DEEP

Davis Economics Energy Program

DEEP WP 013

Residential Building Codes Do Save Energy: Evidence From Hourly Smart-Meter Data

Kevin Novan, Aaron Smith, and Tianxia Zhao

March, 2017

Residential Building Codes Do Save Energy: Evidence From Hourly Smart-Meter Data

Kevin Novan[*], Aaron Smith[†] and Tianxia Zhou[‡]

March 3, 2017

Abstract

In 1978, California adopted building codes designed to reduce the energy used for heating, cooling, and water heating in buildings. Using a rich dataset of hourly electricity consumption for 158,112 California houses during 2012-13, we estimate that single-family homes built from 1980 through 1982 consumed on average 13% less electricity for cooling than premises constructed between 1975 through 1977. This estimate is similar to projected cooling-energy savings made using engineering models at the time the codes were enacted. We argue that the 1978 building codes easily pass a cost-benefit test. Using monthly electricity consumption data, Levinson (2016) finds no evidence that post-1978 California houses use less energy to cool when the weather gets hot. Our results differ because our high-resolution data produce more precise estimates and eliminate a source of bias. In settings where agency problems and other potential market failures cause energy costs not to be passed through to the price of new houses, building energy codes can be a cost-effective policy.

[*]Department of Agricultural and Resource Economics, UC Davis, One Shields Avenue, Davis, CA 95616, (e-mail: *knovan@ucdavis.edu*)

[†]Department of Agricultural and Resource Economics, UC Davis, One Shields Avenue, Davis, CA 95616, (e-mail: *adsmith@ucdavis.edu*)

[‡]Department of Agricultural and Resource Economics, UC Davis, One Shields Avenue, Davis, CA 95616, (e-mail: *txzhou@primal.ucdavis.edu*)

1 Introduction

Following the 1973 energy crisis, U.S. policymakers sought to reduce fossil fuel consumption by imposing minimum efficiency standards on vehicles and buildings. In 1975, the federal government established minimum fuel efficiency (CAFE) standards for new vehicles. California adopted the nation's first state-level energy building codes in 1978, establishing minimum energy efficiency requirements for new residential and non-residential buildings. Supported by the U.S. Department of Energy, almost every state now has minimum efficiency standards for new buildings.[1]

In recent years, the interest in reducing fossil fuel consumption has intensified due to concerns about climate change. Policymakers have responded mostly by increasing the prevalence and stringency of energy efficiency standards. The economics literature almost universally agrees that this is an inefficient outcome. Standards are typically much more expensive than alternatives such as a cap and trade program (CAT) or a carbon tax, which would allow more flexibility in compliance and which would raise the price to consumers thereby creating an incentive to reduce consumption. Anderson and Sallee (2016) outline the inefficiency of CAFE standards relative to a fuel tax. Holland, Hughes and Knittel (2009) estimate that a low-carbon fuel standard in the transportation sector would be at least twice as expensive, and possibly as much as 10 times more expensive, than a cost-effective policy for reducing emissions. Bushnell et al. (2017) document the inefficiency of rate standards in the electricity generation sector relative to CAT.

Minimum energy efficiency standards in the residential sector, which accounted for 21% of total U.S. energy consumption in 2015, have received even stronger criticism in the economics literature.[2] Recent empirical studies suggest that building codes are not only inefficient, but also fail to achieve meaningful reductions in energy use. Levinson (2016), Jacobsen and

[1]The U.S. DOE's Building Energy Codes Program, which is part of the Buildings and Technologies Office, strives to achieve the goal of ensuring that "buildings use the minimum amount of energy required for occupant activities and comfort" (see https://www.energycodes.gov/about).

[2]Information on energy consumption by sector is provided by the U.S. Energy Information Administration's Annual Energy Review.

Kotchen (2013), and Kotchen (2017) present ex-post estimates of the impact of building codes by comparing household-level energy consumption in houses built before and after stricter efficiency standards were adopted. These authors find evidence that houses constructed under stricter efficiency standards use less natural gas for heating, but they find no significant effect on electricity use. In particular, Levinson finds no evidence that houses built after California adopted energy efficiency building codes in 1978 use less electricity for cooling than houses built before 1978.[3] He concludes that (i) Title 24, the policy that established California's residential energy efficiency building standards, was ineffective at reducing electricity consumption significantly, and (ii) any reductions that did occur fell far short of projections. We argue in this paper that both of these conclusions are incorrect.

In contrast to previous studies, which use monthly or annual household data, we examine an extremely rich dataset of hourly household electricity consumption. These data, which were collected throughout 2012 and 2013 from smart meters, cover 158,112 single-family homes constructed from 1960 through 2011 in Sacramento County. We estimate that the average house built just after 1978 uses 13% less energy for cooling than a similar house built just before 1978. This reduction corresponds to a 2.6% reduction in total electricity use. Our replication of Levinson's analysis shows that a 95% confidence interval includes a 2.6% effect, so one reason for our different results is that our data produce much more precise estimates.[4] We also show that Levinson's estimates are biased towards zero because he does not control for trends in electricity consumption across homes of different vintages.

To quantify the impact of Title 24 on electricity consumption, we estimate how each individual house's electricity use varies as a function of the daily temperature. Using the estimated premise-specific temperature response functions, we predict the quantity of electricity used for cooling during 2012 and 2013 within each premise. Our estimates imply that 20% of electricity consumption goes towards cooling. To determine whether Title 24 provided electricity savings, we test whether the level of electricity used for cooling during

[3]This finding is consistent with the results presented by Chong (2012).
[4]We present this replication in Section 3.4.

2012 and 2013 discontinuously drops in houses built immediately after 1978 versus those built immediately before 1978. Consistent with these energy savings being driven by a reduction in cooling, we find that the savings are concentrated on hot days and during the late afternoon and evening hours, precisely when demand for cooling is at it highest levels in the region.

We observe electricity consumption for a large number of houses, all in the Sacramento area, so our estimates of energy saved apply only to this area. The stringency of Title 24 varies around the state depending on climate zone, and the energy saved likely also varies. However, if the houses in our data were spread around the state, then it would be difficult to credibly identify the effect of the building codes. For example, the weather on the coast is milder and has less intra-day variation than the weather inland, which implies that the response of electricity use to temperature varies across the state. The housing stock on the coast is also older than the inland housing stock, so when estimating the response to temperature it would be easy to confound variation across houses of different vintages with variation across space. In contrast, the homogeneity of the weather experienced by the houses in our sample enables us to get precise estimates of the effect in this area.

Because we observe a large number of houses built each year, we are able to compare electricity use in the years immediately before and after 1978. This is important because numerous factors affect the energy efficiency of houses of different vintages. Newer houses tend to be larger and have higher ceilings, more bedrooms, multiple stories, and wealthier owners, but less tree shade. We observe some of these factors, but not others. Even if we did observe all these factors, it would require strong functional form assumptions to attribute to Title 24 any differences in energy efficiency of houses built many years apart.

Matching the smart meter data with County Assessor data, we show that the drop in cooling-driven electricity consumption is not explained by differences in observed premise characteristics (e.g., square footage, stories, bedrooms). Similarly, examining information on household incomes at the Census Block Group level, we find no evidence that the drop in consumption is caused by households discontinuously sorting into houses of different vintages. Finally, we examine whether the drop in consumption is simply due to the fact that the houses built after the codes were adopted are newer than the houses built prior to the code adoption. Although we find clear evidence that aging has meaningful impacts on cooling consumption within houses less than 20 years old, there is no evidence that aging explains the difference in 2012-13 cooling-driven consumption in houses built during the late 1970s and early 1980s. Combined, these results provide strong support for the conclusion that the building codes adopted in 1978 have reduced the quantity of electricity used for cooling.

Levinson's second conclusion is that Title 24 was expensive and had excessive ex ante projected savings. He writes that the codes added $8,000 (10%) to the cost of building the average Sacramento house and were projected to reduce energy consumption by 80 percent. These numbers appear in various California Energy Commission (CEC) documents published in 1979 and 1980, but they are not the relevant numbers for evaluating the initial Title 24 codes. The CEC's 1979 biennial report states that its "long-term goal is to reduce the electricity and gas now used in typical new buildings by at least 80 percent for new buildings constructed after 1990." In 1980, the CEC proposed new standards that it believed could reach this goal for several categories of energy use. Under these proposed standards, the CEC projected that an average house would use 80-95% less energy for space heating and cooling than an identically-sized uninsulated house built prior to 1975 with single-pane windows and no caulking or weather-stripping. This house would also use 50-70% less energy for water heating and 60% less energy for lighting than its pre-1975 counterpart, but it would cost an additional $8,000 to build. These standards were not adopted.[5]

To correctly estimate the ex-ante projected costs and energy savings of Title 24, we focus on the projected costs of the policy that was actually implemented in 1978. Moreover, we need to account for the fact that many houses would have met or exceeded the minimum efficiency standards even without the regulation in place. Precise estimates are elusive,

[5] See Section 2.1 and Table 2 for further details.

but surveys suggest that nearly half of the houses built in the mid 1970s complied with the subsequent 1978 building codes (e.g., CEC (1980*b*); OTA (1979)). Using this survey information and the CEC's ex-ante engineering estimates of the potential energy savings (CEC, 1980*c*), we approximate the increase in the average cost of building a Sacramento home at $782 (in 1980 dollars) and the projected average reduction in projected cooling-driven consumption at 20%. Even if this projection were correct, the realized difference between pre- and post-1978 houses in 2012-13 would be lower because many pre-1978 houses have been retrofitted since the codes were adopted. Our ex-post estimate of a 13% reduction in cooling energy use is congruent with the ex ante projections.

Using our estimate of the electricity savings, we examine whether the benefits provided by Title 24 have exceeded the costs of complying with the regulation. Imposing assumptions regarding the durability of the electricity savings and the marginal social cost of the avoided electricity generation, we estimate that the electricity savings alone have recovered approximately half of the upfront cost of complying with Title 24. Given that the engineering predictions suggest that the natural gas cost savings would exceed the electricity cost savings by a factor of nine, our results support the conclusion that Title 24 would comfortably pass a cost-benefit test.

Of course, simply passing a cost-benefit test does not imply that a policy is efficient. Across many settings, minimum efficiency standards have been shown to be far inferior to price based policies that directly internalize negative externalities (e.g., Holland, Hughes and Knittel (2009), Bushnell et al. (2017)). In the case of the market for new houses, however, there are a variety of market imperfections that may render the typical first-best price policies inefficient. Examining the cooling-driven electricity consumption among houses constructed during the 1980s, a period when electricity prices increased by more than 100% in Sacramento, we find no evidence of an improvement in residential energy efficiency. This finding suggests that a price policy may not work well, perhaps because of a principal-agent problem between the builder and the occupier. In such an environment, well-designed building codes can be effective at improving energy efficiency.

The remainder of the paper proceeds as follows. Section 2 discusses California's building codes and the data we examine. Section 3 presents estimates of how the response of electricity consumption to the outside temperature varies across houses built before and after Title 24 were adopted. Section 4 presents estimates from a regression discontinuity approach to quantify the reduction in cooling-driven electricity consumption caused by the building codes. Section 5 explores the long run trends in the energy efficiency of houses in our sample and Section 6 concludes.

2 Background and Data Sources

2.1 Residential Building Codes

In 1975, the California state legislature passed the Warren-Alquist Act, which created the CEC and led to the nation's first state-level energy building codes in 1978. Since the 1970s, the prevalence and stringency of energy efficiency standards has increased — spurred on not only by energy security concerns, but also growing awareness of the environmental impacts of fossil fuel consumption. In particular, in the residential sector, which accounted for 21% of total U.S. energy consumption in 2015, building codes have become the primary policy tool used to reduce energy use.[6] Nearly every state has established minimum efficiency standards for new houses, and with the support of the U.S. Department of Energy, these efficiency requirements are regularly increased.[7]

The CEC's first building energy codes, known as Title 24, were adopted in 1977 and were effective for all building permits issued after July 1, 1978. Some houses completed in 1979 would have been approved before the codes became effective. Title 24 placed significant

[6] Information on energy consumption by sector is provided by the U.S. Energy Information Administration's Annual Energy Review.

[7] The U.S. DOE's Building Energy Codes Program, which is part of the Buildings and Technologies Office, strives to achieve the goal of ensuring that "buildings use the minimum amount of energy required for occupant activities and comfort" (see https://www.energycodes.gov/about).

stress on local building departments, which were responsible for implementing and enforcing the codes. The CEC writes that "in most cases, building departments did not have staff who were knowledgeable in energy efficient building design" (CEC, 1980*d*). Moreover, building departments faced large budget cuts after Proposition 13, a tax reform initiative, passed in June 1978. The CEC sought to reduce the regulatory burden by getting the state Department of Housing and Community Development to provide a plan checking service for local building departments. For these reasons, we expect Title 24 to have been effective for all 1980-built houses, but not for all 1979-built houses.

Title 24 specified standards for wall, ceiling, and raised-floor insulation, allowable heat loss through windows, and the efficiency of climate control systems in residential and non-residential new buildings. The stringency of the codes varied according to the predicted number of heating degree days (HDD), with more stringent codes imposed in cities with higher HDD.[8] Table 1 shows that the codes added $1,565 to the cost of building an average-sized 1,620 square foot Sacramento house relative to a non-compliant house and $941 relative to a partially compliant house. A CEC survey in 1980 determined that the typical pre-1975 house in Sacramento complied at least partially with Title 24 (CEC, 1980*b*), meaning that it had sufficient ceiling insulation and did not have an oversized air conditioner.

The fact that the building codes were more stringent in cold areas, but not hot areas, is a clue that savings from reduced heating energy were the main goal of the standards. Table 1 shows that in a non- or partially-compliant house, heating used more than four times as much energy as cooling and that the codes were expected to save substantially more heating than cooling energy. CEC estimated that a house in compliance with Title 24 would use 62% less energy for heating and cooling than a non-compliant house and 48% less than a partially compliant house. Focusing on cooling only, the projected savings were 40% and 14%, respectively.

[8]The number of degrees below 65° Fahrenheit is the day's average temperature, summed across days, i.e., $HDD = \sum_d (65 - T_d)\mathbf{1}(T_d < 65)$, where T_d is the average temperature on day d and the function $\mathbf{1}(T_d < 65) = 1$ if $T_d < 65$ and zero otherwise.

Surveys conducted by the National Association of Home Builders reveal that, in 1974, 42% of new houses built in the Pacific region met or exceeded the level of ceiling insulation later required by Title 24 (OTA (1979), Appendix C, pg. 326). In the same year, 69% of new houses met or exceeded the wall insulation standard. The survey provides no information on the presence of measures to reduce air infiltration, such as caulking, sealing and weather-stripping, which were required under Title 24. To approximate the projected average difference between pre- and post-code houses, we assume that the 31% of houses that did not meet the wall insulation standard were fully non-compliant and the 42% of houses that met the ceiling insulation standard were fully compliant. This leaves 27% partially compliant houses. These percentages over-estimate the number of non-compliant houses because 95% of houses in the (OTA, 1979) survey had at least some insulation. It may also over-estimate the proportion of fully compliant houses as we do not have survey evidence of the presence of measures to reduce air infiltration in pre-1978 houses. With these caveats, we approximate the CEC's projection at 43% average savings on cooling and heating energy used, with only a tenth of the projected savings to come from reduced cooling.

