much savings as projected. This paper studies only the codes that apply to new houses. Many other policies affect home energy use, including codes applicable to remodels, retrofit subsidies, appliance and lighting standards, and energy prices. New and old houses might use similar amounts of energy today because owners of older homes have taken steps to increase their energy efficiency, either on their own or motivated by subsidies or building codes applicable to remodels. But if those retrofits do explain the fact that energy use by new and old houses differs less than expected, we shouldn’t credit policy with the *sum* of projected savings from retrofits and new building codes. That would double count the savings. In the analyses below I do control for house characteristics related to retrofits. Those controls do not explain the fact that the estimated energy savings from new building codes fall short of projections.

Before describing the research to date on this question, it is worth looking at the policy and projected savings in detail.

I. Projected Savings and the Evidence So Far

California enacted its first building energy codes in 1978 and has updated them 13 times since.⁸ To describe those codes, in Table 1 I have reproduced one page from a detailed cost-benefit analysis done by CEC in 1980. The report contains 48 separate analyses, 1 each for detached, attached, and multifamily homes in each of 16 parts of the state. The example in Table 1 is for single-family detached homes in Sacramento. Column 1 reports the expenditures on various energy-related home construction features without the new California building codes: the “business-as-usual” costs. Column 2 reports the expenditures associated with the building codes. I’ve added column 3, the difference, demonstrating that the codes added \$8,000 to the cost of constructing a new house, about 10 percent of the median 1980 California

⁸ See the California Energy Commission, “Building Energy Efficiency Program,” www.energy.ca.gov/title24/.

TABLE 1—PROJECTED COSTS AND SAVINGS FROM 1980 CALIFORNIA ENERGY CODES:
SINGLE-FAMILY HOMES, SACRAMENTO

	Business as usual	Regulation	Difference
	(1)	(2)	(3)
Insulation	—	\$2,831	\$2,831
Window glazing	\$879	2,108	1,229
Overhang	—	468	468
Shading	—	360	360
Caulking, sealing, etc.	—	551	551
Thermostat	82	138	56
Heating system	1,360	1,360	—
Cooling system	1,129	965	−164
Duct insulation	—	61	61
Total building envelope	\$3,450	\$8,842	\$5,392
Water heater	284	2,736	2,452
Lighting	97	333	236
Total initial cost	\$3,831	\$11,911	\$8,080
Total energy (1,000 BTU)	187,209	43,025	−144,184
Energy savings			−77%

Note: The median California home price in 1980 was \$80,000.

Source: Horn et al. (1980)

home price. In return for that investment, the home was expected to save nearly 80 percent of the energy that a pre-code home would have consumed. And the Sacramento house described in Table 1 is no outlier: across the 16 regions studied by that 1980 CEC analysis, the average energy savings projected was 75 percent.

Have energy codes like those described in Table 1 lived up to their energy-saving promise? Given the importance of this question and the challenges to answering it, a wide variety of strategies have been taken. Most assessments of the energy savings from building codes rely on engineering analyses. CEC estimated that its residential building codes saved 7,039 gigawatt hours of electricity in 2012, or 7.8 percent of total residential demand.⁹ This calculation presumes the building codes are enforced, the savings predicted by engineers are realized, and there is no behavioral response. But there is reason to doubt all three assumptions. Jaffe and Stavins (1995) show that actual levels of insulation in homes did not increase as required by building energy codes. Metcalf and Hassett (1999) show that when insulation is installed, the realized savings fall short of engineers' predictions. And in theory, when building codes reduce heating and air conditioning costs, the rebound effect may result in people using those systems more (Gillingham, Rapson, and Wagner 2014).

As an alternative to engineers' predictions, some researchers have regressed aggregate local energy consumption on energy prices, weather, population demographics, and some proxy for energy efficiency policies. Haeri and Stewart (2013) use lagged expenditures on utility energy efficiency programs as the measure of policy and conclude that the \$7 billion California utilities spent reduced electricity consumption by

⁹CEC (2014, Table 2 (2012 total) and Table 25 (savings)).

6.5 percent, at an average cost of \$0.03 per kilowatt hour. Horowitz (2007) groups US states into quartiles based on the US Energy Information Administration's reported cumulative energy savings from demand-side management programs and finds that states with the strongest commitments to energy efficiency saw a 9.1 percent *increase* in residential electricity use relative to states with weaker commitments. These types of studies typically ignore the potential endogeneity of the key policy variables. Utilities expecting faster growth in electricity demand or with conservation-minded constituents may invest more in energy efficiency programs.

One clever version of this regression-based approach that does address policy endogeneity is Aroonruengsawat, Auffhammer, and Sanstad (2012). They regress per capita residential electricity consumption in US states on energy prices, weather, and the share of housing stock built since each state's initial implementation of energy building codes. Because implementation is endogenous, the authors use lagged heating and cooling degree-days as an instrument, on the theory that particularly harsh winters or hot summers spurred states to enact building energy codes. They find that states with a higher fraction of housing stock built after building codes were enacted use less energy per capita, and that those savings amount to 2 to 5 percent of nationwide residential energy use.

An altogether different strategy decomposes changes in energy demand into those components due to exogenous trends and attributes the remainder to efficiency. Studies differ in what changes they control for as being unrelated to energy efficiency. Metcalf (2008) shows that US energy consumption per dollar of gross domestic product declined by 47 percent from 1970 to 2003, about one-quarter of which can be explained by changing personal consumption expenditures, value added by businesses, and vehicle miles traveled. The remaining three-quarters he ascribes to energy efficiency, though he is using a broad definition of efficiency that includes other demographic changes and reduced consumption.

Hojjati and Wade (2012) control for shifts in the size and mix of housing types, the regional distribution of households, and weather. Even after accounting for those trends, from 1980 to 2005, US household energy consumption per square foot decreased by 38 percent, which the authors ascribe to *prima facie* "evidence of the efficacy of ... energy-efficiency ... standards and programs" (Hojjati and Wade, p. 304). But that 38 percent decrease is still at least partly attributable to trends their decomposition omits. For example, during that period, the average household size declined by 7 percent, driving down energy consumption per household but driving up energy consumption per person.

The best approaches use household-level data and focus on particular programs. Davis, Fuchs, and Gertler (2014) evaluate a Mexican program that gave consumers subsidies to replace old appliances with newer, more energy-efficient models. Households that replaced their refrigerators did use less electricity, but only by one-quarter of the amount predicted. And households that replaced air conditioners used *more* electricity after the replacement than before. Grimes et al. (forthcoming) study a New Zealand program that retrofitted 12,000 homes with insulation and clean heat sources. They find that homes retrofitted with insulation used 1 percent less energy, but the homes retrofitted with clean heat used more energy.

The ideal approach would randomly assign residents to energy-efficient and inefficient homes. Though that is impractical, Fowlie, Greenstone, and Wolfram (2015)

try the next-best strategy. They encourage a randomly selected subset of eligible homeowners to take up Michigan's 2009 Weatherization Assistance Program, then use that random treatment as an instrumental variable, comparing energy use by households that did and did not receive the encouragement. They find that weatherized homes do use less energy but that the savings are only about one-third of what energy auditors predicted for those very same homes.¹⁰

One final approach, and the one most similar to the one I take here, is to examine energy use by homes constructed before and after a particular change in a building code. Jacobsen and Kotchen (2013) compare the utility bills in 2004–2006 for homes in Gainesville, Florida, built just before and after the city tightened its building energy codes in 2002. They find that homes built after the change use 4 percent less electricity and 6 percent less natural gas.¹¹ One concern their paper cannot address is that the new and old homes may differ in ways that are correlated with energy consumption. Their data contain no information about the number or characteristics of the homes' occupants, for example, and their strategy cannot distinguish building age from year of construction. All the homes subject to the new building codes were recently constructed, conflating building vintage with building age.¹²

Before detailing the three approaches I take here, below I describe the data and discuss two issues: the confounding effects of building vintage, age, and survey year, and trends in electrification of heat and hot water.

II. Data and Two Often-Overlooked Issues

For this project, I use two main sources of data. The RASS contains detailed information about the buildings, occupants, and energy consumption of more than 22,000 California households in 2003 and another 26,000 in 2009. The data come from two-stage mailed surveys to representative samples of California households, with follow-up telephone and in-person interviews for nonrespondents, and with an online version available in 2009. I focus on detached single-family houses with complete information about key building and occupant characteristics where I could match the household to annual energy billing data provided by CEC. That leaves about 7,200 houses in 2003 and 6,800 in 2009.¹³

For the second empirical approach—examining the sensitivity of monthly energy use to outdoor temperatures—I go back to the RASS data and match households by zip code to nearby weather station data maintained by the National Oceanographic and Atmospheric Administration (NOAA). The third empirical strategy compares California with other US states. For that, I turn to the RECS, a nationally representative survey of household characteristics and energy use conducted every three to four years by the US Department of Energy.

¹⁰ Also see Allcott and Greenstone (2015).

¹¹ Below I discuss Kotchen's (2015) follow up in which the electricity savings have disappeared but the gas savings have grown.

¹² Costa and Kahn (2010) take a similar approach using a cross section of homes in one California county, Kahn, Kok, and Quigley (2014) explore a nationally representative cross section of commercial buildings, and Kahn, Kok, and Liu (2016) examine hotels in particular.

¹³ See online Appendix Table A1 for details about the sample construction. More information about the RASS can be found at www.energy.ca.gov/appliances/rass. I obtained access to the utility billing data for RASS households by an open records request to the California Energy Commission.

TABLE 2—SELECTED CHARACTERISTICS OF CALIFORNIA SINGLE-FAMILY HOMES

Variables	RASS		RECS 1993–2009		AHS (CA)
	2003 (1)	2009 (2)	California (3)	US (4)	2011 (5)
Annual electricity (MBTU)	23.76 (12.54)	26.70 (13.63)	27.44 (18.01)	44.74 (26.81)	
Annual gas (MBTU)	53.14 (27.90)	43.09 (23.74)	48.31 (31.86)	53.75 (61.47)	
Square feet (1,000s)	1.84 (0.81)	1.93 (0.84)	2.19 (1.15)	2.57 (1.37)	
Bedrooms [Total rooms in RECS]	3.26 (0.86)	3.32 (0.86)	6.27 (1.64)	6.68 (1.79)	3.32 (0.91)
Electric cooking	0.28	0.23			0.28
Remodeled	0.16	0.15			
Years at address	16.3 (14.5)	18.7 (14.7)			13.8 (13.4)
Number of residents	2.90 (1.50)	2.84 (1.49)	3.23 (1.74)	2.89 (1.46)	3.04 (1.62)
Household income [Thousand \$2010]	97.00 (64.45)	92.04 (60.43)	68.25 (40.57)	62.22 (37.10)	102.5 (130.7)
Residents aged 0–5	0.25 (0.66)	0.22 (0.65)			
Residents aged 65+	0.44 (0.75)	0.54 (0.79)	0.34 (0.65)	0.32 (0.64)	0.40 (0.69)
Household head graduated college	0.56	0.60			0.48
Disabled resident	0.094	0.110			0.156
Household head black	0.032	0.030			0.048
Household head Latino [“Hispanic” in AHS]	0.122	0.134			0.216
Own home	0.92	0.93	0.80	0.88	0.78
Central AC	0.48	0.57	0.42	0.60	0.58
Room AC	0.10	0.11			0.13
Refrigerators	1.29 (0.50)	1.38 (0.55)	1.29 (0.49)	1.28 (0.50)	
Observations	7,201	6,844	1,904	15,868	14,692

Notes: RASS 2003 and 2009, single-family homes without electric heat or hot water. California homes in the Residential Energy Consumption Survey (RECS) 1993–2009. American Housing Survey (AHS) 2011, detached single-family homes in California. For gas, there were 6,391 and 5,967 observations in the 2003 and 2009 RASS, respectively.

Table 2 provides some descriptive statistics for the RASS and RECS data. For comparison, column 5 reports California values from the American Housing Survey for those variables it has in common with the other two surveys. The AHS is conducted by the Census Bureau and may therefore suffer less from nonresponse bias. In general, the values are similar, though the RASS seems to have higher incomes, smaller household sizes, fewer minorities, and more homeownership. And even if the RASS is not entirely representative, that would only bias the results here if

response rates differ systematically by both home vintage and energy use, i.e., if residents of older houses are more likely to respond if they use less energy, while residents of newer homes respond if they use more energy. But that seems unlikely. A larger problem involves the relationship between home vintage and building age.

A. *The Confounding Effects of Building Age, Vintage, and Survey Year*

Even the best of the existing studies fail to account for one important determinant of energy efficiency: building age. The distinction is between building *age*, or how old the building is at the time of the survey, and building *vintage*, or when the building was constructed. A building's vintage determines the stringency of the regulations the builder faced, but in a cross section of data, building age and vintage cannot be separately measured. All ten-year-old homes surveyed in 2009 were built in 1999. If homes become draftier with age, researchers may spuriously attribute newer homes' lower energy use to stricter building codes. But repeated cross sections of data will contain ten-year-old homes built in different years under different standards. That is one of the advantages of the empirical strategies that I take: I use surveys constructed from repeated cross sections.

Recall the example from Gainesville, Florida. That study found energy use in 2004–2006 to be 4 to 6 percent lower for homes built just after Florida's 2002 building code change.¹⁴ But that result confounds the age of the building with its vintage of construction.¹⁵ In particular, the post-2002 houses are all new and have new occupants, and there might be many reasons why those homes and occupants use less energy. The appliances are new, the air filters clean, the windows and doors seal well, and the occupants may still be acquiring some energy-using devices. In an earlier draft of this study, I speculated that “something about the newness of the [Gainesville] homes led them to use less energy, not the building codes when they were constructed.”¹⁶ Prompted in part by that speculation, Kotchen (2015) revisits those Gainesville homes ten years later and finds that the 4 percent drop in electricity use for homes built after the 2002 building code change has disappeared, but the 6 percent drop in natural gas use has doubled. It appears that newly built homes differ in energy consumption because they are new, whether or not they were constructed to meet stricter building codes.

Whatever the explanation, by using repeated cross sections of California houses, I can distinguish between building *age* and *vintage* in several ways. First, CEC issued its first energy efficiency building standards in 1978, and any newness effect will have faded by now for houses built before and after those regulations took effect. Second, I can control for the number of years the residents have lived at the address, separating the effect of a new owner from the effect of a new building.

But one tricky remaining problem involves simultaneously controlling for the year of the survey. In different years, homeowners could well consume different amounts of energy. Appliances change and new models become available, energy prices change, weather differs, and people adopt different patterns of energy use.

¹⁴ See Jacobsen and Kotchen (2013, Figure 3).

¹⁵ This confusion between age and vintage was central to a debate about immigrants' wages back in the 1980s. Chiswick (1978) and others interpreted cross-sectional differences in immigrants' wages to be an age effect, but Borjas (1985) showed it was a cohort effect. Recent cohorts of immigrants have had fewer skills.

¹⁶ Levinson (2014b, p. 7).

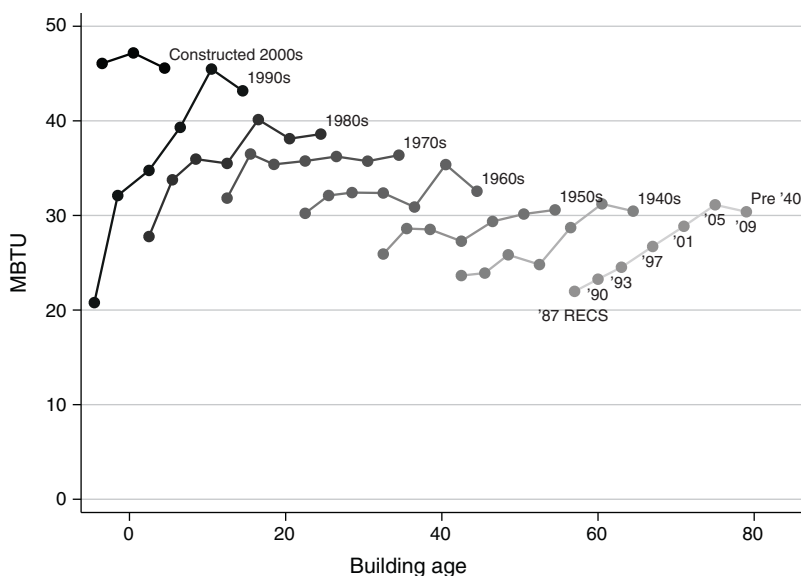


FIGURE 2. HOUSEHOLD ELECTRICITY USE, SYNTHETIC COHORTS BY CONSTRUCTION DECADE

Note: Single-family detached homes without electric heat or hot water, 1993–2009

But the three variables—vintage, age, and survey year—are linearly related. A regression of energy use on home characteristics cannot include all three covariates.

Figure 2 illustrates the problem using seven cross sections of national RECS data going back to 1987. From those data I constructed synthetic cohorts, grouping houses by building age and decade of construction. The figure plots electricity use by building age, separately for each vintage of construction, controlling for no other characteristics. Each line in Figure 2 represents a different vintage of houses, by decade of construction. Each dot on a line represents a different RECS, from 1987 through 2009.

Three features stand out. First, more recently constructed houses (higher lines) use more electricity. As noted, that may be explained by other home characteristics and is what this paper is in large part an attempt to explain. Second, the age-energy profiles are upward-sloping for every vintage. That could be the result of homes aging, or it could be the general time trend of increasing electricity consumption. Third, the age-energy profile is steepest for the very newest houses, those constructed in the 1990s and surveyed in the 1993 or 1997 RECS and those constructed in the 1980s and surveyed in the 1987 or 1990 RECS. This is unlikely to be the result of general trends in electricity consumption because it affects new buildings differently from old buildings.¹⁷ This third distinction is most likely a newness effect that could easily be mistaken for the efficacy of the most recent building code.¹⁸

¹⁷The slopes of the energy-age profiles are statistically indistinguishable for all but the newest buildings. Figure A1 in the online Appendix has a version of Figure 2 that plots the residuals after regressing electricity use on building and occupant characteristics. The plots of the synthetic cohorts' residuals are all still upward sloping and steepest for the newest houses, but they are all centered around zero. That is, homes built more recently do not use any more or less electricity.

¹⁸Note that each of the synthetic cohorts turns down in the final survey year. That phenomenon is observable in national data, as the steadily growing pattern of household electricity consumption seems to have plateaued starting around 2007.

The most common solution to the collinearity of age, cohort, and survey year involves using theory to assume that one of those three variables is nonlinear.¹⁹ I could assume a concave functional form for the effect of building age and assume that the general year effects apply to all buildings equally. But each of those assumptions has different implications for the measured vintage effects, which proxy for the changing building codes at the heart of this paper. I do not want those assumptions or their effects to determine the outcome.

Instead, I control for general time effects with year-of-survey indicators, for vintage of construction with vintage indicators, and for length of occupancy by current residents, but I do not control for building age. That means that the vintage indicators, which report residential energy consumption for houses constructed at different times controlling for other characteristics, combine the vintage and age effects. In this way I bias the results in favor of finding that more newly constructed houses (which are also newer) use less energy. But because the newness effect fades over time, that bias will be strongest in the most recent years and will stand out in the patterns of vintage coefficients.

A building's vintage also matters when accounting for a second overlooked issue: the rising and falling trend in electrification of heat and hot water. If ignored, it could seem as though homes built since California's 1978 building codes use less electricity and more natural gas because of those codes, rather than because of trends in home construction.