The CEC has updated the building codes several times since 1978. In the first revision, which occurred in 1982, the CEC added flexibility in compliance. The 1978 standards were prescriptive; they specified particular requirements for the components of a building. The 1982 and later standards allowed compliance either with a prescriptive or a performance standard. The prescriptive standards specify a menu of packages that would be sufficient to meet the standard. To meet the performance standard, a builder must demonstrate using approved software that the building has the same expected use of energy for heating and cooling as a building that meets one of the prescriptive packages.

Table 2 shows representative prescriptive packages for a 1,620 square feet house in Sacramento under the various updates to Title 24. Updates were issued approximately every three years during this period, but we list in the table only those that made material changes to the residential standard. We also show the standard that was proposed in 1980 to help meet the goal of 80% reduction in energy use but was not adopted. The insulation requirements did not reach the level of the proposed 1980 standards until 2001.

Ceiling insulation requirements increased in 1982 and 2001 and wall insulation requirements increased in 1992 and 2001. The specified infiltration control requirements, which include caulking, weather-stripping, sealing, damping, and gasketing to reduce air leakage, have not changed meaningfully since 1978. Windows are regulated through glazing, area, and shading requirements. The 1982 codes essentially introduced double-paned window requirement because single-paned windows cannot achieve a 0.65 U-factor. Window standards then changed little from 1982 to 2010. Maximum window area was essentially 16% of the floor area in the house throughout this period, and the shading requirements changed only for windows that get little direct summer sunlight.[9] In 2010, the CEC increased the allowable window area by 25% but tightened the glazing standard by 38% to a 0.4 U-factor.[10]

Surveys conducted by the U.S. Energy Information Administration suggest that 31% of the energy consumed in California houses is used for space heating and cooling, 25% is used for water heating, and the remaining 44% is used for appliances, electronics, and lighting.[11] The building code components listed in Table 2 relate only to heating and cooling. Reducing heating and cooling use to zero would only reduce residential energy use by 31%. The CEC building codes also regulate water heating systems and, since 1982, lighting. Reducing water heating energy use to zero along with heating and cooling would reduce residential energy use by 56%. The CEC also sets appliance standards for the myriad appliances and electronics used in houses, including those that contribute to heating, cooling, water heating and lighting efficiency, but these are separate from building codes.

[9] In 1982 and 1992, the CEC required south-facing window area no less than 6.4% and non-south-facing windows area no more than 9.6% of total floor area. If these restrictions were both binding, then the windows area would equal 16%. The minimum requirement for south facing windows aims to improve heating efficiency; south facing windows allow direct sunlight into rooms during the winter. The shading requirements, which can be met by mesh screens or roof overhangs among other measures, aim mostly to improve cooling efficiency by keeping direct sunlight from shining into rooms during summer.

[10] The 2010 codes also introduced standards for roofing materials with the goal of increasing solar reflectance.

[11] Information on residential energy consumption by end-use is available from the Energy Information Administration's 2009 Residential Energy Consumption Survey.

Clearly, Title 24 building codes cannot achieve an 80% reduction in electricity use or in total energy use, nor were they intended to. The best approach to estimate the effects of building codes is to focus on specific components, in our case cooling, and evaluate them relative to their costs and projected benefits. That is the approach we take in this paper.

2.2 Premise-Level Data

We focus exclusively on houses located in the Sacramento Municipal Utility District (SMUD) service area – i.e. Sacramento County and the surrounding cities and communities to the north, east, and south. For nearly the universe of residential consumers in SMUD's service territory, we observe the hourly electricity consumed at each individual premise from January 1, 2012 through December 31, 2013.[12] We also use billing records, which record the monthly aggregate consumption at each individual premise over a longer period, 2008 through 2013.

We observe information on the physical characteristics of each premise from the County Assessor. Importantly, the Assessor data provides the year each premise was constructed as well as information on the type of housing (i.e. single-family vs. multi-family). To ensure that we do not compare the consumption patterns of individual apartments in large complexes to detached, single-family homes, we focus exclusively on single-family premises. Our first set of estimates uses the 39,913 single-family premises in our sample that were constructed in the years surrounding the adoption of Title 24 — 1975 through 1982. For our second set of estimates, we use the 158,112 single-family premises in our sample constructed between 1960 and 2011.

Table 3 summarizes the information observed from the single-family premises constructed from 1975 through 1982. Several important patterns emerge. First, during 2012 and 2013, single-family homes built from 1980 through 1982 consumed an average of 4.65 kWh/day

[12]Our sample does not include a small share of households that pay unique rate codes (e.g., plug-in electric vehicle rates). In addition, a small subset of houses that were chosen to participate in a SmartPricing Option Pilot Study conducted by the Department of Energy are excluded from our sample. Finally, an extremely small minority of customers have elected to pay a one time $127 fee and monthly charges of $14 to retain their old analog meter, and as a result, we do not observe hourly consumption from these houses.

more than premises constructed between 1975 through 1977. This, however, does not imply that Title 24 failed to save energy. Instead, the higher consumption among the houses constructed after 1980 can in part be explained by other trends displayed in Table 3. For example, houses built from 1980 through 1982 were larger than houses built from 1975 through 1977 by an average of 96 square feet and were also more likely to have central air conditioning and electric heat.

Title 24 established minimum standards for a house's thermal insulation. Therefore, if adopting the building codes saved energy, it would have come mostly in the form of reduced energy consumption for cooling and heating. In California as a whole, space cooling only accounts for 4% of total residential energy use and only 40% of houses have central air conditioning (AC) units.[13] However, in the inland regions of California which experience high summer temperatures (e.g., Sacramento), space cooling is a much larger driver of residential energy consumption. The reliance on air conditioning is highlighted in Table 3. Among the households constructed in SMUD's service territory from 1975 though 1982, 96% have central air conditioning (AC) units. Later, we estimate that space cooling accounts for approximately 20% of residential electricity consumption.

2.3 Electricity Use and Temperature

To determine whether Title 24 resulted in electricity savings, we ask the following question: controlling for changes in the size of houses, do houses built after the adoption of the building codes consume less electricity for cooling during 2012 and 2013? To answer this question, we follow the approach taken by Jacobsen and Kotchen (2013) and Levinson (2016). Specifically, we examine whether electricity consumption responds differently to the outdoor temperature in houses built before versus after 1978.

Our measure of the outdoor temperature comes from a NOAA weather station that

[13]Combined, space cooling and heating accounts for 31% of California's residential energy consumption. Residential energy consumption by end-use and region is provided by the U.S. Energy Information Administration's 2009 Residential Energy Consumption Survey.

records hourly temperature at the Sacramento International Airport.[14] We use as our temperature variable the simple average of the 24 intra-day temperature readings, which is extremely highly correlated with the hourly temperature (see Table A2 in the appendix). The upper right panel of Figure 1 displays the distribution of the daily average temperatures from 2012 through 2013.

To highlight the extent to which cooling and heating affects residential electricity consumption in the region, the upper left panel of Figure 1 plots the average daily electricity consumption among the premises built from 1975 through 1982 as a function of the average daily temperature. To construct the figures, each day from January 1, 2012 through December 31, 2013 is placed in $1°F$ wide bins based on the daily average temperature. Within each bin, we calculate the average daily electricity consumption as well as the 25^{th} and 75^{th} percentiles of the daily consumption. The figure reveals that the minimum average daily consumption occurs on days with an average daily temperature in the range of $60°F$ to $62°F$.

The temperature in Sacramento varies over a wide but predictable range during a typical day. A day with an average temperature of $60°F$ will reach a high of $73°F$, and a day with an average of $80°F$ will reach $100°F$. When the daily average temperature increases above the minimum point, the use of electricity for cooling drives substantial changes in electricity consumption. On a day with an average temperature of $80°F$, the average electricity consumption is twice as much as day with an average temperature of $60°F$. More electricity is also used when the weather gets cold. The majority of houses do not use electricity as the primary energy source for heating, but even in gas-heated homes some electricity is required for heating (e.g., to power fans to distribute the heat throughout the house).

The bottom panels of Figure 1 highlight that the impact of temperature on consumption

[14] Hourly temperatures are also available from NOAA weather stations at other locations in SMUD's service territory. The temperature readings at these additional locations are nearly identical to the Sacramento Airport temperature readings – which is to be expected given the very uniform elevation and climate across SMUD's service region. Given that the Sacramento Airport is the only station to report without any missing observations, we use it as our source of the regional temperature.

is very heterogeneous across hours of the day. During the early morning hours, temperatures in the region are well below the daily average temperature (see Table A2). As a result, there is very little use of air conditioning in the morning. In contrast, during the hot, late afternoon hours, electricity consumption is much higher on hot days than cool days.

We report two sets of results in the subsequent sections. First, in Section 3 we use houses built from 1975 through 1982 to fit a model of electricity use as a function of temperature. We estimate whether electricity use responds less to high temperatures in post-Title-24 houses than in pre-Title-24 houses. Second, in Section 4 we estimate the energy used for cooling for each house and then we test for a discontinuous drop in energy used for cooling at the 1978 vintage. The first approach requires stronger assumptions because it pools across houses built in different years, but it may yield more precise estimates. It also allows a direct comparison to the estimates in Levinson (2016). The second approach requires fewer assumptions, but may be less precise.

3 Temperature Response: Pooled Model

In this section, we focus on houses built during three vintages around the adoption of the building codes. Houses constructed during the three years preceding the building codes, 1975 through 1977, serve as the 'Pre-Adoption' vintage of houses. Houses built during the initial two years of Title 24's adoption, 1978 and 1979, serve as the 'Adoption' vintage of houses. Finally, the houses built from 1980 through 1982 serve as the 'Post-Adoption' vintage of houses. We estimate whether the average response of electricity consumption to temperature differs between the 1975-77 vintage houses and the 1980-82 vintage houses.

3.1 Model Specification

Using the observed premise-level, daily electricity consumption spanning January 1, 2012 through December 31, 2013, we estimate the following model:

$$\text{Cons}_{i,d} = \alpha_i + \sum_j \left(\boldsymbol{\beta}_j \cdot \mathbf{T}_d \cdot \text{Vintage}_{i,j}\right) + \boldsymbol{\theta} \cdot \mathbf{T}_d \cdot \mathbf{X}_i + \varepsilon_{i,d}, \tag{1}$$

where i indexes each individual premise, d indexes each day during the two year sample, and j indexes the three vintages (i.e. pre-adoption, adoption, post-adoption). $Cons_{i,d}$ represents the total consumption (kWh) for household i on day d. We model the daily household consumption as a function of the daily average temperature, Temp_d, which is measured in °F. The daily temperature enters the model through $\mathbf{T_d}$, a piecewise linear spline with three knot points (at 52°F, 62°F, and 72°F). Specifically, $\mathbf{T_d}$ represents the following 4×1 vector:

$$\mathbf{T_d} = \begin{bmatrix} min(\text{Temp}_d, 52) \\ min\left(max(\text{Temp}_d - 62, 0), 62 - 52\right) \\ min\left(max(\text{Temp}_d - 72, 0), 72 - 62\right) \\ max(\text{Temp}_d - 72, 0) \end{bmatrix}. \tag{2}$$

The top panel of Figure 2 provides the graphical intuition for the model presented above. Eq. (1) specifies the daily electricity consumed by household i as a non-linear function of the daily average temperature, $f_i(Temp; X_i)$. The middle knot is set at 62°F because this is the approximate temperature where the mean consumption is minimized (see Figure 1). The remaining knots are set at approximately the 25^{th} and 75^{th} percentiles of average daily temperatures, allowing consumption to increase non-linearly as temperatures move away from 62°F.

We allow the temperature response function to flexibly vary across households. Premise-level fixed effects (α_i in Eq. (1)) allow the function $f_i(\cdot)$ to shift vertically — controlling for the fact that different premises will have different average levels of consumption. In addition, we allow the slopes of each segment of the temperature response function to vary with observed premise-level physical characteristics by interacting the temperature spline with a vector of premise characteristics ($\mathbf{X}_i$). The vector $\mathbf{X}_i$ includes indicator variables for whether household i has $1, 2, 4, 5$ or 6 bedrooms, an indicator variable for multi-story houses, indicator variables that identify premises as less than 1,000 square feet, greater than 2,500 square feet, or in one of nine bins that divide the remaining houses into 150 square foot intervals, and finally, an indicator variable for premises with electric heat.[15] We exclude indicators for premises with 3 bedrooms, a single story, square footage between 1,600 and 1,750, and without electric heat. These values represent the mean square footage and median stories and bedrooms among the houses constructed from 1975 through 1982. Therefore, the main results we report will be estimates of how the temperature impacts electricity consumption in the baseline type of house (i.e. three bedrooms, single story, gas heat, 1,600 to 1,750 square feet).

The coefficients of interest from Eq. (1) are the slope coefficients of the temperature spline ($\boldsymbol{\beta}_j$), which we allow to vary based on the vintage of the house. That is, we estimate a different temperature demand response function for houses built from 1975-77, 1978-79, and 1980-82. We also present estimates from an alternative specification that allows the temperature response functions to differ across each individual year of construction. If the building codes caused the thermal insulation of the houses to improve, then we would expect the estimates of $\boldsymbol{\beta}_j$ to move closer to zero for the houses built during the 1980-82 post-adoption period. Referring back to the top panel of Figure 2, this would be seen as a flattening of the temperature response response function, $f_i(Temp; X_i)$, in the post-adoption houses.

[15] The 6-bedroom indicator variable includes houses with 6 or more bedrooms.

3.2 Pooled Model Estimates

Table 4 reports the point estimates of the temperature response spline, $\boldsymbol{\beta}_j$ from Eq. (1), for each of the three different vintages of houses (1975-77, 1978-79, and 1980-82).[16] The reported standard errors are robust to two-way clustering by premise and week-by-year. Table 4 also reports the change in the slope of each segment of the temperature response function relative to the 1975-77 vintage of houses.

For all three vintages of houses, the slopes of the temperature response functions are negative for temperatures below 62°F and positive for temperatures above 62°F.[17] That is, as temperatures move away from 62°F, average daily electricity consumption increases. Focusing on the slope estimates for temperatures ranging from 62°F to 72°F, we find that the slope is 0.05 kWh/day per °F lower among the houses constructed during the building code adoption phase (1978-79) relative to the pre-adoption vintage houses (1975-77). This decline is even more pronounced among the houses built exclusively after the adoption of Title 24 (1980-82), with a slope that is 0.12 kWh/day per °F lower. For temperatures above 72°F, the point estimates of the slope of the temperature response functions are again lower among the houses constructed from 1978-79 and 1980-82, however the differences are not significant. Combined, these estimates reveal that electricity consumption in houses constructed after the building codes were implemented (1980-82) is significantly less responsive to hot outdoor temperatures.

Focusing next on the response of electricity consumption to temperatures below 62°F, the changes in the slope estimates reported in Table 4 do not display a clear pattern. For temperatures from 52°F to 62°F, the slope of the temperature response function is slightly less steep (less negative) among the post-Title-24 houses (1980-82). However, the slopes do not differ significantly across the three vintages of houses. For temperatures below from

[16] Table A3 in the appendix presents estimates of $\boldsymbol{\beta}_j$ from Eq. (1) allowing the temperature response function to vary by each year of construction.