B. Electrification of Heat and Hot Water

The proportion of houses with electric space heat and hot water in California (as opposed to gas heat or water), peaked in the late 1970s when 15 percent of houses had electric heat, hot water, or both. After that, the trend reversed so that very few houses built recently have electric hot water and almost none have electric heat.²⁰ Why? In the 1950s a consortium of utilities and appliance manufacturers launched "Live Better Electrically" campaigns, granting allowances to homebuilders to construct all-electric homes throughout the United States.²¹ But by the 1980s, the program had ended, along with popularity of all-electric homes. The pattern has obvious implications for electricity use by building vintage. In what follows, I drop from the sample the 7 percent of single-family houses with electric heat or hot water.²²

All of this will be clearer with some results in hand, and so with those preliminary caveats out of the way, the next three sections discuss each of the three empirical approaches to assessing the energy savings from California's building energy codes.

¹⁹In the context of wages, Deaton (1985), Foster (1990), and Borjas (1994, 2013) have all discussed the difficulties of simultaneously controlling for age, cohort, and year.

²⁰In online Appendix Figure A2 I plot the shares of homes with electric heat and hot water, by year of construction. Both peak for houses built between 1978 and 1982, at 7 percent for heat and 13 percent for hot water.

²¹Not-yet-Governor Ronald Reagan promoted the program on his show "General Electric Theater." See Diane Wedner, "The All-Consuming Bills of an All-Electric Home," *Los Angeles Times*, August 13, 2001, <http://articles.latimes.com/2001/aug/13/news/mn-33663> (accessed August 12, 2016).

²²In the online Appendix, I report alternative specifications that include homes with electric heat or hot water. The results are nearly identical.

III. Strategy 1: Controlling for Building and Occupant Characteristics

The first approach is straightforward. I regress the log of annual household energy use on occupant and building characteristics and a set of indicators for each of the different construction vintages. If building codes have been effective, we should expect houses constructed after California's 1978 standards to be using less energy today than houses built before the codes were enacted, controlling for other observable features of the houses and their occupants.

The basic specification is

$$(1) \quad \ln(E_i) = \mathbf{X}_i\boldsymbol{\beta} + \sum_j \theta_j \text{ConstructEra}_{ji} + \varepsilon_i,$$

where E_i is household i 's energy use, in MBTU, and \mathbf{X}_i is a vector of house and occupant characteristics, including survey year and region fixed effects.²³ The dependent variable is in logs because that specification has the lowest residual sum of squares after a Box-Cox transformation, but linear versions yield qualitatively similar conclusions. The goal of estimating (1) is to examine whether the construction era coefficients (the θ s) are smaller or more negative for later eras than for earlier eras, which would suggest that all else equal, houses constructed under more stringent building codes use less energy today.

I start with electricity because patterns of electricity use are often cited as evidence for the success of California's standards (Rosenfeld and Poskanzer 2009) and because electricity generation has become a focus of energy and environmental policy now that greenhouse gas emissions are a concern. Table 3 presents the results for electricity using the RASS survey and a full set of control variables in column 1. Larger houses with electric ovens and more and wealthier occupants in hotter places use more electricity.²⁴ Importantly, residents who have lived at the house longer use more electricity. Since length of occupancy is correlated with house age and vintage, any analysis that fails to control for occupancy could falsely attribute energy savings to newer buildings that simply have newer occupants. And homeowners use less than otherwise similar renters, which makes sense given that renters typically aren't responsible for choosing their appliances or insulation, and sometimes aren't responsible for the utility bills (Levinson and Niemann 2004; Myers 2015). Year and region indicators absorb any variation over time or across parts of California, including differences in climate and energy price schedules.

The important coefficients are those on the construction era dummies. To help understand them, rather than display them in Table 3 I have plotted them in Figure 3. The first line in Figure 3 (dark dots) is from a version of equation (1) that excludes all controls except for the construction era dummies. The pattern of those

²³The construction era indicators correspond to the 12 vintages identified in the RASS, dropping the one for homes built before 1940. The year and geographic fixed effects absorb differences in weather and energy price schedules, among other characteristics that vary across survey years or regions of the state. (Price differences would be relevant only if they differed systematically by vintage of house construction.) The idea is to compare energy use by otherwise similar houses in the same place during the same year that just happen to have been built at different times.

²⁴A degree-day is the difference between the average of the daily maximum and minimum temperatures and 65°F. A heating degree-day occurs when that average temperature is less than 65°, and a cooling degree-day when it is greater than 65°.

TABLE 3—ANNUAL ENERGY USE BY CALIFORNIA HOUSEHOLDS IN THE RASS SURVEY

Dependent variable: ln(annual MBTUs)	Electricity		Natural gas	
	Full controls (1)	Age of AC (2)	Full controls (3)	Age of heater (4)
Cooling degree-days (100s)	0.021 (0.003)	0.021 (0.003)	−0.016 (0.006)	−0.016 (0.006)
Heating degree-days (100s)	−0.001 (0.004)	−0.001 (0.004)	0.029 (0.007)	0.028 (0.007)
ln (square feet)	0.266 (0.016)	0.266 (0.016)	0.377 (0.021)	0.387 (0.025)
Bedrooms	0.025 (0.007)	0.025 (0.007)	0.016 (0.008)	0.009 (0.007)
Electric cooking	0.036 (0.007)	0.036 (0.007)	−0.037 (0.007)	−0.032 (0.008)
Remodeled	0.027 (0.010)	0.026 (0.010)	−0.010 (0.013)	−0.011 (0.013)
ln (years at address)	0.026 (0.005)	0.027 (0.005)	0.011 (0.004)	0.010 (0.004)
ln (number of residents)	0.243 (0.009)	0.243 (0.010)	0.131 (0.013)	0.138 (0.013)
ln (household income)	0.095 (0.008)	0.095 (0.008)	0.064 (0.008)	0.058 (0.007)
Household head graduated college	−0.051 (0.007)	−0.051 (0.007)	−0.034 (0.011)	−0.038 (0.012)
Disabled resident	0.143 (0.009)	0.142 (0.009)	0.080 (0.017)	0.083 (0.016)
Own home	−0.055 (0.017)	−0.055 (0.017)	−0.078 (0.025)	−0.087 (0.024)
Refrigerators	0.191 (0.007)	0.191 (0.007)		
Room AC	0.058 (0.011)	0.058 (0.011)		
Central AC	0.141 (0.029)	0.153 (0.031)		
Central AC × sq. feet (1,000s)	0.030 (0.009)	0.030 (0.009)		
Age of central AC		−0.0012 (0.0005)		
Home heater age				0.0017 (0.0005)
Year home built	Coefficients displayed in Figures 3 and 4			
Observations	14,045	14,045	12,358	11,644
R ²	0.437	0.437	0.266	0.267

Notes: RASS 2003 and 2009, standard errors clustered by county. Regressions also include 13 climate zone indicators, kids, seniors, black, Latino, and an indicator for the 2009 survey year. Excluded construction category is homes “Built pre-1940.” Full set of coefficients in online Appendix Tables A2 and A3.

coefficients mimics the raw data plotted in Figure 1. The lower line (hollow symbols) plots coefficients from the regression in column 1 of Table 3. Controlling for other characteristics, new houses do not appear to consume statistically significantly less electricity than houses built earlier. Only the very newest houses built after 2005 have coefficients statistically significantly lower than houses built before 1978. And

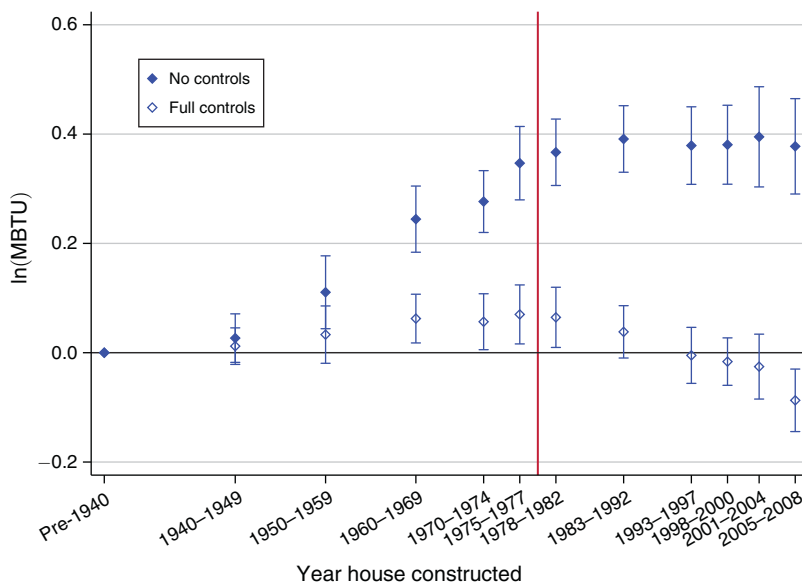


FIGURE 3. RESIDENTIAL ELECTRICITY USE IN CALIFORNIA, CONTROLLING FOR CHARACTERISTICS

Note: RASS 2003 and 2009, single-family detached California homes without electric heat or hot water

as we have seen from Figure 2 and the two Gainesville papers, very new homes use less electricity for reasons likely unrelated to building codes: new appliances, well-sealed windows, etc.

Because the dependent variable in column 1 is in logs, the construction era coefficients can be interpreted as percentage differences relative to houses built before 1940. If we ignore the newest houses, houses built after 1990 appear to use 10 to 15 percent less electricity than houses built in the 1970s. But that difference is not statistically significant and is far smaller than projected at the time the building codes were enacted.²⁵

Why aren't otherwise similar houses built recently saving more electricity? One possible explanation is that homeowners may have retrofitted the pre-1978 houses, upgrading the insulation, windows, and appliances. The RASS data lack detailed information about whether such energy upgrades were done, but they do indicate whether the house was ever remodeled in any way and the age of its central air conditioner. Both measures work in the opposite direction. The "remodeled" coefficient in Table 3 is positive. Houses that have been remodeled use more electricity, all else equal. And the air conditioner age, added in column 2, has a negative coefficient, suggesting that people who buy new air conditioners buy larger ones or use them more.

Columns 3 and 4 of Table 3 estimate versions of equation (1) with natural gas as the dependent variable. As before, larger houses with more occupants who are

²⁵ Online Appendix Table A2 contains full set of coefficients and some additional specifications, including one where I include the 7 percent of homes with electric heat and hot water. The construction era coefficients in those specifications show even less variation.

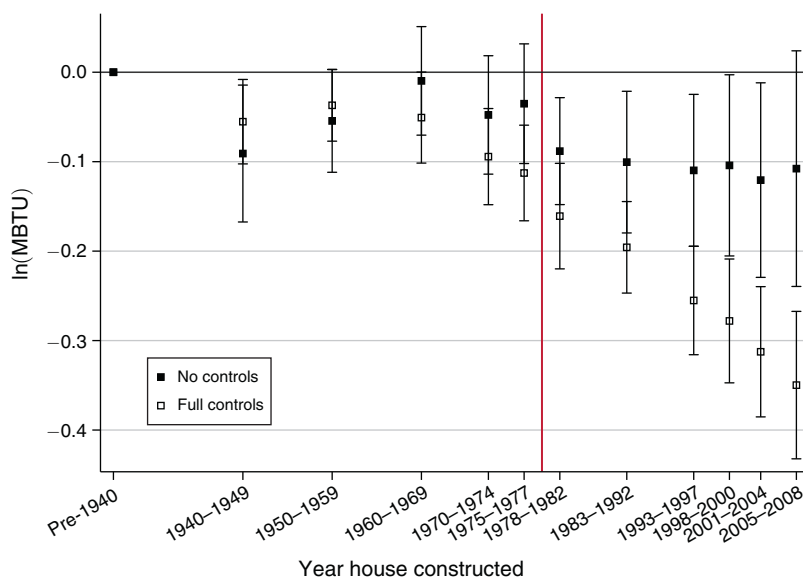


FIGURE 4. RESIDENTIAL NATURAL GAS USE IN CALIFORNIA, CONTROLLING FOR CHARACTERISTICS

Note: RASS 2003 and 2009, single-family detached California homes without electric heat or hot water

wealthier and have lived there longer use more gas. Of course, houses use less gas if they have electric stoves, and more gas in cold weather rather than hot. And houses with older heaters use more gas—about 1.7 percent for every ten years of heater age.

Figure 4 plots the construction era coefficients from column 3 of Table 3. As in Figure 3, the top line (dark dots) plots the construction era coefficients when those are the only control variables, and the pattern mimics that seen in Figure 1. The lower line (hollow symbols) plots the coefficients from Table 3. The figure depicts a steady decline in natural gas consumption. Houses built in each successive era after the 1950s are using less natural gas today. And controlling for other house and occupant characteristics increases that decline in gas consumption.

One interpretation of Figure 4 is that the building codes enacted first in 1978 and strengthened every few years thereafter have worked. But that interpretation would come with two caveats. First, although the confidence intervals are large, the trend appears to have begun before 1978. Something reduced gas consumption by otherwise similar houses built in the 1970s relative to those built earlier, and the building codes enacted starting in 1978 cannot be credited with that part of the trend. Second, even the largest post-1978 declines in gas use do not exceed 20 or 25 percent, short of the reduction anticipated when the building codes were enacted.

Not surprisingly, versions of this analysis for total household energy use look like a combination of Figures 3 and 4, depending on the units used to combine electricity and natural gas. If I sum the two according to their cost to the homeowners, energy expenditures are about 10 percent lower for houses built in the 1980s and 1990s, relative to those built before 1978, controlling for other building and occupant characteristics. If I sum the two by carbon content, houses built more recently use

15 percent less carbon. And, if I sum the two by heat content (BTUs), the newer houses use almost 20 percent less energy. All of this suggests that there may be some pollution and cost savings from the building codes, though they fall short of the savings projected when the regulations were enacted and come mostly from natural gas rather than electricity.²⁶

The simple analysis so far does ignore one potential problem: selection by residents into energy-efficient homes. If people who really like air conditioning and heating choose to live in energy-efficient newer houses, while people who prefer open windows or are often away from home choose less efficient older houses, that might explain the lack of observed differences in energy use.²⁷ The next two strategies attempt to address the potential selection issue. The idea is to look at energy consumption by house vintage, as in strategy 1, but to differentiate the effect along two dimensions that are unlikely to be associated with residents' preferences for energy: unseasonably hot or cold temperatures, and comparisons between California and other states.

IV. Strategy 2: Temperature Effects

Most of the building code costs described in Table 1 involve weatherization. Half of the \$8,000 cost for Sacramento houses was for insulation and window glazing, and another one-sixth was for other building envelope and space cooling or heating features. If the codes save energy as projected, energy use should increase less on hot or cold days for buildings constructed under more stringent standards. I cannot entirely eliminate the possibility that homeowners who are likely to use more air conditioning when the weather gets hot, or more heat when the weather is cold, are more likely to select newer homes because they are energy-efficient. But if that hot or cold weather is unexpected or unseasonable for a region, that may mitigate the selection problem. This is a type of difference-in-differences approach, where the first difference is between houses of different vintages, and the second is between houses experiencing extreme or mild temperatures. Strategy 1 examined the first difference—between houses of different vintages. Here I examine how that difference changes when the outdoor temperature varies.

This strategy builds on Chong (2012), who matches tax assessment data with electric utility billing records in Riverside, California. He finds that homes use more electricity during hot months and, surprisingly, that post-1978 homes have an even larger hot-weather electricity increase. Chong controls for home size in square feet, but because he uses census block data, he has little other information about specific homes' characteristics or residents' demographics. New homes have more occupants with higher incomes, and that could in theory explain his finding. He also does not examine home heating in cold weather or study unseasonable temperatures.

²⁶Natural gas has lower prices and carbon content per BTU than electricity, and most of the post-1978 reductions come from natural gas, which is why the cost and pollution savings are lower than the energy savings. The combined results can be seen in Appendix Figure A3 and Table A4.

²⁷Note however, that this selection story conflicts with a major justification for the building codes in the first place: that housing markets underprovide energy efficiency because home purchasers cannot see or will not pay for the up-front costs. If homebuyers don't value energy efficiency, it's hard to imagine that unobserved selection by homeowners can explain the gap between projected and observed savings.

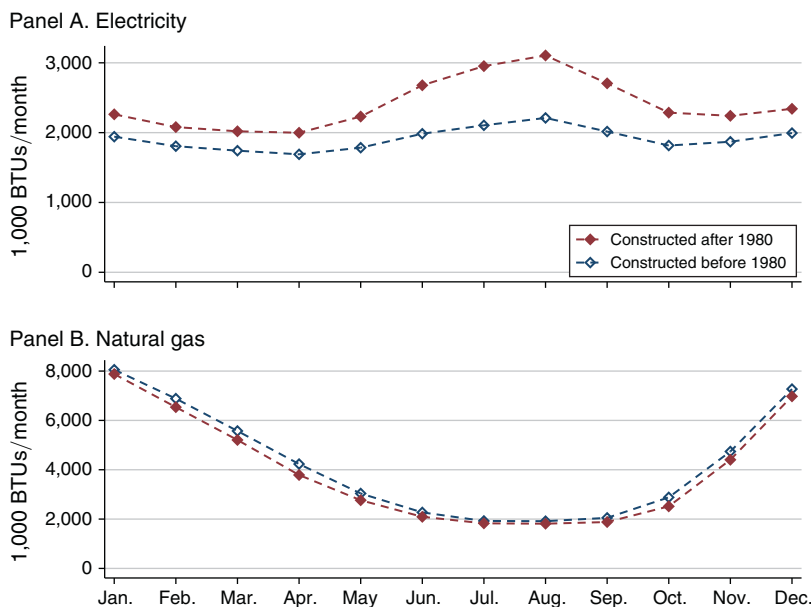


FIGURE 5. SEASONS AND ENERGY

Note: RASS 2003 and 2009, single-family detached California homes without electric heat or hot water

To replicate Chong, but with a full set of building and occupant characteristics, I turn to the monthly billing data in the RASS and match those with the number of heating and cooling degree-days at nearby weather stations each month.²⁸ For each RASS house, I know the latitude and longitude of the population-weighted centroid of that house's zip code, from the Census Bureau. I draw a 30-kilometer circle around that centroid and calculate a weighted average of the reported weather variables for all the NOAA weather stations inside that circle and where the weights are the inverse of the distance from the weather station to the zip code centroid.

Figure 5 plots average energy use by month for houses built before and after 1980. The top panel shows electricity. Houses constructed after 1980 use more electricity in every month, and during summer months electricity use appears to grow relatively more for new houses than for old. But again, new houses are larger, in hotter places, etc., and in what follows I control for those characteristics. The bottom panel plots natural gas, for which there appears to be little difference between the new and old houses, in either the monthly averages or the increase during winter months.

²⁸ Billing dates do not correspond exactly to months because billing dates are not typically the first or last day of the month. To match utility bills to monthly temperature data I "calendarized" the billing data by assigning usage proportionally to the months spanned by each utility bill. The 2003 RASS data I received from CEC had already been calendarized this way; I followed its method for 2009.

To examine whether energy use increases during hot or cold weather less for newer houses, controlling for other house characteristics, I estimate versions of

$$(2) \quad \ln(E_{im}) = \mathbf{X}_i\beta + \alpha CDD_{im} + \sum_j \theta_j \text{ConstructEra}_{ji} \\ + \sum_j \pi_j (CDD_{im} \times \text{ConstructEra}_{ji}) + \gamma_m + \varepsilon_{im}.$$

Subscript i refers to houses and m refers to months. Again, \mathbf{X}_i includes year and county fixed effects.²⁹ For the regressions where natural gas is the energy measure on the left-hand side, I replace cooling degree-days (CDD_{im}) on the right-hand side of equation (2) with heating degree-days (HDD_{im}).³⁰ As in the first approach, the semi-log specification in (2) has the best Box-Cox fit, but linear versions of (2) have qualitatively similar conclusions.