[17] Recall that an intra-day average temperature of $60°F$ implies an intra-day high of $73°F$, an average of $70°F$ implies a high of $87°F$, and an average of $80°F$ implies a high of $100°F$.

52°F, the slope of the temperature response function is slightly steeper (more negative) among the post-Title-24 houses (1980-82). Recall from Table 3, the majority of premises constructed from 1975 through 1982 do not rely on electricity as their primary source of heat. Therefore, it is not surprising that there are no meaningful changes in the post-code temperature response function for temperatures below 62°F.[18]

To quantify the reduction in electricity used for cooling among the post-Title-24 houses, we estimate the average daily use of electricity for cooling in houses of different vintages. To do so, we assume that, regardless of a house's vintage, zero electricity is used for cooling on days when the average temperature is 62°F. Under this assumption, the predicted electricity consumption used for cooling is simply equal to the temperature response function specified by Eq. (1) normalized to have a value of zero at a temperature of 62°F.

The top panel of Figure 3 displays the predicted daily consumption of electricity for cooling and heating for a house constructed during 1975-77 and 1980-82. The bottom panel displays the change in the predicted daily electricity used for heating and cooling among the 1980-82 houses relative the to 1975-77 houses. The plots reveal that, after controlling for changes in the size of houses, the post-adoption era houses consume significantly less electricity for cooling. Moreover, the reduction in daily electricity used for cooling is found to increase as the average daily temperature grows.

Combining the estimates displayed in the top left of Figure 3 with the observed average daily temperatures from January 1, 2012 through December 31, 2013, we estimate the total electricity consumed for cooling over the two year period in a 1975-77 vintage house and a 1980-82 vintage house – both of which are assumed to have three bedrooms, a single story, gas heating, and 1,600 to 1,750 square feet. Over the two year sample, there were 357 days with an average temperature above 62°F. Aggregating over these 357 days, we estimate that the 1975-77 vintage house would have consumed 3,627 kWh of electricity for cooling, or an average of 1,814 kWh per year. In contrast, the house constructed during the 1980-82 post-

[18]Ideally, we would estimate the improvement in heating efficiency for the homes that use primarily electric heat. However, as we explain in Appendix A, we are unable to identify this effect well, so we focus on cooling.

adoption era would have consumed 1,644 kWh per year – which represents a 9.4% reduction is electricity used for cooling relative to the 1975-77 vintage house.

3.3 Timing of Demand Reductions

The preceding results provide evidence that the average daily level of electricity consumed for cooling and heating fell among the houses constructed after Title 24 was adopted. If there truly has been a reduction in the use of electricity for temperature control, then we would expect that the savings would not be evenly distributed over the course of a day. For example, if less electricity is consumed for cooling among the 1980-82 vintage houses, we would expect the energy savings to occur specifically during the warm afternoon hours when air conditioning is more heavily used.

To test whether this is the case, we re-estimate the model specified by Eq. (1) separately for each hour of the day. Instead of using the daily aggregate consumption at household i on day d as the dependent variable, we use the hourly consumption at household i on day d during hour h. The resulting estimates of the vintage-specific temperature response functions now predict how electricity consumption during each specific hour of the day responds to the average daily temperature.

Figure 5 plots the predicted change in electricity used for cooling by hour-of-day for two different average daily temperatures.[19] These estimates are again based on the assumption that, during each hour of the day, zero electricity is used for heating and cooling when the average daily temperature is 62°F. The results reveal that, on warm days, houses constructed from 1980-82 consume significantly less electricity for cooling compared to houses constructed from 1975-77. The reduction in cooling driven consumption begins in the late morning hours and increases throughout the afternoon, peaking around 8pm on warm days (with an average temperature of 68°F) and peaking later, around 10pm, on hotter days (with an average temperature of 80°F).

[19] Appendix Figure A2 presents the estimates of the changes in the temperature response function slopes from the 1980-82 era houses relative to the 1975-77 era houses.

In contrast, during the cool early morning hours when little energy is used for cooling, electricity consumed for temperature control does not vary significantly across the two vintages of houses. The pattern displayed by the predicted changes in cooling – specifically, larger energy savings on the hottest days, particularly in the warmest late afternoon hours – provides strong evidence that the 1980-82 era houses were constructed with superior thermal insulation.

3.4 Why do our Results Differ from Levinson (2016)?

Levinson (2016) estimates using monthly data from around California that electricity use became more responsive hot temperatures immediately after Title 24, albeit by a statistically insignificant amount (see his Table 4, Appendix Table A5, and Figure 6). In contrast, we find a statistically significant decrease in the responsiveness. To understand why the findings differ, we replicated Levinson's analysis and compared it directly to our own.[20]

Our data clearly differ in depth and breadth compared to Levinson's. We have deep hourly data from a narrow homogeneous region, whereas he has monthly data from broad set of locations around the state. In addition, our results in Table 3 are based on houses built around the adoption of Title 24 (1975-82), whereas Levinson's model uses houses over a much wider range of vintages. There are also several differences in model specification that may drive the difference in results. First, Levinson uses consumption data from the 2003 and 2009 Residential Appliance Saturation Study (RASS). The 2009 RASS identifies the multi-year window in which a house was built rather than reporting the exact year. The 2003 RASS identifies the exact year built for all houses built since 1970. Because he pools the 2003 and 2009 RASS data, Levinson models vintage using multi-year windows. We show that this grouping across vintages obscures important variation.

A second difference in model specification is that we specify the dependent variable in levels (kWh), whereas Levinson uses log of kWh. We use the level because the effect of

[20]We obtained Levinson's data and code from the additional materials published alongside the paper on the *American Economic Review* website.

operating an air-conditioner on electricity use does not depend on how much electricity is being used for other purposes. We find that this difference is not important qualitatively. We conduct our comparison using levels so that coefficients estimated from daily and monthly models are directly comparable.

A third difference is that Levinson uses heating and cooling degree days (HDD and CDD) to measure the outdoor temperature, whereas we use a more flexible function. To obtain comparable estimates, we re-estimate Eq. (1) using our data and these temperature variables rather than a spline with three knots. Specifically, we set

$$\mathbf{T_d} = \begin{bmatrix} HDD_d \\ CDD_d \end{bmatrix} = \begin{bmatrix} max(65 - \text{Temp}_d, 0) \\ max(\text{Temp}_d - 65, 0) \end{bmatrix}. \tag{3}$$

We interact HDD_d and CDD_d with the same set of $\mathbf{X}_i$ variables as in Table 3.

For comparison with our results, we estimate the model in Levinson's Figure 6 after making four modifications. First, we use only data for homes built from 1975 through 1982. Second, we use only the 2003 RASS so we could identify year built. Third, we use levels rather than logs. Fourth, we use premise fixed effects rather than the full set of controls, which improves precision and which controls for building and occupant characteristics in a more flexible way.[21] Table A5 shows the estimation results with and without these four modifications.

Figure 4 shows estimates of the coefficients on CDD interacted with vintage for the two datasets, with 1977 the base year. Negative values indicate a decline in the response of electricity use to temperature, which is what we expect if the building codes reduce electricity use. Consistent with the results reported in Tables 3 and A3, the SMUD data show that responsiveness to temperature declines after Title 24. The Levinson data show the same result, although the estimates are much less precise. It appears that our results differ from

[21] We also added HDD to the model, which Levinson excludes, and we dropped the average monthly CDD variable. These changes made little difference to the coefficients of interest, but they ease comparison with our results. Also, we measure HDD and CDD in degrees Fahrenheit, whereas these variables were measured in degrees Celcius in the dataset Levinson used.

Levinson's in large part because his data doesn't allow precise identification of the effect.

The imprecision highlights the perils of grouping across vintages. The 1975 houses in Levinson's sample pull down the average response to temperature in the pre-adoption period. The 1982 houses pull the average post-adoption response up. As a result, the estimated response to temperature is higher in 1978-82 than it was in 1975-77, making it appear that Title 24 failed to save electricity.

4 Temperature Response: Premise-Specific Model

The preceding estimates of the amount of electricity used for cooling assumed that all households begin cooling once the temperature exceeds 62°F. Under this assumption, heterogeneity across households in the amount of electricity used for cooling will only arise due to differences in the slopes of the temperature response functions (i.e. households with steeper estimated temperature response functions are predicted to use more electricity for cooling). In reality, the amount of electricity used for cooling will differ across premises not only due to differences in the slope of the households' temperature response functions, but also due to differences in when households begin cooling. Some households may begin using air conditioning on days with average temperatures well below 62°F while other households may reserve the use of air conditioning for only the hottest days.

In this section, we relax the assumption that each household begins cooling at the same temperature. To do so, we estimate a separate temperature response function for each individual premise using the daily consumption data spanning 2012 and 2013. Estimating a separate model for each premise also frees us from having to model the effects of building characteristics (e.g., square footage) on the temperature demand response function. As a result, we are able to study how cooling-driven electricity consumption varies among premises built over a longer time span in which house characteristics changed substantially.

We present premise-specific estimates of the quantity of electricity used for cooling during

2012 and 2013. Rather than focusing exclusively on the houses constructed in a narrow window of time around the adoption of Title 24, we examine houses constructed from 1960 through 2011. To quantify the reduction in cooling-driven electricity consumption caused by the adoption of Title 24, we estimate the magnitude of the discontinuous change in cooling-driven consumption that occurs between premises constructed immediately before and after 1978.

4.1 Model Specification

For each single-family premises in our sample constructed between 1960 and 2011, we estimate a separate model specifying the daily electricity consumption as a function of the daily average temperature. To allow the temperature at which the minimum average consumption occurs to vary flexibly across premises, we model the relationship between premise-level daily electricity consumption and the daily temperature using a restricted cubic spline. We continue to use three knot points at 52°F, 62°F, and 72°F. However, rather than restricting the premise-specific temperature response functions to be linear between the knot points, the cubic spline specifies the temperature response functions as (1) being a cubic function between 52°F and 62°F as well as between 62°F and 72°F, (2) being a linear function for temperatures below 52°F and above 72°F, and (3) being continuous in the levels, first, and second derivatives.

For each household i, and for each day d during the two years spanning January 1, 2012 through December 31, 2013, we estimate the following model:

$$\text{Cons}_{i,d} = \alpha_i + \beta_{1,i} \cdot \text{Temp}_d + \beta_{2,i} \cdot S_d + \varepsilon_{i,d}. \tag{4}$$

$Cons_{i,d}$ again represents the total electricity consumption (kWh) for household i on day d

and Temp_d is the daily average temperature (°F). The variable S_d is specified as follows:

$$S_d = (\text{Temp}_d - 52)^3_+ - 2 \cdot (\text{Temp}_d - 62)^3_+ + (\text{Temp}_d - 72)^3_+, \tag{5}$$

where $(x)_+$ equals x if $x > 0$ and zero otherwise.

The bottom panel of Figure 2 provides the graphical intuition for the premise-specific model. By modeling the premise-specific temperature response function $f_i(Temp)$ as a cubic polynomial for temperatures between 52°F and 72°F, we allow $Temp_i^{min}$, the temperature where average consumption is minimized for premise i, to vary flexibly from 52°F to 72°F. On days when the average temperature exceeds $Temp_i^{min}$ (e.g., $Temp'$ in the diagram), premise i's daily consumption of electricity for cooling can be estimated as the difference between $Cons'$ and $Cons_i^{min}$. Using the estimates of the household-specific temperature response functions specified by specified by Eq. (4), we predict (1) the temperature at which each household begins to use electricity for cooling, and (2) the quantity of electricity each household uses for cooling.

If Title 24 improved the thermal insulation of houses, then post-adoption vintage houses should start using their air conditioners at a warmer outdoor temperature. This would show up as a higher predicted values of $Temp_i^{min}$ in post-1978 houses. Of course, among the subset of premises that use electricity as their primary energy source for heat, improvements in thermal insulation could also lead to a reduction in $Temp_i^{min}$, as households potentially restrict their use of electric heat for only the coldest days. Therefore, improvements in thermal insulation would have an ambiguous effect on the level of $Temp_i^{min}$ among houses with electric heat. For this reason, we use only the 158,112 single-family premises constructed between 1960 and 2011 that do not use electricity as their primary energy source for heating.[22]

[22] Very few houses constructed prior to the mid-1970s use electricity as their primary source of heating. Therefore, we are unable to provide estimates of the use of electricity for temperature control in electric heat houses over a longer time span.

4.2 Premise-Specific Estimates

Figure 6 displays the distribution of the predicted minimum consumption temperatures ($\widehat{Temp}_i^{min}$) for 95% of the 158,112 premises. The 5% of premises excluded from the distribution did not have a well defined estimate for the predicted minimum consumption temperature. Specifically, the estimated temperature response function specified by Eq. (4) was monotonically increasing over all temperatures for 3.7% of the premises and monotonically decreasing for 1.4% of the premises. Among the 95% of premises with a predicted minimum consumption temperature between 52°F and 72°F, we find an average value of $\widehat{Temp}_i^{min}$ of 59.98°F.

Using the premise-specific estimates of Eq. (4), we predict the total quantity of electricity used for cooling ($\widehat{\text{Cooling}}_i$) during 2012 through 2013. For the premises with a predicted minimum consumption temperature between 52°F and 72°F, we predict the average electricity consumed for cooling on each day during 2012 and 2013. For the 1.4% of premises with a monotonically decreasing temperature response function, we assume that zero electricity is used for cooling. For the remaining 3.7% of premises with monotonically increasing temperature response functions, we are unable to estimate the electricity used for cooling.[23]

To explore how the quantity of electricity used for cooling differs across vintages of houses and building characteristics, we estimate the following model:

$$\widehat{\text{Cooling}}_i = \sum_t \left(\gamma_t \cdot \text{Vintage}_{i,t}\right) + \boldsymbol{\theta} \cdot \mathbf{X}_i + \varepsilon_i, \tag{6}$$

where i indexes each premise and t indexes each year of construction from 1960 through 2011. To control for variation across vintages in the physical characteristics of houses, $\mathbf{X}_i$

[23] By dropping this subset of premises which clearly increase consumption with temperature, we potentially underestimate the average electricity used for cooling among the different vintages of houses. However, the share of houses dropped is very stable across year-of-construction. Moreover, in the window surrounding the building code adoption (1975-82), the share of houses with monotonically increasing temperature response functions falls slightly across year-of-construction. This suggests that the difference between the average electricity consumed for cooling in the post and pre-adoption vintages of houses would underestimate the energy savings following the implementation of Title 24.

includes a fully saturated set of 144 indicator variables separating houses into groups based on the number of bedrooms $(1, 2, ..., 6+)$, whether the house is single versus multi-story, and the square footage (twelve bins ranging from $< 1,000$ square feet to $> 2,500$ square feet). As before, we exclude the indicator for three bedroom, single story houses with 1,600 to 1,750 square feet.

The estimates of γ_t represent the average quantity of electricity used for cooling among the houses constructed during year t. The top panel of Figure 7 presents the estimates of γ_t from Eq. (6), as well as the corresponding 95% confidence intervals.[24] To account for possible correlation among the errors of neighboring households, the confidence intervals are robust to heteroskedasticity and clustering at the Census Block Group level. In addition, the gray line in the top panel of Figure 7 shows the unconditional means of the predicted cooling electricity used by vintage (i.e., estimates of γ_t from a model that excludes $\mathbf{X}_i$).