This is basically the same regression as in equation (1), except that instead of one annual observation on energy and weather for each house, I use monthly observations spanning at least a year, the temperature measurements are the monthly CDDs and HDDs in the zip code in which the house is located, and I interact those monthly temperature measurements with the construction era indicators. The coefficients π_j on the interaction between CDDs and construction era estimate whether during hot months, houses of vintage j use more electricity.

Table 4 shows estimates of equation (2) for electricity. To conserve space, I report only the interactive terms (the π_j s) and a few other key coefficients. (Full results are in online Appendix Table A5.) Column 1 of Table 4 contains estimates of equation (2) with the full set of home characteristics and two measures of monthly temperature: the actual number of CDDs in the house's zip code for the month, and the average number of CDDs in that zip code during that month for the past ten years. This average can be thought of as the climate a homeowner can expect in any particular month, compared with the climate actually experienced, in the first row. In other words, if August is typically a hot month in Sacramento, that effect is absorbed by the average monthly CDD in row 2. But if August 2009 is particularly hot in Sacramento, that effect is identified by the CDD coefficient in row 1 and its interactions with the construction era indicators.

As before, rather than display all of the interaction coefficients in the table, I have plotted them. The top panel of Figure 6 plots the interaction coefficients (the π_j s) from column 1 of Table 4. The height of the markers can be thought of as the weather sensitivity of electricity use for houses built in different eras. And those coefficients generally increase, rather than decrease, with building vintage. On average, each extra 10 CDDs in a month adds about 2 percent to electricity use above that of the pre-1940s houses (the omitted category), and an additional 0.5 percent or more to houses built post-1990. Electricity use in newer houses rises faster when the temperature increases, even controlling for observable house and occupant characteristics, consistent with Chong (2012).

²⁹ As with equation (1), the year, month, and county fixed effects here absorb differences in price schedules.

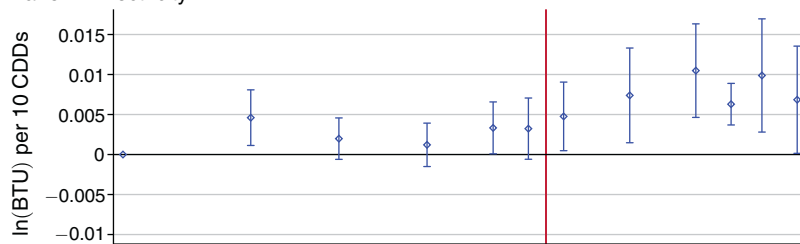
³⁰ Versions of equation (2) that include both HDD and CDD yield results with larger confidence intervals but nearly identical coefficients.

TABLE 4—MONTHLY ELECTRICITY USE AND MONTHLY COOLING DEGREE-DAYS (CDD) IN CALIFORNIA

Dependent variable: ln(monthly electricity)	Full controls (1)	Only homes with central AC	
		Age of AC (2)	AC age \times CDD (3)
CDD per month (10s)	0.0005 (0.0030)	0.0014 (0.0032)	0.0003 (0.0044)
Avg. monthly CDD in zip code	0.0208 (0.0031)	0.0185 (0.0040)	0.0185 (0.0040)
Age of AC		−0.0023 (0.0005)	−0.0017 (0.0007)
CDD \times year home built	Coefficients displayed in Figures 6 and 7		
Observations	265,599	135,840	135,840
R^2	0.368	0.323	0.323

Notes: Standard errors clustered by county. Other controls: ln(square feet), bedrooms, electric cooking, remodeled, ln(years at address), ln(residents), ln(household income), residents aged 0–5, residents aged 65–99, household head graduated college, disabled resident, household head black, household head Latino, own home, refrigerators, central AC, room AC, and fixed effects for survey year, vintage of construction, county, and month. Column 3 includes interactions between age of air conditioner and CDDs. Full set of coefficients in online Appendix Table A5.

Panel A. Electricity



Panel B. Natural gas

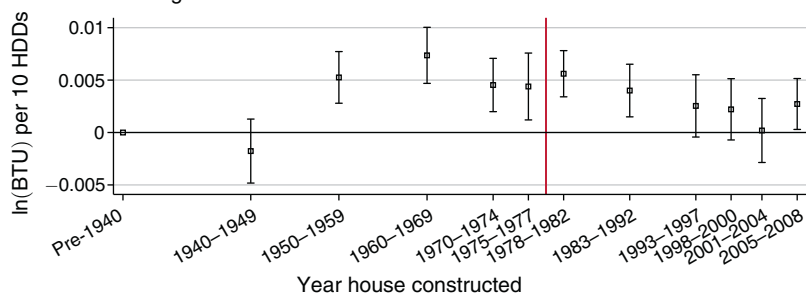


FIGURE 6. ENERGY USE PER DEGREE-DAY

Note: RASS 2003 and 2009, single-family detached homes

Why might electricity use increase with temperature more in newer houses than in older ones, controlling for other house and occupant characteristics? One possible omitted variable is tree shade. Older houses may be surrounded by taller trees that

reduce air conditioning demand by providing shade. Maher (2013) estimates that homes in Florida that have had nearby trees removed use 3 percent more electricity the following year, and Pandit and Laband (2010) estimate that homes with average shading use 4 percent less summertime electricity than homes with no tree shade.

Another possibility is remodeling. Perhaps the older houses have new, energy-efficient air conditioners. The regressions in Table 4 contain the same “remodel” indicator as in the annual specifications in Table 3, and as before it has a positive and statistically significant coefficient. But remodeling is broadly defined in the RASS, and in this weather-sensitivity analysis in Table 4 I can distinguish the vintage of the air conditioner from the vintage of the house, using only the 52 percent of houses with central air conditioning.

Columns 2 and 3 of Table 4 add a variable for the age of the air conditioner, reported in the RASS data in six vintage categories, ranging from less than one year to more than 35 years. I converted that to a continuous measure by taking midpoints of those ranges. As with the annual data in Table 3, here in column 2 of Table 4 each year of air conditioner age *reduces* average electricity use. Older air conditioners must be either smaller or used less.

In column 3 of Table 4 I interact the measure of CDD per month with the air conditioner vintage categories:

$$\begin{aligned}
 (2a) \quad \ln(E_{im}) = & \mathbf{X}_i\beta + \alpha CDD_{im} + \sum_j \theta_j \text{ConstructEra}_{ji} \\
 & + \sum_j \pi_j (CDD_{im} \times \text{ConstructEra}_{ji}) \\
 & + \sum_j \omega_j (AC\ age_{ji}) + \sum_j \gamma_j (CDD_{im} \times AC\ age_{ji}) + \gamma_m + \varepsilon_{im}.
 \end{aligned}$$

Those coefficients (the γ s) are displayed in the top panel of Figure 7. Electricity use does not increase less during hot weather for houses with new air conditioners. If anything, it increases more, though the confidence intervals are large. More importantly, controlling for air conditioner age does not change the house vintage interactions (the π_j s). Upgraded air conditioners in older houses do not explain why those older houses do not use more electricity in hot months.

Turning from electricity to natural gas, in Table 5 I estimate versions of equation (2) for natural gas use and heating degree-days. Column 1 shows the results controlling for other house and occupant characteristics, and the bottom panel of Figure 6 plots the interaction coefficients. The trend seems to be declining, with houses built after 1978 using less natural gas per HDD than those built in the 1950s through the 1970s. But that decline is statistically insignificant and small. Houses in the RASS sample experienced an average of 200 January HDDs, with a standard deviation of 90. If we look at just the point estimates in Figure 6, ignoring their statistical significance, newer houses use about 5 percent less gas than pre-1978 houses in response to a one standard deviation increase in HDDs.

Perhaps here remodeling explains the small energy savings in newer houses. The remodeled indicator (reported in online Appendix Table A6) is small and statistically insignificant. In column 2 of Table 5 I include the age of the house’s main

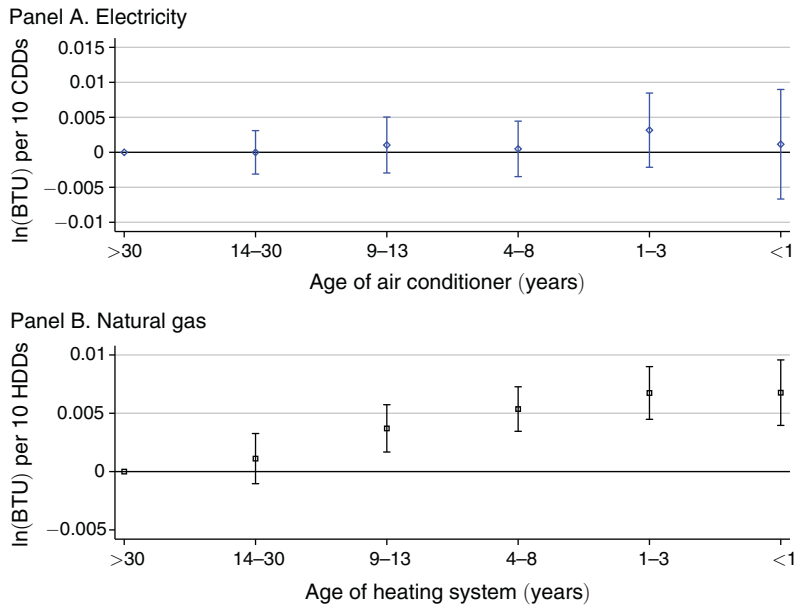


FIGURE 7. ENERGY USE AND AGE OF AIR CONDITIONER AND HEATER

Note: RASS 2003 and 2009, single-family detached homes

TABLE 5—MONTHLY GAS USE AND MONTHLY HEATING DEGREE-DAYS (HDD) IN CALIFORNIA

Dependent variable:	Full controls	Age of heating system	Heater age × HDD
ln(monthly gas)	(1)	(2)	(3)
HDD per month (10s)	0.0147 (0.0014)	0.0058 (0.0021)	0.0029 (0.0023)
Avg. monthly HDD in zip code	0.0172 (0.0016)	0.0578 (0.0031)	0.0577 (0.0031)
Age of heating system		0.0031 (0.0003)	0.0050 (0.0004)
HDD × year home built	Coefficients displayed in Figures 6 and 7		
Observations	227,931	218,792	218,792
R ²	0.554	0.543	0.543

Notes: Standard errors clustered by county. Other controls: see footnote to Table 4. Column 3 includes interactions between age of heating system and HDDs. Full set of coefficients in online Appendix Table A6.

heating system. Otherwise similar houses with older heaters use more natural gas—about 3 percent more for each ten years of heater age. Column 3 includes interactions between HDDs and heater age categories, similar to equation (2a) but in the context relevant to natural gas. Those interaction coefficients are displayed in the bottom panel of Figure 7. Controlling for other characteristics, including building vintage, houses with newer heaters use *more* gas per HDD than houses built earlier, not less. The pattern is similar to that for air conditioners and CDDs, but in this case it is more pronounced and more statistically significant.

One possible explanation for this otherwise puzzling pattern is that newer systems are larger, cover more of the house, or have other features that mean they get used more intensively when the weather gets colder. More importantly, controlling for heater age does change the house vintage interactions (the π_{js}). After controlling for heater age and other house characteristics, there is a pronounced downward trend in those interactions. Post-1978 houses do use less natural gas in response to cold weather, though again some of that trend predates 1978 and the savings are smaller than predicted.³¹

The ever-present concern with these strategies is the possibility that some omitted variable is correlated with both building vintage and energy use. Perhaps post-1978 California houses or the occupants of those houses have some characteristic that increases their energy consumption relative to the pre-1978 houses or their purchasers. If that omitted variable works similarly in California and other states, then the difference between the vintage-energy profiles in California and other states will reveal the efficacy of the building codes. In the next section, I explore this alternative difference in differences: comparing energy consumption by new and old houses in California relative to that same difference in other states.

V. Strategy 3: Comparing California with Other States

Proponents of energy efficiency standards have for a long time pointed to the sharp differences between electricity consumption per capita in California and other states as evidence of the effectiveness of California's policies. Since the 1970s, electricity use per capita has remained roughly flat in California while growing by 75 percent in the rest of the United States (Rosenfeld and Poskanzer 2009). In Levinson (2014a) I show that most of that gap can be explained by demographic trends unrelated to building codes. But that doesn't mean the building codes were ineffective, only that their effectiveness cannot be assessed by simple comparisons of electricity consumption over time.

Instead of comparing energy consumption in California and other states directly, in this section I compare the relationship between energy consumption and building vintage in California and other states. If California's building codes reduce energy use, the difference between energy consumption in California and other states should be even larger for houses constructed after 1978.

For this strategy I turn to the RECS, a nationally representative survey of household characteristics and energy use. The basic approach can be seen in Figure 8. The top panel displays the difference between average annual household electricity consumption in California and in other US states, by decade of house construction.³² Houses in California use 10 to 20 MBTU less electricity per year than houses in other states. That gap increases with the decade of construction for houses built before 1978, and then flattens out or even shrinks for houses built later, implying that California's building codes have not reduced electricity use. But Figure 8 does not account for other building and occupant characteristics, which may differ

³¹ See online Appendix Table A6.

³² In most years the RECS does not report the location of the home by state, only by one of nine census divisions. But starting in 1993, the RECS reports the state for homes in California and three other large states.

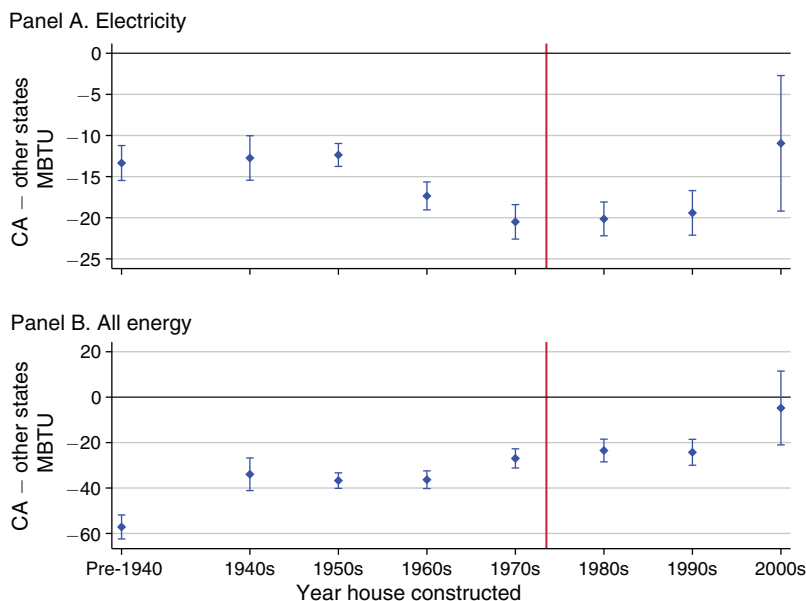


FIGURE 8. ENERGY USE IN CALIFORNIA COMPARED WITH OTHER STATES

Notes: This plots, for each construction decade, average energy use in California *minus* average energy use in other states. Negative numbers mean California uses less. RECS, 1993–2009, single-family detached homes.

systematically with construction vintage in ways that offset any relative savings in post-1978 California houses.

The bottom panel of Figure 8 plots the same difference for all energy: the sum of electricity, natural gas, and fuel oil, all measured in MBTU.³³ Houses in California use less overall energy than houses in other states, but again, without controlling for other characteristics, that gap is smaller for houses built after 1978 than before, not larger.

To control for those other home characteristics, I modify equation (1) to add an indicator for houses in California and interactions between that indicator and the decade-of-construction fixed effects:

$$(3) \quad \ln(E_i) = \mathbf{X}_i\beta + \sum_j \theta_j \text{ConstructEra}_{ji} + a(CA_i) + \sum_j \sigma_j (CA_i \times \text{ConstructEra}_{ji}) + \varepsilon_i.$$

The coefficients on the interactions (the σ_j s) report the difference between houses in California and other states, separately for each construction decade, after controlling for other observable house and occupant characteristics.³⁴

³³Very little fuel oil is used by California homes, and other states have a mix of fuel oil, natural gas, and electricity. A version this figure drawn for just fuel oil and natural gas looks similar to the bottom panel of Figure 8.

³⁴Energy prices are included here, in case different trends in California and other states affect energy use. They are population-weighted averages by census region for non-California homes, and California-specific prices in that state. Their inclusion has no effect on the vintage indicators (θ) or their interactions with the California dummy (σ).

TABLE 6—COMPARING CALIFORNIA AND OTHER US STATES

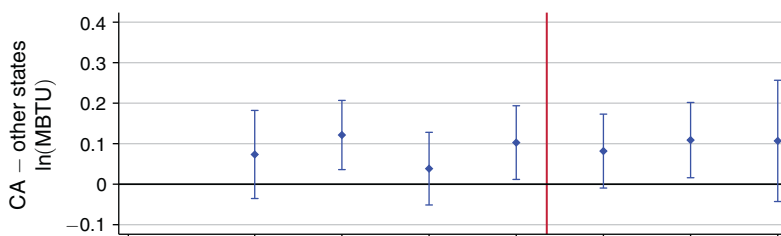
Dependent variable: ln(annual MBTUs)	Electricity (1)	Natural gas and fuel oil (2)	All energy (3)
California	−0.217 (0.065)	−0.390 (0.056)	−0.412 (0.088)
Electricity price (2010 \$/MBTU)	−0.016 (0.008)		0.003 (0.010)
Natural gas price		−0.093 (0.041)	−0.088 (0.043)
Fuel oil price		−0.063 (0.036)	−0.124 (0.035)
ln(square feet)	0.158 (0.011)	0.188 (0.014)	0.229 (0.012)
Rooms	0.045 (0.003)	0.054 (0.004)	0.056 (0.003)
ln(household size)	0.366 (0.011)	0.106 (0.012)	0.199 (0.010)
ln(household income) (\$2010)	0.061 (0.007)	0.017 (0.007)	0.051 (0.006)
Children ≤ 12 yrs old ^a	−0.045 (0.005)	−0.004 (0.007)	−0.013 (0.005)
Seniors ≥ 65 years old	−0.026 (0.007)	0.045 (0.008)	0.001 (0.007)
Own home	0.022 (0.014)	−0.038 (0.015)	−0.023 (0.012)
Central AC	0.224 (0.010)	0.015 (0.011)	0.127 (0.010)
Refrigerators	0.153 (0.008)	0.004 (0.010)	0.044 (0.008)
Heating degree-days (× 100)	0.001 (0.000)	0.006 (0.001)	0.002 (0.001)
Cooling degree-days (× 100)	0.008 (0.001)	−0.014 (0.001)	−0.007 (0.001)
Decade of construction × California dummy	Coefficients displayed in Figure 9		
Observations	12,187	14,629	17,768
R ²	0.473	0.371	0.323

Notes: Residential Energy Consumption Survey (RECS) 1993–2009. Heteroskedastic-consistent standard errors in parentheses. Regressions include five RECS survey-year fixed effects, nine census division fixed effects, and seven construction decade fixed effects. Column 1 includes only homes without electric heat or hot water. Columns 2 and 3 drop that restriction.

^aChildren are defined as ≤ 14 years old in RECS 2009.