The premise-specific estimates of Eq. (6) also provide predictions of the temperature at which households begin cooling ($\widehat{Temp}_i^{min}$). If Title 24 resulted in an improvement in thermal insulation, then the average $\widehat{Temp}_i^{min}$ would be higher in post-Title-24 houses. To explore whether this is the case, we re-estimate the model specified by Eq. (6) using the premise-specific estimates of $\widehat{Temp}_i^{min}$ as the dependent variable.[25] The bottom panel of Figure 7 presents the estimates of γ_t from Eq. (6), the average minimum consumption temperature by year of construction.

Focusing on the years immediately surrounding 1978, Figure 7 reveals a clear decrease in the quantity of electricity used for cooling and increase in the temperature at which cooling begins. The changes in these quantities between 1977 and 1980 vintages are larger than any three year changes observed across houses constructed from 1960 through the mid-1990's. In the next section, we use a regression discontinuity approach to quantify the changes around

[24]We divided the estimates by two to convert them to the average annual consumption of electricity used for cooling over the two year period.

[25]We now focus specifically on the 95% of premises that did not have monotonically increasing or decreasing temperature response functions. The remaining 5% of houses did not have a well defined estimate for $Temp_i^{min}$.

1978. Later, in Section 5 we discuss the longer run trends in cooling energy efficiency that are apparent in Figure 7.

4.3 Discontinuity in Predicted Cooling

To quantify the change in cooling-driven electricity consumption following the adoption of Title 24, we estimate the following model:

$$\widehat{\text{Cooling}}_i = \delta \cdot Post_i + \beta_1 \cdot \Big(\text{Year}_i - 1978\Big)_- + \beta_2 \cdot \Big(\text{Year}_i - 1978\Big)_+ + \boldsymbol{\theta} \cdot \mathbf{X}_i + \varepsilon_i, \quad (7)$$

where Year_i represents the year premise i was constructed and $Post_i$ is an indicator which equals one for premises constructed during or after 1978, the year Title 24 was adopted. The function $(x)_-$ equals x for $x < 0$ and zero otherwise. Similarly, $(x)_+$ equals x for $x > 0$ and zero otherwise. To control for differences in the physical characteristics of houses, $\mathbf{X}_i$ again includes the same set of saturated controls for stories, square footage, and bedrooms. In addition, we also present estimates in which $\mathbf{X}_i$ includes average household income at the Census Block Group level, the average household income squared, as well as community fixed effects. These community fixed effects, which are based on geographic boundaries designated by SMUD, divide Sacramento County into seven geographic regions.

The model specified by Eq. (7) allows the predicted annual cooling to vary continuously with the year of construction among the houses built before 1978 and after 1978. The previous estimates summarized in the top panel of Figure 7 reveal that the assumption of linear trends is a reasonable approximation within the set of houses constructed in the 20 year window around the adoption of Title 24. Therefore, our primary estimates of Eq. (7) are based on the houses constructed from 1968 through 1989. Given that the Title 24 building codes were not enforced for all 1978 and 1979 vintage houses, we drop houses constructed during these two years from the sample.

With the inclusion of the $Post_i$ indicator in Eq. (7), we allow the predicted annual cooling to change discontinuously in 1978, the year Title 24 were initially phased in. Assuming that any factors that can affect the demand for cooling – other than Title 24 – do not vary discontinuously across the 1977 and 1980 vintages of houses, any discontinuous change in the predicted cooling between the pre and post-adoption vintage of houses can be attributed to the adoption of Title 24. Specifically, δ represents the average difference in annual cooling-driven electricity consumption that would occur in 1978 vintage houses had Title 24 been enforced for all 1978 houses versus the case where Title 24 was enforced for none of the 1978 houses.[26]

Table 5 presents the estimates of Eq. (7). The first column displays the estimates of the baseline model, without the inclusion of Block Group income controls or spatial fixed effects, and the top panel of Figure 8 displays the predicted linear trends and the discontinuity from the baseline specification. The estimate of δ suggests that the adoption of Title 24 results in an average reduction in cooling of 257 kWh/year.[27] The second and third columns of Table 5 reveal that the predicted reduction in cooling is effectively unchanged by the inclusion of Census Block Group level income controls.[28] Finally, the last three columns of Table 5 present the estimates of discontinuity in cooling consumption with the inclusion of spatial fixed effects. Although the point estimate of δ falls, the results continue to reveal that significant reductions in cooling-driven electricity consumption occur in the houses built after the adoption of Title 24.

To test for a discontinuous change in the minimum consumption temperature following

[26] One possibility is that an increase in energy prices caused a discontinuous change in the energy efficiency of new houses in 1978. Over the six years from 1974 to 1980 the average price per kWh paid by SMUD customers increased smoothly in nominal terms, but was essentially unchanged in real terms. The wellhead price of California natural gas quintupled from 1974-1980, which corresponds to a tripling of the real price. However, although the increase in real natural gas prices was large, it was also smooth. There was no abrupt jump in prices that coincided with Title 24.

[27] Table A6 in the appendix presents estimates of the discontinuity in cooling for different ranges of years and for linear and quadratic trends. The estimated reduction in cooling that occurs following the adoption of Title 24 is stable across the alternative specifications.

[28] With the inclusion of income controls, the upward trends in cooling across vintages decrease slightly. This suggests that the positive correlation between income and the year of construction explains little of the upward trend in cooling consumption. However, it's possible that our income data are too coarse to control well for income differences. We observe average income at the block group level from a five-year rolling survey, rather than by premise in the same years that we observe electricity consumption.

the adoption of Title 24, we re-estimate the model specified by Eq. (7) using $\widehat{Temp}_i^{min}$ as the dependent variable. The bottom panel of Figure 8 displays the predicted trends and the discontinuity in the minimum consumption temperatures across the 1968 through 1989 vintages of houses and Table A8 in the appendix presents the estimates of Eq. (7). Consistent with Title 24 improving the thermal insulation of houses, the estimates suggest that the building codes significantly increased the minimum cooling temperature by 0.66°F.

4.4 Accuracy of Ex-Ante Projections

Based on the 1980 CEC projections, a 1,620 square feet Title-24-compliant home was expected to use 1,869 kWh per year for cooling (see Table 1). Figure 7 shows that cooling energy consumption in the early 1980's was remarkably close to the amount. The γ_t coefficients for 1980, 1981, and 1982 are 1832, 1780, and 1896, respectively.

The projected cooling energy used for pre-Title 24 homes is somewhat higher than we observe. Table 1 shows that a non-compliant house was expected to use 3108 kWh and a partially compliant house 2178 kWh per year. Accounting for the estimated proportion of homes that were non-, partially, and fully compliant prior to 1978, we approximated the pre-Title-24 cooling energy use at 2336 kWh per year. These projections are somewhat higher than our estimated cooling energy consumption in the pre-adoption years. We estimate cooling energy used in our baseline house in each of 1975, 1976, and 1977 to be 1927, 1955, and 2008 kWh per year.

One reason that actual use in pre-1978 houses is less than projected is that many of these homes have likely been retrofitted. SMUD has long operated rebate programs that provide incentives for customers to weatherize their houses. In addition, since Title 24 was enacted, the CEC targeted retrofits as an important source of improvements in residential energy efficiency. Thus, although our estimated average savings of 257 kWh per year (13%) are less than the projected savings of 467 kWh per year (20%) listed in Table 1, the ex ante projections are quite close once we consider that retrofits likely occurred and the error is in estimating pre- rather than post-Title-24 cooling energy use.

4.5 Cost Benefit Analysis

The estimates in Table 5 imply that Title 24 reduced cooling energy by an average of 257 kWh per year. This reduction in energy use is the only benefit of the standards that we can measure. Other benefits, such as reductions in energy used for heating and increases in comfort due to a less drafty and more temperate home, are not observable to us. In this section, we argue that the the estimated reduction in cooling energy used indicates that the benefits of the 1978 introduction of Title 24 exceed the costs.

To approximate the benefits of the cooling energy saved, we make several assumptions. First, we assume the electricity savings are constant across years. Second, we assume the nominal social cost of electricity is $0.10/kWh. To obtain this number, we assume the long-run marginal cost of natural gas generation is $0.06/kWh (Borenstein) and the social cost of carbon is $50/ton, which adds $0.02/kWh. An additional $0.02/kWh comes from line losses of 7-9% and the fact that much of the savings during peak hours. Thus, we estimate savings of 257*0.1 = $25/year. Using a 3% discount rate and annual savings of $25/year from 1980 through 2016, we obtain average savings of $340 in 1980 dollars.

Table 1 shows that Title 24 had average costs of approximately $782. Thus, the savings from reduced energy used for cooling are approximately 340/782 = 43% of the cost. Table 1 also shows that the projected savings in natural gas used for heating were 9 times the electricity savings. The improvement in comfort adds further to the benefits from Title 24. Thus, it seems clear that the benefits of Title 24 exceed the costs.

5 Longer Run Trends in Cooling Efficiency

Apart from the intervention of Title 24, the average use of electricity for cooling shows a clear upward trend for vintages between the late 1960's and the early 1990's (top panel of

Figure 7). Similarly, average $\widehat{Temp}_i^{min}$ shows a downward trend over the same period but for Title 24. The trends persist after we control for square footage, stories, and bedrooms in Eq. (6), which implies that changes in those house characteristics do not explain the trends.

There are several potential explanations for these trends. There could be trends in physical house characteristics that we are unable to observe. For example, ceiling heights could be increasing over this time period, resulting in higher energy requirements for cooling. In addition, exterior shade tree coverage, which increases steadily with house age, results in meaningful reductions in cooling-driven electricity consumption and could explain part of this trend.[29] Finally, households sorting into premises may result in demographic trends across vintages of houses. For example, people with higher income tend to live in newer houses. Given that we might expect higher income households to have a higher demand for cooling, this pattern of sorting could explain part of the upward trend in cooling-driven consumption.

In addition to displaying a drop in cooling-driven electricity consumption across the pre-adoption and post-adoption houses, the top panel of Figure 7 also reveals a clear downward trend in the amount of electricity used for cooling among the houses constructed after the early 1990s. Similarly, the bottom panel of Figure 7 reveals a steady increase in the minimum consumption temperature beginning in the early 1990s. Next, in Section 5.1, we demonstrate that much of the post-1990 decline in cooling can be explained by the fact that the houses are simply newer.

5.1 Vintage Versus Age Effects

Levinson (2016) and Kotchen (2017) show that, by comparing energy consumption in houses built before versus after the adoption of building codes, it is possible to confound the impact of a house's vintage on consumption with the impact of a house' age. To explore how building

[29] Donovan and Butry (2009), focusing specifically on houses in Sacramento, CA, find that the existing tree coverage on the western and southern sides of houses reduced summertime electricity consumption by 185 kWh (a 5.2% reduction in consumption).

age impacts cooling-driven electricity consumption, we no longer focus on how the response to temperature differs across vintages of houses. Instead, we examine how the response to temperature differs over time within each vintage of houses. To do so, we take advantage of the fact that we observe billing data which records the monthly aggregate electricity consumed at each premise from 2008 through 2013. If aging an additional three years makes houses of a specific vintage less energy efficient (e.g., more air leaks), then we would expect to find that the temperature response function is less flat (i.e. more responsive to the outdoor temperature) in the 2011-13 period versus the 2008-10 period.

Using the same set of houses examined in the premise-specific analysis — i.e. single-family premises that do not use electricity as their primary energy source for heating — we estimate the following model over two different time periods; once using all of the observed bills from 2008 through 2010 and then again using all bills from 2011 through 2013:

$$\overline{\text{Cons}}_{i,m} = \alpha_i + \sum_y \left(\boldsymbol{\beta}_y \cdot \overline{\mathbf{T}}_{i,m} \cdot \text{Vintage}_{i,y} \right) + \varepsilon_{i,m}, \tag{8}$$

where i indexes each individual premise, m indexes each monthly bill, and y indexes the individual years of construction. $\overline{\text{Cons}}_{i,m}$ represents the average daily consumption (kWh) for household i during billing cycle m. $\text{Vintage}_{i,y}$ is an indicator variable which equals one if household i was constructed during year y. We focus premises constructed from 1960 through 2004.[30]

Similar to Eq. (1), we model the average daily consumption during month m as a function of the average daily temperatures during the month. Importantly, the start and end dates for each billing cycle differ across households, so the set of daily temperatures faced during a monthly billing period also differ across premises. To account for this fact, we first calculate the 4×1 vector $\mathbf{T_d}$ specified by Eq. (2) for each day included in the 2008 through 2013

[30]To increase the likelihood that the 2008 monthly bills reflect the consumption of fully occupied premises, we do not include houses constructed beyond 2004. Given that our goal is to compare how the responsiveness to temperature changes over time in a given set of houses, we do control for differences in the slope of the temperature response function across vintages that can be explained by bedrooms, square footage, etc., as was the case with Eq. (1).

billing data.[31] For each observed monthly bill, we then calculate the average daily values of the temperature spline across each of the $N_{i,m}$ days during billing cycle m for household i as follows:

$$\overline{\mathbf{T}}_{i,m} = \frac{1}{N_{i,m}} \cdot \sum_{d \in m} \mathbf{T}_d. \tag{9}$$

To quantify how aging impacts electricity consumption, we use the temperature response functions estimated over the 2008-10 and 2011-13 periods to produce two predictions of the average annual cooling that would occur in houses of each vintage if they were exposed to the observed daily temperatures during 2012 and 2013. To do so, we again assume that, regardless of a houses age or vintage, zero electricity is used for cooling when the average daily temperature is 62°F. The top panel of Figure 9 plots the predictions of the average annual electricity consumed for cooling by vintage using the temperature response functions estimated from the 2008-10 and 2011-13 periods.[32] The bottom panel of Figure 9 displays the percentage difference between the prediction based on the 2011-13 temperature response functions versus the 2008-10 response functions.[33]

For houses constructed prior to 1990, the predicted cooling-driven electricity consumption is, on average, 3% higher when using the temperature response functions estimated over the more recent billing period (2011-13). The differences are small and stable, suggesting that aging is no longer causing meaningful changes in consumption among these older houses. In contrast, beginning with houses constructed around 1990, there is a clear divergence between the predictions of cooling-driven electricity consumption. The predictions based on the 2011-13 temperature response functions are consistently above the predictions based on the 2008-10 response functions, and these differences steadily grow as the age of the houses

[31] The daily average temperature is again calculated from the Sacramento Airport NOAA weather station. The January, 2008 bills include consumption that occurred during December, 2007. Therefore, the temperature spline values are calculated for December, 2007 through the end of 2013.

[32] Note, the estimates of temperature response functions do not condition on the observed house characteristics. Therefore, unlike the results displayed in Figure 7, the estimates of the annual cooling-driven electricity consumption in Figure 9 do not compare similar houses across vintages.

[33] Figure A4 in the appendix presents the estimates of $\boldsymbol{\beta}_y$ from Eq. (8) for the 2008-10 and 2011-13 time periods.

falls. This suggests that aging an additional three years results in meaningful increases in cooling-driven electricity consumption among houses that are newer than 20 years old, and that these age-effects are most pronounced in newer houses.