Table 6 reports estimates of equation (3). The building and occupant coefficients are similar to those for the RASS data. Electricity use increases with size, income, cooling degree-days, etc. As before, rather than report the interaction coefficients (σ_j s) I have plotted them, in Figure 9. (Figure 8 plotted the raw difference between energy consumption by houses in California and houses in other states; Figure 9 plots that percentage difference, controlling for other house characteristics, and relative to the reference group of houses built before 1940.) California houses use less electricity (the California dummy in Table 6). That difference is largest for the

Panel A. Electricity



Panel B. All energy

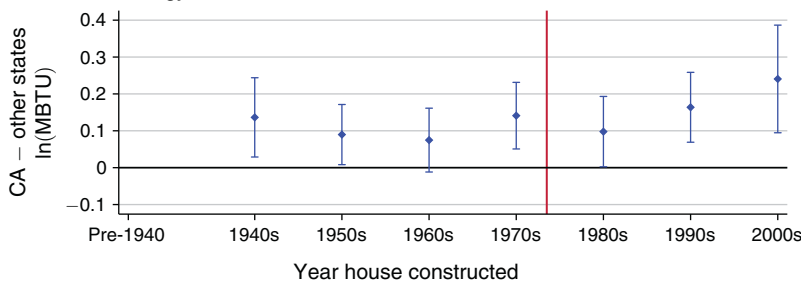


FIGURE 9. ENERGY USE IN CALIFORNIA, CONTROLLING FOR OTHER CHARACTERISTICS

Notes: This plots the coefficients (the σ_s from equation (3)), as estimated in Table 6. RECS, 1993–2009, single-family detached homes.

reference group of pre-1940 houses and is about 10 percent smaller thereafter. The gap in residential electricity consumption between California and other states is not larger for houses built after 1978.

Column 2 of Table 6 runs that same regression for the sum of natural gas and fuel oil, and column 3 does the same for the sum of all three fuels. The interaction coefficients (σ_s s) are similar, so in the bottom panel of Figure 9 I plot the coefficients for all fuels, from column 3. As with electricity alone, California houses use less total energy (the California dummy in Table 6), and that gap is largest for houses constructed long ago. The gap in overall residential energy consumption between California and other states is not larger for houses built since 1978.

VI. Conclusion

California's original building energy codes aimed to reduce energy consumption for new buildings by 80 percent, and multiple subsequent revisions of those codes have projected further savings. The results here suggest that any energy savings due to California's new building codes fall significantly short of those projections. For electricity, post-1978 houses in California may be using up to 15 percent less than pre-1978 houses, but do not use less per degree-day when the weather gets hot, and do not use relatively less than similar post-1978 houses in other states with less strict building codes. For natural gas, post-1978 houses use up to 25 percent less, and use less per degree-day when the weather is cold. But both trends predate the building codes, and post-1978 houses in California use relatively more heating fuel than post-1978 houses in other states.

The analysis does not explain why such a large gap remains between the promise and the reality. One possible reason why pre-1978 houses use no more energy, other things equal, is that they may have been remodeled or retrofitted with new windows, additional insulation, or more efficient heating and cooling systems. And those retrofits may be motivated by subsidies or construction codes applicable to remodels. I do attempt to control for those upgrades by including an indicator for whether the house was remodeled, and by examining the effect of the ages of heaters and air conditioners. Neither approach alters the basic findings.

Another reason may involve the selective destruction of older buildings. Perhaps the most poorly constructed, least efficient older houses are most likely to be demolished, leaving only the best older houses in the current data. In that case this exercise may appear stacked against finding an energy-saving benefit of the building codes. But if that pattern of demolition represents the business-as-usual lifetimes of buildings, those poorly built older houses were not destined to last long anyway and do not belong in the baseline case for calculating the long-run energy savings from building codes.

Or, it may simply be that the projected energy savings were overstated, failing to account for human nature, owners' failure to maintain insulation or appliances, the rebound effect, or noncompliance with building codes. If any of those explanations accounts for the result, the building codes may well have served their purpose of protecting some homeowners from hidden cost-cutting, saving homeowners money, or making them more comfortable. But the codes will not have reduced energy use as much as projected. In that case, policymakers should be hesitant to rely on forecasted carbon reductions from building energy codes as part of environmental policy.

On the other hand, the projected savings may be correct and the results here wrong. I may have failed to account for some building or occupant characteristics that increase energy consumption in new houses relative to old houses, increase energy use in hot or cold weather faster in new houses than old houses, and increase energy consumption in new houses in California more than new houses in other states. If so, building codes may be saving energy and reducing pollution as promised, but those reductions are tremendously difficult to measure empirically.

REFERENCES

- Allcott, Hunt, and Michael Greenstone. 2015. "Maximizing Money vs. Utility: Measuring the Welfare Effects of Energy Efficiency Programs." Unpublished.
- Architectural Energy Corporation. 2007. *Impact Analysis: 2008 Update to the California Energy Efficiency Standards for Residential and Nonresidential Buildings*. Prepared for California Energy Commission. San Francisco: Architectural Energy Corporation.
- Aroonruangsawat, Anin, Maximilian Auffhammer, and Alan H. Sanstad. 2012. "The Impact of State Level Building Codes on Residential Electricity Consumption." *Energy Journal* 33 (1): 31–52.
- Borjas, George J. 1985. "Assimilation, Changes in Cohort Quality, and the Earnings of Immigrants." *Journal of Labor Economics* 3 (4): 463–89.
- Borjas, George J. 1994. "The Economics of Immigration." *Journal of Economic Literature* 32 (4): 1667–1717.
- Borjas, George J. 2013. "The Slowdown in the Economic Assimilation of Immigrants: Aging and Cohort Effects Revisited Again." National Bureau of Economic Research Working Paper 19116.
- California Air Resources Board (CARB). 2008. *Climate Change Scoping Plan*. Sacramento: California Air Resources Board. <http://www.arb.ca.gov/cc/scopingplan/document/scopingplandocument.htm>.
- California Energy Commission. 1979. *Biennial Report*. Sacramento: California Energy Commission.

- California Energy Commission.** 2003. *California Statewide Residential Appliance Saturation Study*. <http://www.energy.ca.gov/appliances/rass/>.
- California Energy Commission.** 2009. *California Statewide Residential Appliance Saturation Study*. <http://www.energy.ca.gov/appliances/rass/>.
- California Energy Commission.** 2013. *Impact Analysis: California's 2013 Building Energy Efficiency Standards*. Consultant Report CEC-400-2013-008.
- California Energy Commission.** 2014. *California Energy Demand 2014–2024 Final Forecast*. Report CEC-200-2013-004-V1-CMF.
- Chiswick, Barry R.** 1978. "The Effect of Americanization on the Earnings of Foreign-Born Men." *Journal of Political Economy* 86 (5): 897–921.
- Chong, Howard.** 2012. "Building Vintage and Electricity Use: Old Homes Use Less Electricity in Hot Weather." *European Economic Review* 56 (5): 906–30.
- Costa, Dora L., and Matthew E. Kahn.** 2010. "Why Has California's Residential Electricity Consumption Been So Flat since the 1980s?: A Microeconomic Approach." National Bureau of Economic Research Working Paper 15978.
- Davis, Lucas W., Alan Fuchs, and Paul Gertler.** 2014. "Cash for Coolers: Evaluating a Large-Scale Appliance Replacement Program in Mexico." *American Economic Journal: Economic Policy* 6 (4): 207–38.
- Deaton, Angus.** 1985. "Panel Data from Time Series of Cross-Sections." *Journal of Econometrics* 30 (1-2): 109–26.
- Foster, Andrew.** 1990. "Cohort Analysis and Demographic Translation: A Comparative Study of Recent Trends in Age Specific Fertility Rates from Europe and North America." *Population Studies* 44 (2): 287–315.
- Fowle, Meredith, Michael Greenstone, and Catherine Wolfram.** 2015. "Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program." National Bureau of Economic Research Working Paper 21331.
- Gillingham, Kenneth, David Rapson, and Gernot Wagner.** 2014. "The Rebound Effect and Energy Efficiency Policy." RFF Discussion Paper 14-39.
- Grimes, Arthur, Nicholas Preval, Chris Young, Richard Arnold, Tim Denne, Philippa Howden-Chapman, and Lucy Telfar-Barnard.** Forthcoming. "Does Retrofitted Insulation Reduce Household Energy Use? Theory and Practice." *Energy Journal*.
- Haeri, Hossein, and Jim Stewart.** 2013. "The View from the Top: Application of Macro-Economic Models to Measure Energy-Efficiency Program Savings in California." Paper presented at the 2013 International Energy Program Evaluation Conference, Chicago, IL.
- Hojjati, Behjat, and Steven H. Wade.** 2012. "U.S. Household Energy Consumption and Intensity Trends: A Decomposition Approach." *Energy Policy* 48 (1): 304–14.
- Horn, Mickey, Dean Tibbs, and Mike Borden.** 1980. "Cost Effectiveness." 1980 Residential Building Standards Development Project. Sacramento: California Energy Commission.
- Horowitz, Marvin J.** 2007. "Changes in Electricity Demand in the United States from the 1970s to 2003." *Energy Journal* 28 (3): 93–119.
- Jacobsen, Grant D., and Matthew J. Kotchen.** 2013. "Are Building Codes Effective at Saving Energy? Evidence from Residential Billing Data in Florida." *Review of Economics and Statistics* 95 (1): 34–49.
- Jaffe, Adam B., and Robert N. Stavins.** 1995. "Dynamic Incentives of Environmental Regulations: The Effects of Alternative Policy Instruments on Technology Diffusion." *Journal of Environmental Economics and Management* 29 (3): S43–63.
- Kahn, Matthew E., Nils Kok, and Peng Liu.** 2016. "Is California More Energy Efficient than the Rest of the Nation? Evidence from Commercial Real Estate." National Bureau of Economic Research Working Paper 21912.
- Kahn, Matthew E., Nils Kok, and John M. Quigley.** 2014. "Carbon Emissions from the Commercial Building Sector: The Role of Climate, Quality, and Incentives." *Journal of Public Economics* 113: 1–12.
- Kotchen, Matthew J.** 2015. "Do Building Energy Codes Have a Lasting Effect on Energy Consumption? New Evidence from Residential Billing Data in Florida." National Bureau of Economic Research Working Paper 21398.
- Levinson, Arik.** 2014a. "California Energy Efficiency: Lessons for the Rest of the World, or Not?" *Journal of Economic Behavior and Organization* 107: 269–89.
- Levinson, Arik.** 2014b. "How Much Energy Do Building Energy Codes Really Save? Evidence from California." National Bureau of Economic Research Working Paper 20797.
- Levinson, Arik.** 2016. "How Much Energy Do Building Energy Codes Save? Evidence from California Houses: Dataset." *American Economic Review*. <http://dx.doi.org/10.1257/aer.20150102>.

- Levinson, Arik, and Scott Niemann.** 2004. "Energy Use by Apartment Tenants When Landlords Pay for Utilities." *Resource and Energy Economics* 26 (1): 51–75.
- Maher, Joe.** 2013. "Measuring the Energy Savings from Tree Shade." http://ageconsearch.umn.edu/bitstream/150567/2/Maher_AAEA_P3348_TreeShade.pdf (accessed August 12, 2016).
- Massachusetts Office of Energy and Environmental Affairs.** 2010. *Massachusetts Clean Energy and Climate Plan for 2020: A Report to the Great and General Court pursuant to the Global Warming Solutions Act*. <http://www.mass.gov/eea/docs/eea/energy/2020-clean-energy-plan.pdf>.
- Metcalf, Gilbert E.** 2008. "An Empirical Analysis of Energy Intensity and Its Determinants at the State Level." *Energy Journal* 29 (3): 1–26.
- Metcalf, Gilbert E., and Kevin A. Hassett.** 1999. "Measuring the Energy Savings from Home Improvement Investments: Evidence from Monthly Billing Data." *Review of Economics and Statistics* 81 (3): 516–28.
- Myers, Erica.** 2015. "Asymmetric Information in Residential Rental Markets: Implications for the Energy Efficiency Gap." Energy Institute at Haas Working Paper 246R.
- Pandit, Ram, and David N. Laband.** 2010. "Energy Savings from Tree Shade." *Ecological Economics* 69: 1324–29.
- Rosenfeld, Arthur H., and Deborah Poskanzer.** 2009. "A Graph Is Worth a Thousand Gigawatt-Hours: How California Came to Lead the United States in Energy Efficiency." *Innovations* 4 (4): 57–79.
- US Energy Information Administration.** 1993–2009. Residential Energy Consumption Survey. <http://www.eia.gov/consumption/residential/>.

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4. Hui Yun Rebecca Neo, Nyuk Hien Wong, Marcel Ignatius, Chao Yuan, Yong Xu, Kai Cao. 2021. Spatial analysis of public residential housing's electricity consumption in relation to urban landscape and building characteristics: A case study in Singapore. *Energy & Environment* **40**, 0958305X2110560. [[Crossref](#)]
5. Kenneth T. Gillingham, Pei Huang, Colby Buehler, Jordan Peccia, Drew R. Gentner. 2021. The climate and health benefits from intensive building energy efficiency improvements. *Science Advances* **7**:34. . [[Crossref](#)]
6. Yujie Xu, Vivian Loftness, Edson Severnini. 2021. Using Machine Learning to Predict Retrofit Effects for a Commercial Building Portfolio. *Energies* **14**:14, 4334. [[Crossref](#)]
7. Meredith Fowlie, Robyn Meeks. 2021. The Economics of Energy Efficiency in Developing Countries. *Review of Environmental Economics and Policy* **15**:2, 238-260. [[Crossref](#)]
8. Gunjan Kumar, Biswajit Thakur, Sudipta De. 2021. Energy performance of typical large residential apartments in Kolkata: implementing new energy conservation building codes of India. *Clean Technologies and Environmental Policy* **23**:4, 1251-1271. [[Crossref](#)]
9. Antoine Levesque, Robert C Pietzcker, Lavinia Baumstark, Gunnar Luderer. 2021. Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5°C scenario. *Environmental Research Letters* **16**:5, 054071. [[Crossref](#)]
10. Dalia Ghanem, Aaron Smith. 2021. What Are the Benefits of High-Frequency Data for Fixed Effects Panel Models?. *Journal of the Association of Environmental and Resource Economists* **8**:2, 199-234. [[Crossref](#)]
11. Mathias Reynaert, James M. Sallee. 2021. Who Benefits When Firms Game Corrective Policies?. *American Economic Journal: Economic Policy* **13**:1, 372-412. [[Abstract](#)] [[View PDF article](#)] [[PDF with links](#)]
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14. Jim Clayton, Avis Devine, Rogier Holtermans. 2021. Beyond building certification: The impact of environmental interventions on commercial real estate operations. *Energy Economics* **93**, 105039. [[Crossref](#)]
15. Anjelita Cadena, Thomas A. Thomson. 2021. The Value of “Green” in Resale Residential Real Estate: Premium by Neighborhood Value Quintile, Homestead Status and Year. *Journal of Sustainable Real Estate* **13**:1, 12-29. [[Crossref](#)]
16. Fiona Burlig, Christopher Knittel, David Rapson, Mar Reguant, Catherine Wolfram. 2020. Machine Learning from Schools about Energy Efficiency. *Journal of the Association of Environmental and Resource Economists* **7**:6, 1181-1217. [[Crossref](#)]

17. Erica Myers. 2020. Asymmetric information in residential rental markets: Implications for the energy efficiency gap. *Journal of Public Economics* **190**, 104251. [[Crossref](#)]
18. Petrik Runst, Anita Thonipara. 2020. Dosis facit effectum why the size of the carbon tax matters: Evidence from the Swedish residential sector. *Energy Economics* **91**, 104898. [[Crossref](#)]
19. Derek Lemoine. 2020. General equilibrium rebound from energy efficiency innovation. *European Economic Review* **125**, 103431. [[Crossref](#)]
20. Andrew O'Callaghan, Karl Purcell, Phil Hemmingway. 2020. Tackling the energy efficiency gap in the Irish residential sector. *Proceedings of the Institution of Civil Engineers - Energy* **173**:2, 49-59. [[Crossref](#)]
21. Lucas W. Davis, Sebastian Martinez, Bibiana Taboada. 2020. How effective is energy-efficient housing? Evidence from a field trial in Mexico. *Journal of Development Economics* **143**, 102390. [[Crossref](#)]
22. Judson Boomhower, Lucas Davis. 2020. Do Energy Efficiency Investments Deliver at the Right Time?. *American Economic Journal: Applied Economics* **12**:1, 115-139. [[Abstract](#)] [[View PDF article](#)] [[PDF with links](#)]
23. Matthew J. Holian. 2019. The impact of building energy codes on household electricity expenditures. *Economics Letters* . [[Crossref](#)]
24. Xia Wang, Wei Feng, Weiguang Cai, Hong Ren, Chao Ding, Nan Zhou. 2019. Do residential building energy efficiency standards reduce energy consumption in China? – A data-driven method to validate the actual performance of building energy efficiency standards. *Energy Policy* **131**, 82-98. [[Crossref](#)]
25. Garth Heutel. 2019. Prospect theory and energy efficiency. *Journal of Environmental Economics and Management* **96**, 236-254. [[Crossref](#)]
26. Anita Thonipara, Petrik Runst, Christian Ochsner, Kilian Bizer. 2019. Energy efficiency of residential buildings in the European Union – An exploratory analysis of cross-country consumption patterns. *Energy Policy* **129**, 1156-1167. [[Crossref](#)]
27. Yueming Qiu, Matthew E. Kahn. 2019. Impact of voluntary green certification on building energy performance. *Energy Economics* **80**, 461-475. [[Crossref](#)]
28. Wadim Strielkowski, Elena Volkova, Luidmila Pushkareva, Dalia Streimikiene. 2019. Innovative Policies for Energy Efficiency and the Use of Renewables in Households. *Energies* **12**:7, 1392. [[Crossref](#)]
29. Chris Bruegge, Tatyana Deryugina, Erica Myers. 2019. The Distributional Effects of Building Energy Codes. *Journal of the Association of Environmental and Resource Economists* **6**:S1, S95-S127. [[Crossref](#)]
30. Yueming Qiu, Matthew E. Kahn. 2018. Better sustainability assessment of green buildings with high-frequency data. *Nature Sustainability* **1**:11, 642-649. [[Crossref](#)]
31. Kenneth Gillingham, Amelia Keyes, Karen Palmer. 2018. Advances in Evaluating Energy Efficiency Policies and Programs. *Annual Review of Resource Economics* **10**:1, 511-532. [[Crossref](#)]
32. Meredith Fowle, Michael Greenstone, Catherine Wolfram. 2018. Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program*. *The Quarterly Journal of Economics* **133**:3, 1597-1644. [[Crossref](#)]
33. Massimo Filippini, Lin Zhang. 2018. Impacts of Heat Metering and Efficiency Retrofit Policy on Residential Energy Consumption in China. *SSRN Electronic Journal* . [[Crossref](#)]
34. Sebastian Rausch, Hagen Schwerin. 2018. Does Higher Energy Efficiency Lower Economy-Wide Energy Use?. *SSRN Electronic Journal* . [[Crossref](#)]
35. Li Zhang, Jing Wu, Hongyu Liu. 2018. Turning green into gold: A review on the economics of green buildings. *Journal of Cleaner Production* **172**, 2234-2245. [[Crossref](#)]

36. Erdal Aydin, Nils Kok, Dirk Brounen. 2017. Energy efficiency and household behavior: the rebound effect in the residential sector. *The RAND Journal of Economics* 48:3, 749-782. [[Crossref](#)]
37. Martin Achtnicht, Robert Germeshausen, Kathrine von Graevenitz. 2017. Does the Stick Make the Carrot More Attractive? State Mandates and Uptake of Renewable Heating Technologies. *SSRN Electronic Journal* . [[Crossref](#)]
38. Meredith Fowlie, Michael Greenstone, Catherine D. Wolfram. 2015. Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program. *SSRN Electronic Journal* . [[Crossref](#)]
39. Derek Lemoine. 2014. Long-Run Backfire from Energy Policies. *SSRN Electronic Journal* . [[Crossref](#)]