There are certainly other possible explanations for the trend displayed in Figure 9. In particular, the time period over which we examine the monthly bills (2008 through 2013) straddles a large economic downturn which could cause meaningful changes in residential electricity demand. For example, during periods with higher unemployment rates, individuals may be house more often, resulting in higher levels of residential electricity consumption. While the unemployment rate in the Sacramento region was very similar across the two periods we examine – 10.11% from 2008-10 and 10.26% from 2011-13 – that may not necessarily be true within each vintage of houses.[34] If the unemployment rate remained higher following the recession among the residents of newer houses, then this could potentially explain the increasing trend displayed in Figure 9 among the houses constructed after 1990.

Even stronger evidence in support of the age-effects is found by comparing the results to the previous estimates displayed in Figure 7. The meaningful impact of age on consumption that begins in the early 1990's houses corresponds precisely with the reversal in the upward trend in cooling consumption (top panel of Figure 7) and the downward trend in the minimum consumption temperature (bottom panel of Figure 7) that occurs among houses built in the early 1990's and more recently. This suggests that the estimated decline in cooling-driven electricity consumption that begins with the houses constructed in the early 1990's cannot be attributed solely to improvements in the energy efficiency of the houses. Instead, the decline is, at least in part, due to the fact that the houses constructed after 1990 are still experiencing energy efficiency declines as they continue to age. Most importantly, however, the results presented in Figure 9 suggest that differences in age across the pre-adoption vintage of houses (1975-77) versus the post-adoption vintage (1980-82) cannot explain the decline in cooling-driven electricity consumption that is observed across these houses.

[34]Information on the monthly unemployment rate in the Sacramento-Arden Arcade-Roseville, CA region is provided by the U.S. Bureau of Labor Statistics.

5.2 Effects of Title 24 Updates

As shown in Table 2, notable updates to Title 24 occurred in 1982, 1992, 2001, and 2010. The 2010 update occurs too late in our sample to infer its effects, but Figure 7 provides clues about the effects of the other three updates. The 1982 update came out of the 1980 Residential Building Standards Development Project, which also generated the proposed, but not adopted, standards that were projected to save 80% of cooling, heating, and water heating energy use (last column of Table 2).

The standards that were enacted in 1982 included a stronger ceiling insulation standard and a windows requirement. Figure 7 suggests that the 1982 update had little effect on cooling energy efficiency. One possible explanation is that the new insulation and window requirements were not binding for many houses. Another possible explanation is that the main benefits of Title 24 came from parts of the regulation that did not change in 1982, such as the infiltration control requirements (i.e., caulking, weather-stripping, and sealing).

Measuring the effects of the 1992 and 2001 updates requires consideration of the aging effect. The bottom panel of Figure 9 suggests that the aging effect is continuous. Thus, a discontinuous change in cooling energy use around the time of a Title 24 update would suggest that the update had an effect on energy use. Figure 7 shows an apparent change in trend in both 1992 and 2001. In the few years before 1992, cooling energy use was flat, but it dropped quickly in the mid 1990s. Similarly, cooling energy use was increasing in the late 1990s and decreasing after the 2001 update.

Figure 9 implies that cooling energy use is 7% higher in 8 year old houses than in 5 year old houses, which implies that cooling energy efficiency depreciates at an average of about 2.3% per year during this period.[35] Figure 9 also suggests that cooling energy use is the same in 19 year old houses as in 22 year old houses, suggesting no depreciation in energy efficiency

[35]This can be seen by noting that cooling energy use in a 2004 house was 10% larger in 2011-13 when the house was on average 8 years old than in 2008-10 when the house was on average 5 years old. Because homes of all vintages used use 3% more cooling energy in 2011-13, the net aging effect from year 5 to year 8 is 10-3=7%.

after the 19^{th} year. Between year 5 and year 19, the figure implies that the depreciation rate declines approximately linearly as the home ages.

We assume that the annual rate of depreciation in cooling energy used decreases linearly from 2.3% in its 5th year to 0 in its 19th year. This assumption implies that a 2004 house in 2012 is 21% more efficient than it will be after it is 19 years old.[36] A 21% efficiency decline moves this 2004 house from our estimate of 1,556 kWh per year of cooling energy use in 2012-13 to 1,884 kWh of cooling energy use. Thus, a fully depreciated 2004 house is predicted to use about as much cooling energy as a 1980 house.[37] This does not mean that the updates to Title 24 have not been effective because many things vary across home vintages; it is impossible to infer the effect of building codes from homes built decades apart. Looking at the years around the building code changes in Figure 9, it is reasonable to conclude that the updates to Title 24 generate some further energy savings, but we do not attempt to quantify these here.

6 Conclusion

In this paper, we examine the impact California's building energy codes have had on residential electricity consumption. The codes, which were initially adopted in 1978, were designed largely to reduce the quantity of energy used for space heating and cooling. To evaluate whether the codes have succeeded at reducing energy used for temperature control, we take advantage of an extremely rich dataset of hourly, premise-level electricity consumption from 158,112 single-family houses in Sacramento, California. Using the detailed consumption data, we estimate how much electricity is used for cooling during 2012 and 2013 within each individual house. To determine whether California's initial building codes have reduced cooling-driven consumption, we test whether the predicted cooling energy usage discontinuously falls in houses built immediately after the adoption of the energy codes in 1978 versus

[36] $\prod_{i=5}^{19}(1 + 0.023/(19 - i)) = 1.21$

[37] See Appendix figure A5 for an illustration of fully depreciated cooling energy use using this approach.

those built immediately before 1978.

Our estimates reveal that the quantity of electricity used for cooling falls by 257 kWh/year within the houses built immediately after the codes were adopted. This discontinuous drop in cooling-driven consumption can not be explained by observed differences in the type of houses built before and after the codes were adopted or by households sorting discontinuously into houses of different vintages. Moreover, the drop in consumption cannot be explained by the fact that, relative to the pre-building code houses, the houses built after 1978 are newer and have aged less. Therefore, our results support the conclusion that California's 1978 building energy codes have resulted in significant and meaningful electricity savings.

Finding that the benefits of Title 24 exceed its costs is not sufficient to conclude that Title 24 is a cost-effective policy. There may be other policies that are more efficient, such as a carbon tax or a cap and trade program (CAT). The efficiency gains from a carbon tax or CAT comes from flexibility in compliance and the reductions in energy use incentivized by an increase in the price to consumers.

There are reasons to believe that putting a price on carbon through a tax or CAT may not improve building energy efficiency. In particular, there is an agency problem because the builder of the house is a different person than the consumer of the heating and cooling services. Moreover, the purchaser of a house may not observe the energy efficiency of the house and therefore energy efficiency may not be priced into the house. As a result, there is little incentive for the builder to incur extra costs to improve energy efficiency. As one example, we note that the price of electricity to SMUD customers doubled in the 1980s, but we see no sign of improvements in energy efficiency during this period (see Figure A6).

In sum, Title 24 building codes proved to be an inexpensive policy with substantial benefits. Given the potential ineffectiveness of price-based policies, we conclude that building efficiency standards can be an effective policy.

References

Anderson, Soren T, and James M Sallee. 2016. "Designing Policies to Make Cars Greener." *Annual Review of Resource Economics*, 8: 157–180.

Bushnell, James B, Stephen P Holland, Jonathan E Hughes, and Christopher R Knittel. 2017. "Strategic Policy Choice in State-Level Regulation: The EPA's Clean Power Plan." *American Economic Journal: Economic Policy*, forthcoming.

CEC. 1980*a*. "1980 Residential Building Standards Development Project: Alternative Conservation Measure Costs." California Energy Commission Project Report No. 10.

CEC. 1980*b*. "1980 Residential Building Standards Development Project: Base Case Buildings." California Energy Commission Project Report No. 2.

CEC. 1980*c*. "1980 Residential Building Standards Development Project: Cost Effectiveness." California Energy Commission Project Report No. 16.

CEC. 1980*d*. "1980 Residential Building Standards Development Project: Implementation." California Energy Commission Project Report No. 14.

Chong, Howard. 2012. "Building vintage and electricity use: Old homes use less electricity in hot weather." *European Economic Review*, 56(5): 906–930.

Donovan, Geoffrey H, and David T Butry. 2009. "The value of shade: Estimating the effect of urban trees on summertime electricity use." *Energy and Buildings*, 41(6): 662–668.

Holland, Stephen P, Jonathan E Hughes, and Christopher R Knittel. 2009. "Greenhouse gas reductions under low carbon fuel standards?" *American Economic Journal: Economic Policy*, 1(1): 106–146.

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.

Kotchen, Matthew J. 2017. "Longer-Run Evidence on Whether Building Energy Codes Reduce Residential Energy Consumption." *Journal of the Association of Environmental and Resource Economists*, forthcoming.

Levinson, Arik. 2016. "How Much Energy Do Building Energy Codes Save? Evidence from California Houses." *American Economic Review*, 106(10): 2867–2894.

OTA. 1979. "Residential Energy Conservation." United States Congress, Office of Tecnology Assessment.

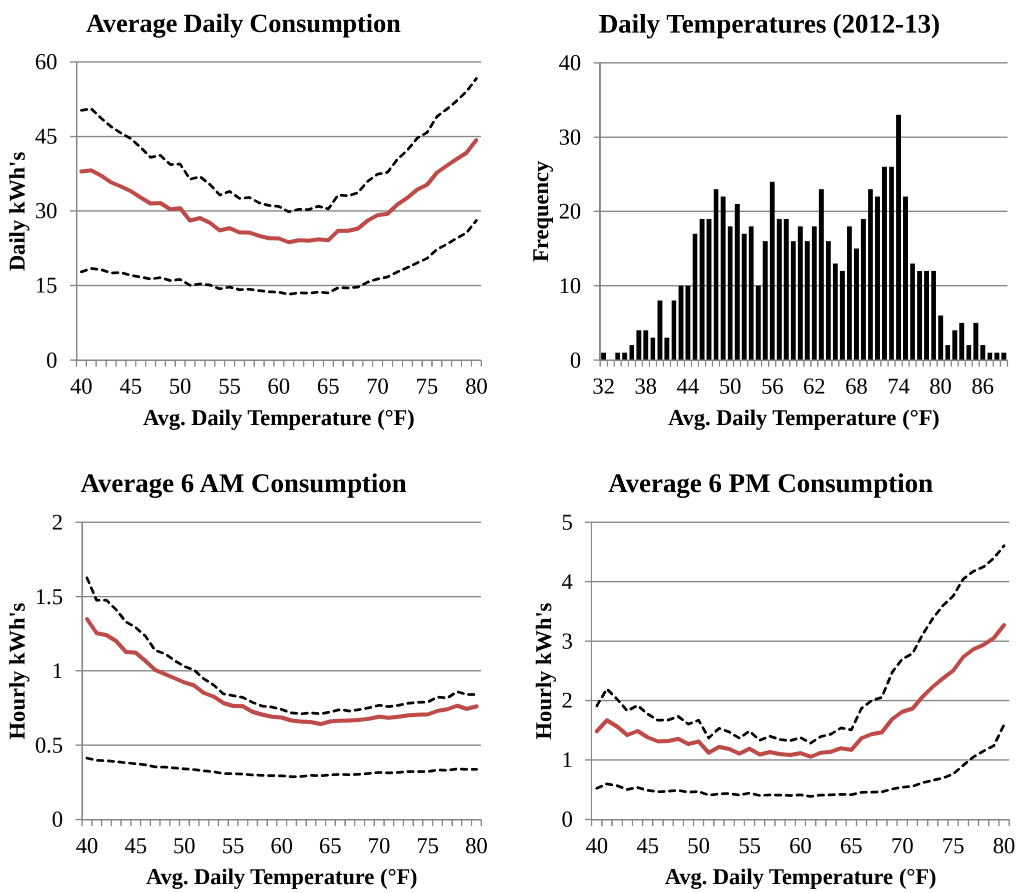


Figure 1: The upper left panel plots the average daily household consumption during 2012 through 2013 by the average daily temperature. The figure also displays the 25^{th} and 75^{th} percentiles of the daily household consumption by temperature. The bottom panels display the average hourly consumption during the 6 AM and 6 PM hours, as well as the corresponding 25^{th} and 75^{th} percentiles of hourly consumption. The upper right panel displays the frequency distribution of the average daily temperature in the Sacramento region during 2012 and 2013.

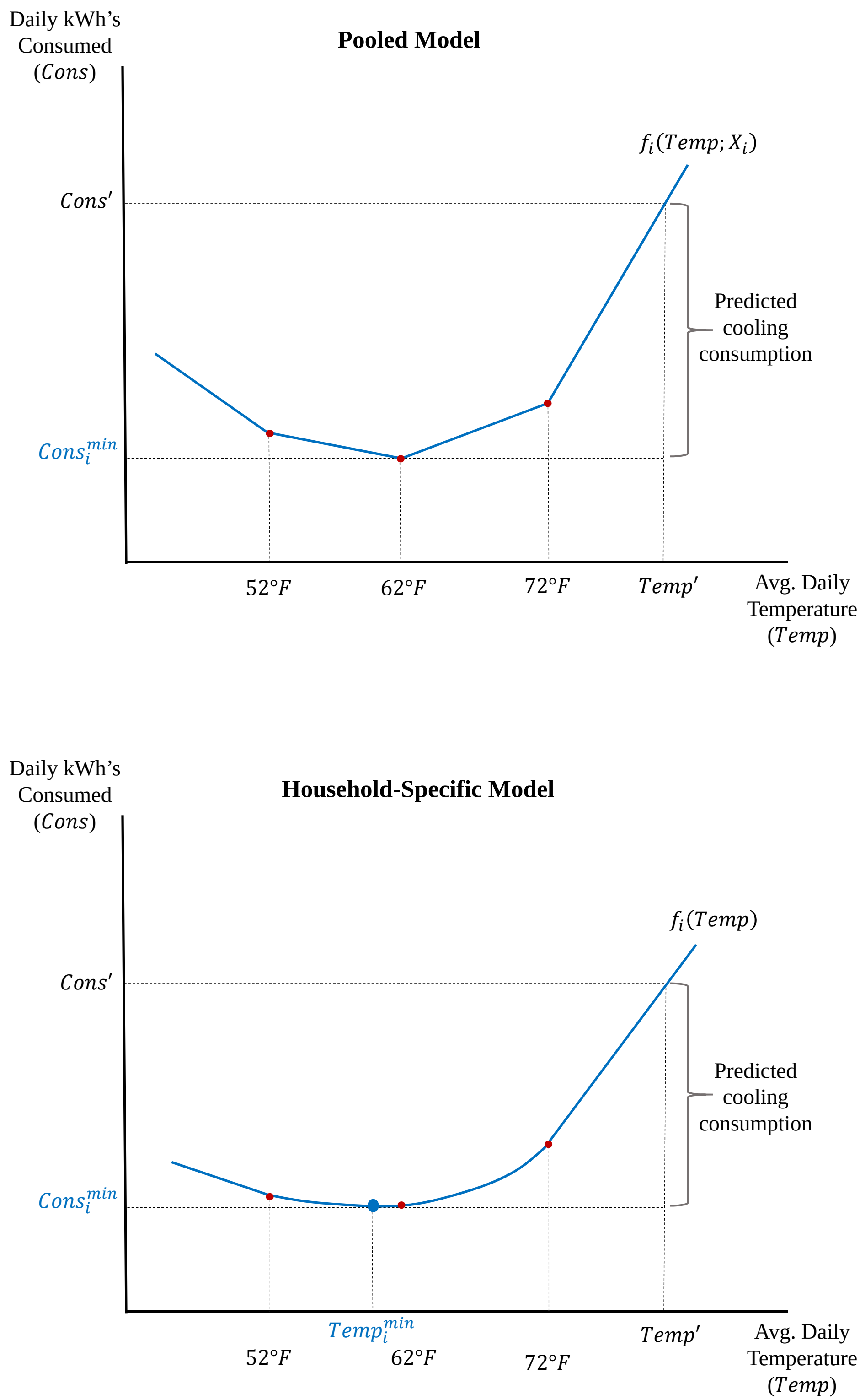


Figure 2: Note:

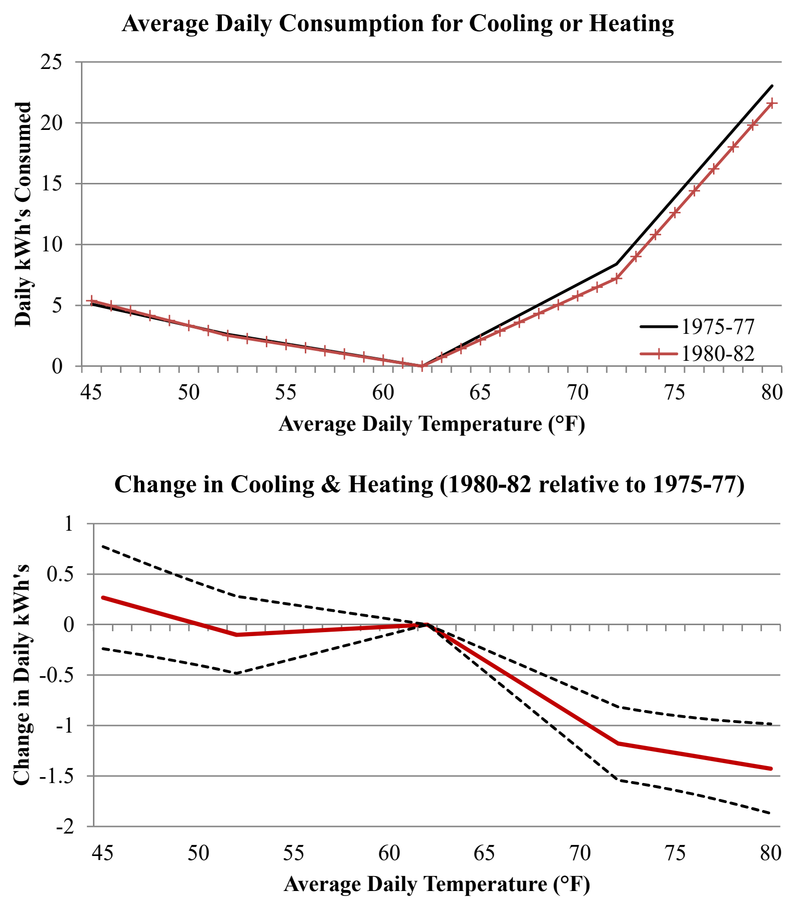


Figure 3: Note:

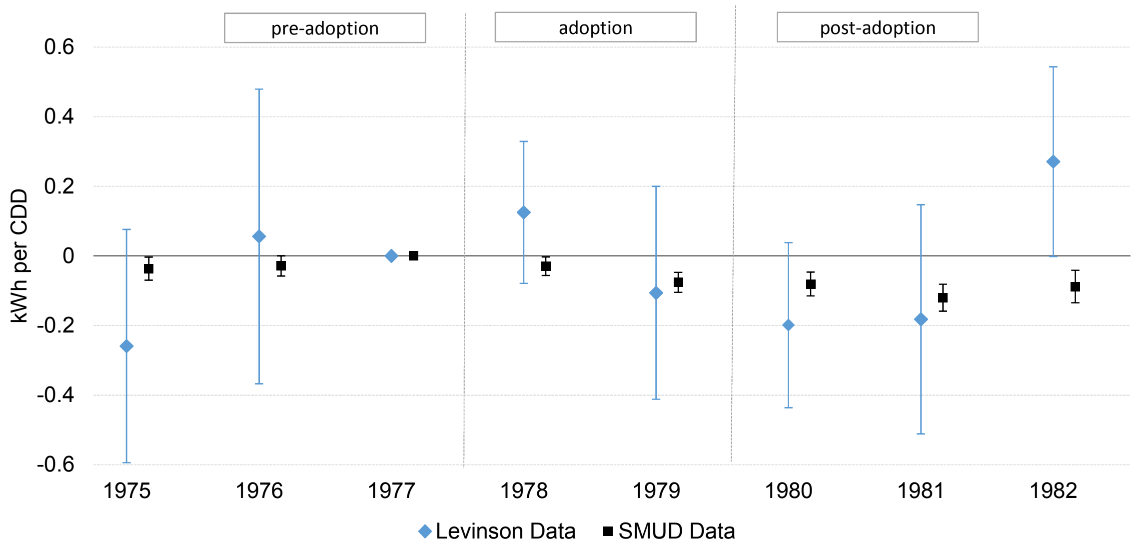


Figure 4: Note:

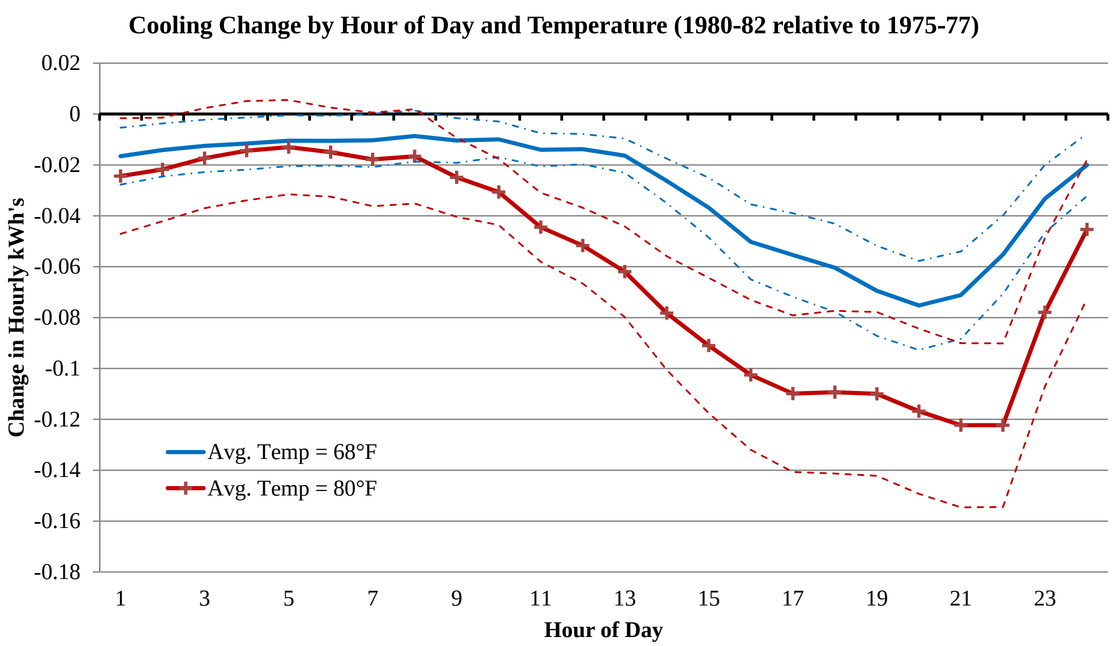


Figure 5: Note:

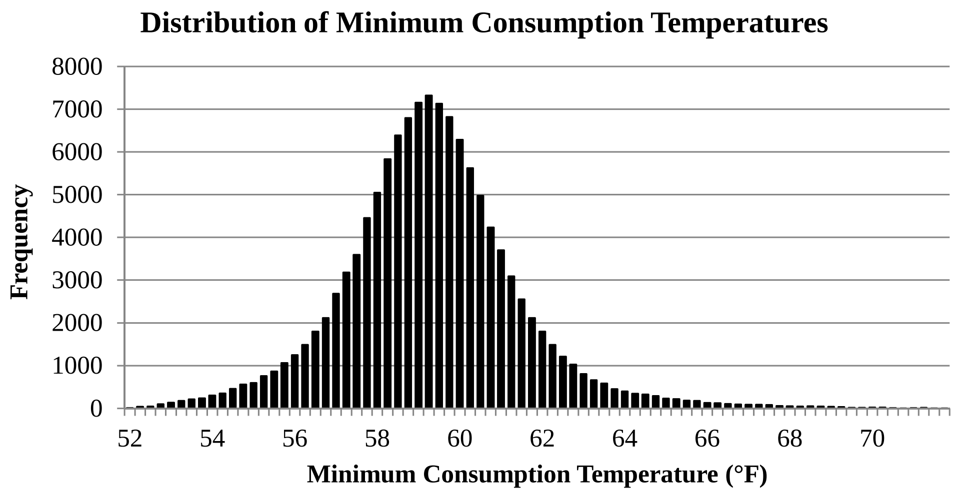


Figure 6: Note:

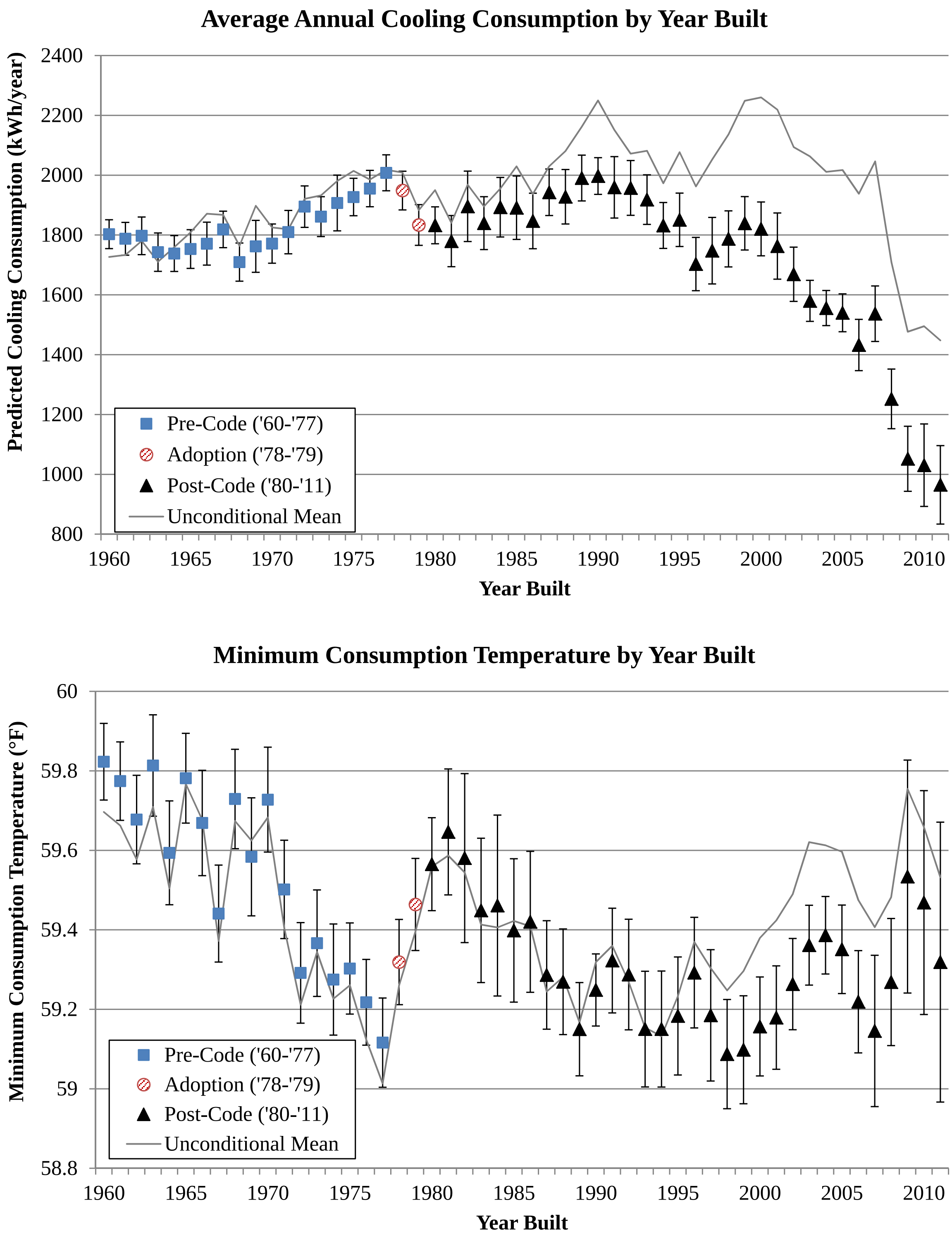


Figure 7: Note:

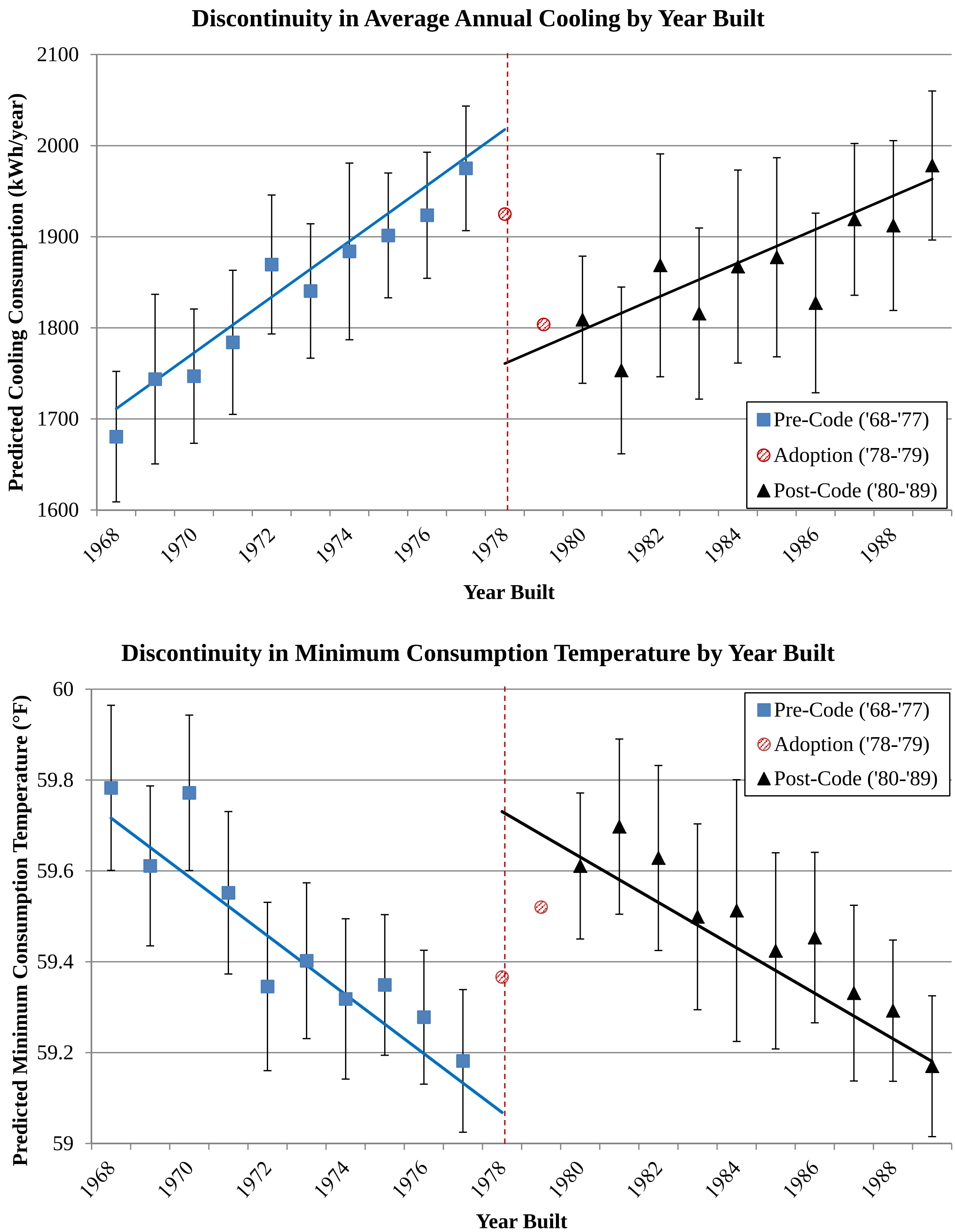
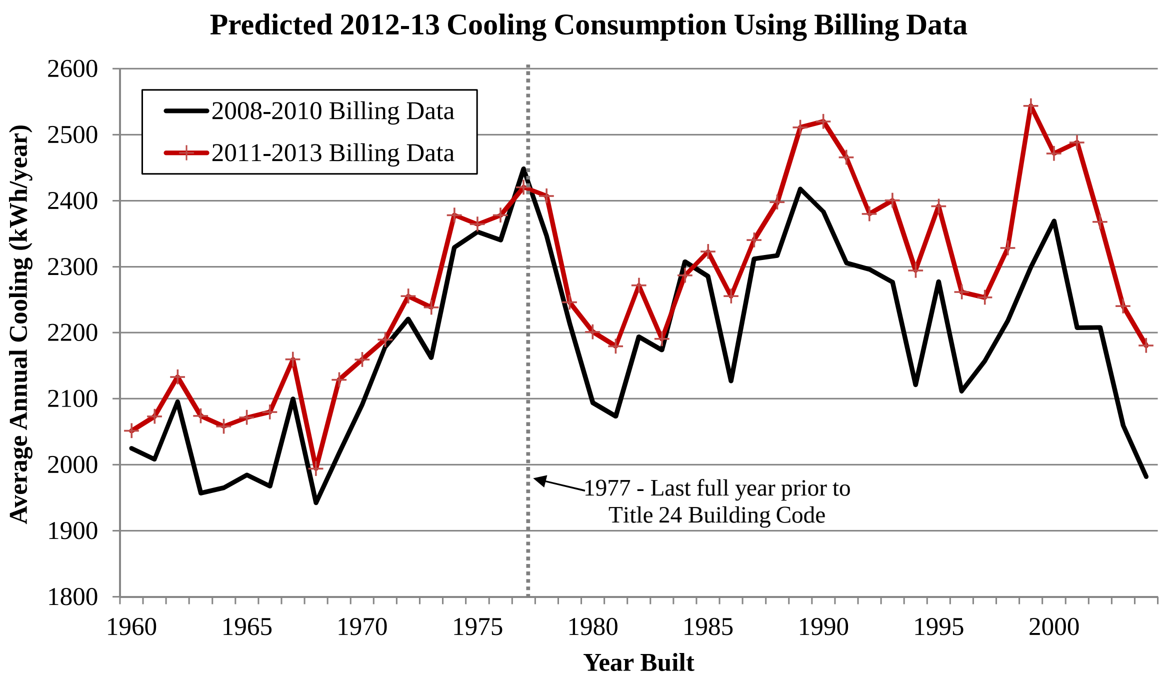


Figure 8: Note:



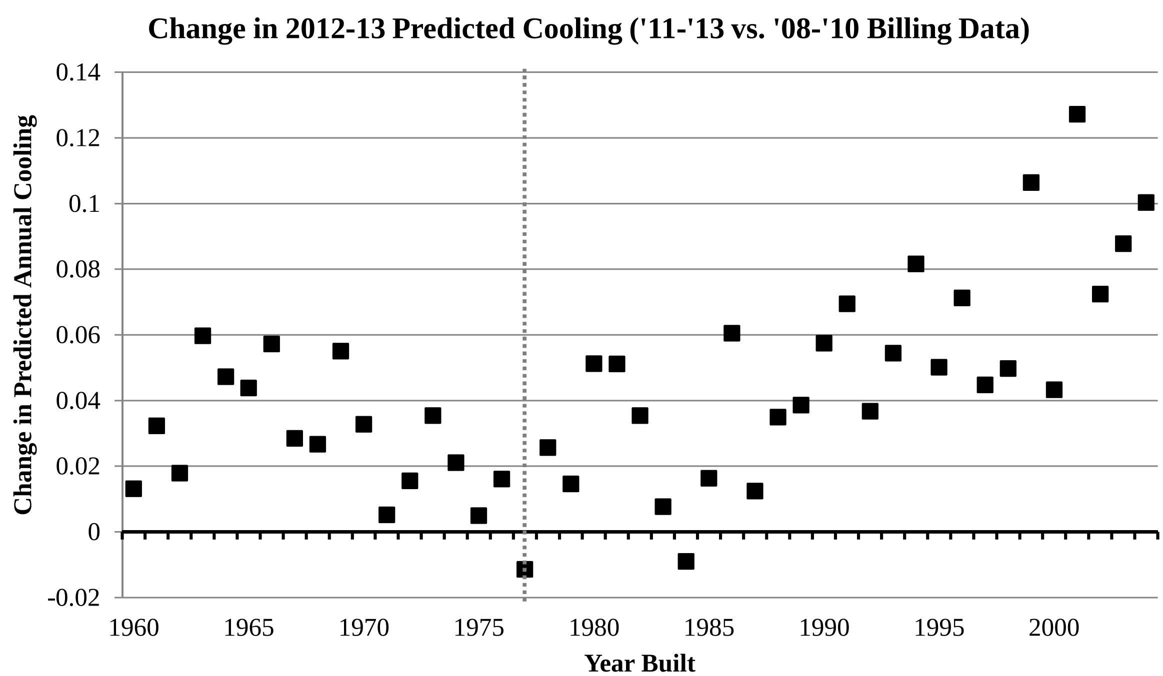


Figure 9: Note:

Table 1: Projected Costs and Savings from 1978 Title 24 Building Codes
1,620 sq.ft. single-family house in Sacramento

	Compliance			Differences		Approx.
	None	Partial	Full			Ave.
	(1)	(2)	(3)	(3)-(1)	(3)-(2)	Diff.
House Construction Costs (1980$)						
Ceiling insulation	-	627	627	627	-	194
Wall insulation	-	-	452	452	452	262
Windows	1,029	1,029	1,029	-	-	-
Infiltration control	-	-	650	650	650	377
Thermostat	82	82	82	-	-	-
Heating system	1,360	1,360	1,360	-	-	-
Cooling system	1,129	965	965	-164	-	-51
Total building envelope	$3,600	$4,063	$5,165	$1,565	$1,102	$782
Space conditioning energy used (kBTU)						
Heating	133,082	98,560	43,562	-89,520	-54,998	-42,601
Cooling	31,817	22,308	19,149	-12,669	-3,159	-4,780
Heating + Cooling	164,899	120,868	62,711	-102,189	-58,157	-47,381
Heating and cooling energy saved				*62%*	*48%*	*43%*
Space cooling energy used (kWh)						
Cooling	3,108	2,178	1,869	-1,238	-309	-467
Cooling energy saved				*40%*	*14%*	*20%*

For an average-sized 1,620 square feet single-story detached single family Sacramento house. CEC (1980*c*) reports costs for a 1,384 sq.ft. house (see Appendix Table A1). To obtain insulation, window, and infiltration control costs for this table we assume constant cost per square foot of floor area, i.e., we multiply the CEC numbers by 1620/1384=1.17. As long as the window area was less than 16% of the gross floor area of the building, the standard imposed no glazing requirements on windows for Sacramento houses, although it did impose such requirements in colder areas. Infiltration control implies that windows, doors, joints, and other openings in the building envelope that are potential sources of air leakage are caulked, gasketed, weatherstripped, or otherwise sealed to limit infiltration and exfiltration. The codes also did not require programmable thermostats or more efficient heating or cooling systems, but the CEC's cost effectiveness study assumed that non-compliant houses would have an oversized air conditioner. Cooling energy in kBTU is 10.24 times cooling energy in kWh. A kWh is equivalent to 3.41 kBTU of energy, and the CEC assumes a 1/3 efficiency ratio for electricity generation and transmission, i.e. 10.24=3.413*3. To obtain the estimated average differences we assume that, in the absence of building codes, there would be 31% non-compliance, 27% partial compliance and 42% full compliance (see text). Sources: CEC (1980*c*), CEC (1980*a*), OTA (1979).

Table 2: Packages Sufficient to Meet Title 24 Building Energy Codes
1,620 sq.ft. detached single family house in Sacramento

	1978	1982	1992	2001	2010	1980 (proposed)
Insulation minimums						
Ceiling	R-19	R-30	R-30	R-38	R-38	R-38
Wall	R-11	R-11	R-13	R-19	R-19	R-19
Infiltration control	yes	yes	yes	yes	yes	yes
Windows						
Max U-factor	-	0.65	0.65	0.65	0.40	0.50
Max total area (sq.ft.)	259	-	-	259	324	259
Min south-facing area (sq.ft.)	-	104	104	-	-	110
Max non-south area (sq.ft.)	-	156	156	-	-	-
Shading (max SHGC)						
South-facing windows	-	0.36	0.40	0.40	0.40	0.36
East-facing windows	-	-	-	0.40	0.40	0.36
North-facing windows	-	-	-	0.40	0.40	0.36
West-facing windows	-	0.36	0.40	0.40	0.40	0.36
Effective date	7/1/78	7/13/82	7/1/92	6/1/01	1/1/10	-

For 1978, the package applies to an area with 2,782 heating degree days; for the other years, it applies to climate zone (CTZ) 12. We assume a slab floor. The building code documents report several packages that can be used for compliance. For 1982 and 1992, we report package A, which was discontinued in 2001. For 2001 and 2010, we report package D. The R-value of insulation is a measure of thermal resistance; larger values imply a more stringent standard. Infiltration control implies that windows, doors, joints, and other openings in the building envelope that are potential sources of air leakage are caulked, gasketed, weatherstripped, or otherwise sealed to limit infiltration and exfiltration. The U-factor of a window measures the rate of heat loss; smaller values imply a more stringent standard. SHGC denotes the solar heat gain coefficient, which is the fraction of incident solar radiation admitted through a window. Source: `http://www.energy.ca.gov/title24/standards_archive/`.

Table 3: Summary of Building Characteristics by Vintage

	Year Built								Change
	Pre-Title 24					Post-Title 24			1980-82 vs.
	1975	1976	1977	1978	1979	1980	1981	1982	1975-77
N	3,814	4,116	7,054	5,930	8,116	5,573	3,618	1,692	
Daily kWh	28.74	28.14	29.55	30.91	30.58	32.98	33.83	35.20	4.65**
	(14.98)	(14.19)	(15.27)	(15.38)	(16.80)	(17.28)	(17.89)	(18.06)	(0.20)
Square Feet	1,709	1,577	1,512	1,611	1,617	1,741	1,601	1,621	96.02**
	(593)	(468)	(446)	(488)	(453)	(605)	(503)	(562)	(6.68)
Bedrooms	3.51	3.48	3.44	3.44	3.46	3.46	3.38	3.24	-0.07**
	(0.72)	(0.66)	(0.63)	(0.72)	(0.68)	(0.74)	(0.68)	(0.76)	(0.01)
Stories	1.21	1.21	1.18	1.20	1.18	1.21	1.17	1.18	-0.002
	(0.50)	(0.49)	(0.42)	(0.43)	(0.40)	(0.43)	(0.41)	(0.41)	(0.005)
Central AC	0.91	0.92	0.96	0.97	0.99	0.98	0.97	0.98	0.04**
	(0.29)	(0.27)	(0.20)	(0.18)	(0.12)	(0.15)	(0.18)	(0.15)	(0.003)
Electric Heat	0.08	0.13	0.24	0.35	0.31	0.42	0.56	0.69	0.33**
	(0.27)	(0.34)	(0.43)	(0.48)	(0.47)	(0.49)	(0.50)	(0.46)	(0.005)

Table presents the mean daily household electricity consumption, household square footage, number of bedrooms, and number of stories for single family houses built in the Sacramento Metropolitan Utility District's service area from 1975 through 1982. The table also reports the share of houses with central air conditioning (AC) and electric heat. Standard deviations are presented in parentheses below the year-specific means. The standard deviation reported for daily electricity consumption is the standard deviation of the household-level means. The last column reports the difference in the means of the household characteristics from 1980-82 relative to 1975-77. The standard error of the difference in means is reported in parentheses. Significant at the 5% level; ** = Significant at the 1% level.

Table 4: Pooled Estimates of Temperature Response by Vintage

Slope		Estimate	Std. Err.	Change Relative to 1975-77	Std. Err.
Temp. < 52°F					
	1975-77	-0.35**	(0.03)	-	-
	1978-79	-0.35**	(0.03)	0.001	(0.01)
	1980-82	-0.41**	(0.03)	-0.05**	(0.02)
52° F≤ Temp. < 62°F					
	1975-77	-0.26**	(0.03)	-	-
	1978-79	-0.26**	(0.03)	0.002	(0.01)
	1980-82	-0.25**	(0.04)	0.01	(0.02)
62°F ≤ Temp. < 72°F					
	1975-77	0.84**	(0.06)	-	-
	1978-79	0.79**	(0.06)	-0.05**	(0.01)
	1980-82	0.72**	(0.05)	-0.12**	(0.02)
Temp. > 72°F					
	1975-77	1.83**	(0.07)	-	-
	1978-79	1.81**	(0.07)	-0.02	(0.01)
	1980-82	1.80**	(0.07)	-0.03	(0.02)

Model includes premise fixed effects and interactions between temperature spline and indicators for number of bedrooms, electric heat, multi-level houses, and square footage bins. Standard errors are robust to clustering at the premise level and at the year-by-week level. * = Significant at the 5% level; ** = Significant at the 1% level.

Table 5: Discontinuity in Annual Cooling (kWh/year): 1968–1989 Premises

	Without Spatial FE			With Spatial FE		
	Pre & Post Trends	With Income	Constant Trend	Pre & Post Trends	With Income	Constant Trend
Post	-256.9**	-253.5**	-271.3**	-155.4**	-153.3**	-150.6**
	(42.8)	(42.6)	(42.0)	(38.5)	(38.1)	(36.1)
Pre-Trend	30.7**	29.1**	-	23.2**	22.2**	-
	(4.2)	(4.2)		(3.7)	(3.7)	
Post-Trend	18.4**	18.3**	-	24.2**	24.0**	-
	(5.5)	(5.3)		(4.9)	(4.8)	
Trend	-	-	24.3**	-	-	23.0**
			(3.3)			(2.9)
Income Controls	N	Y	Y	N	Y	Y
Community FE	N	N	N	Y	Y	Y
N	46,246	46,246	46,246	46,246	46,246	46,246
R^2	0.058	0.059	0.059	0.080	0.081	0.081

Models include saturated set of controls for number of bedrooms, multi-story indicator, and square footage bins. Standard errors are robust to clustering at the Census block group level. ** = Significant at the 1% level.

APPENDIX

A Heating Efficiency in Electric Heat Houses

To estimate whether the building codes have affected electricity used for heating, we re-estimate the model specified by Eq. (1) using only the premises that use electricity as their primary source for heat. We do not expect these houses to be informative about the improvements in heating energy efficiency due to Title 24. In the mid-to-late 1970s, most houses with electric heat used resistance technology, whereas those built in the early 1980s used heat pumps. In contrast, most home heating in California is down through forced air systems with a natural gas furnace as the heat source.

The slope estimates from the temperature response functions are reported in Table A4. Again, we find that electricity consumption in premises constructed after the building codes were adopted (1980-82) are significantly less responsive to temperatures above $62°F$. In this subset of houses with electric heat, we now also find evidence that electricity consumption in the post-building code era houses is also less responsive to the temperatures below $62°F$, suggesting that less energy is being used for both cooling and heating.

Figure A1 compares the predicted electricity consumed for heating and cooling among the 1975-77 and 1980-82 vintage houses specifically with electricity as their primary source for heat. Again, the 1980-82 houses consume significantly less electricity for cooling. In addition, there is also evidence that the 1980-82 vintage houses consume significantly less electricity for heating. Using the same approach we used for cooling, we can also predict the total electricity consumed for heating among the subset of houses that use electricity as their primary source for heat.

From 2012 through 2013, there were 374 days with an average temperature below $62°F$. Using the temperature response functions presented in the top panel of Figure A1, we estimate that the on these 374 days, a 1975-77 vintage house with electric heat would have consumed an average of 5,726 kWh, or 2,863 kWh per year. In contrast, a 1980-82 vintage house with electric heat would have consumed 2,794 kWh per year — a 2.4% reduction in heating-driving electricity consumption relative to the pre-adoption houses.

B Appendix Figures and Tables

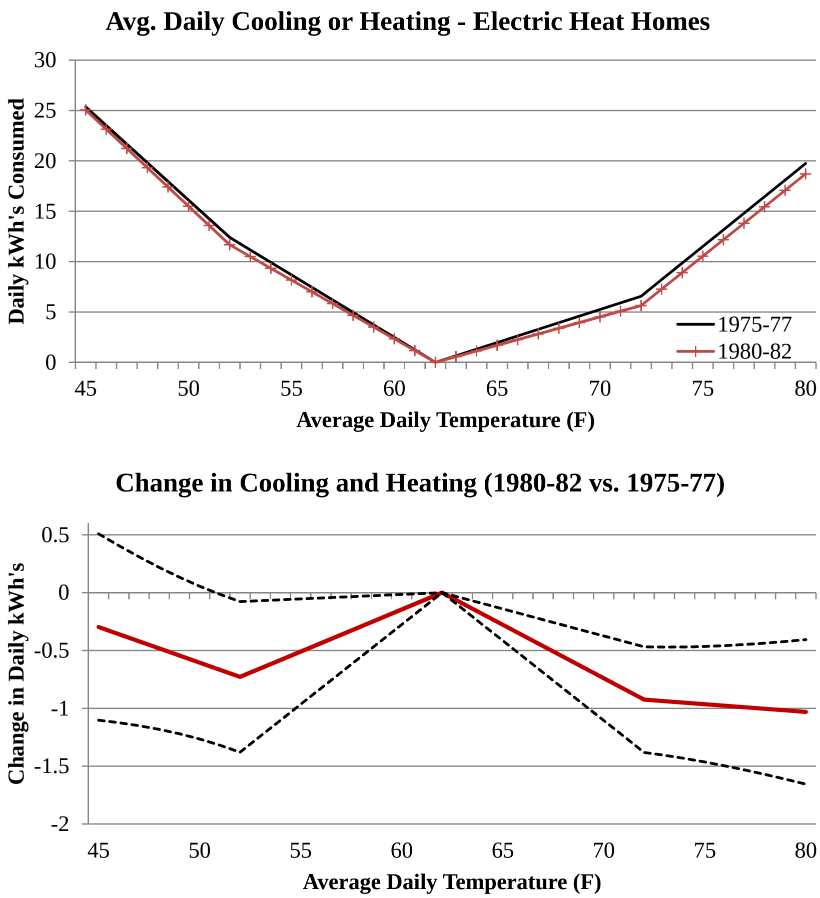


Figure A1: Note:

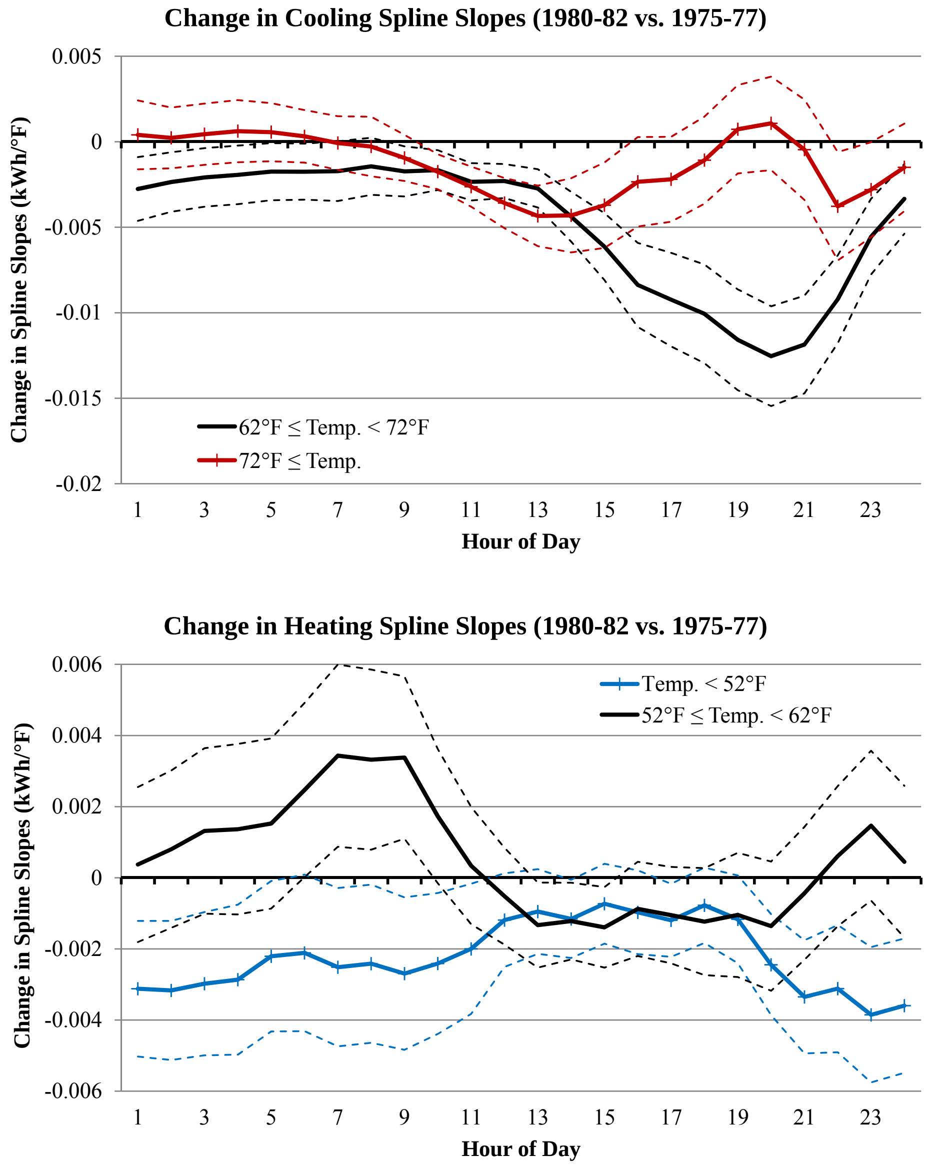


Figure A2: Note:

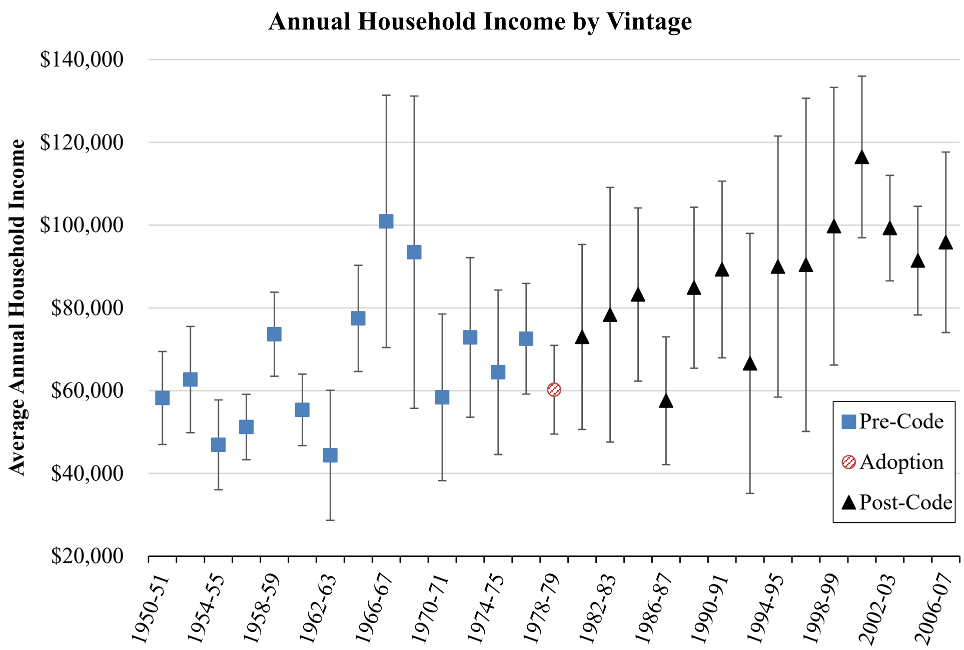
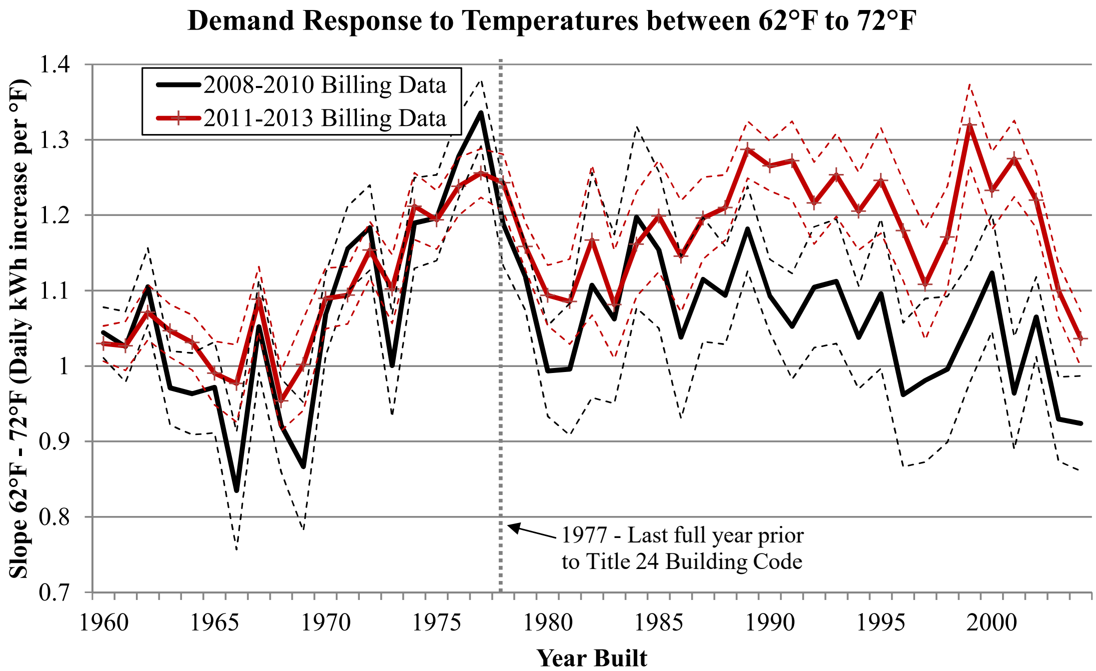


Figure A3: Note:



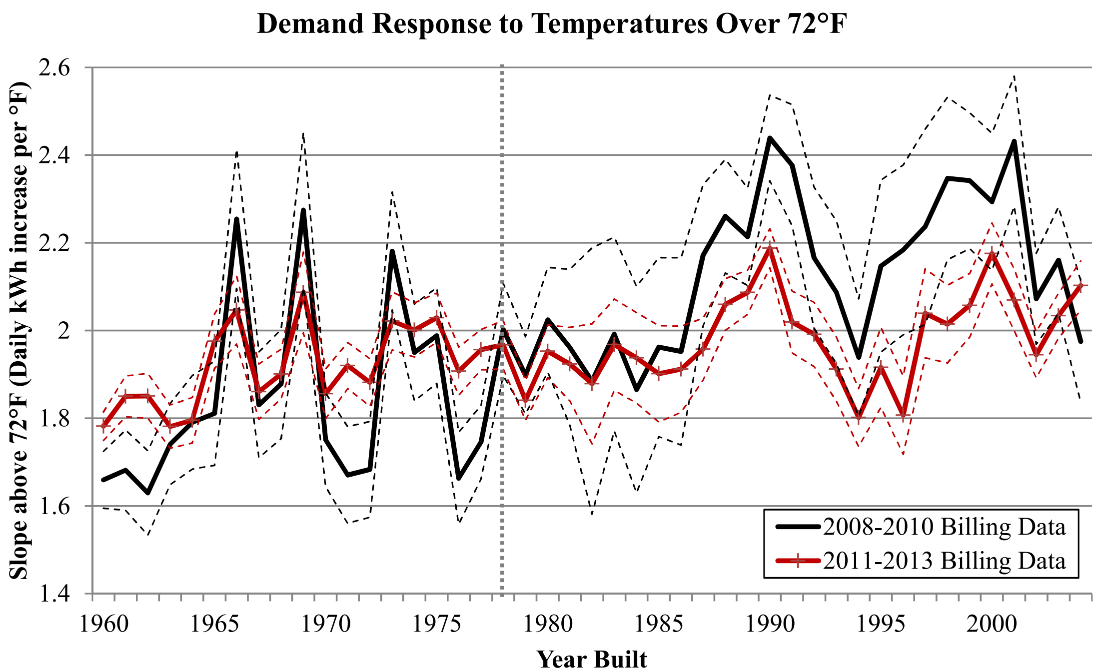


Figure A4: Note:

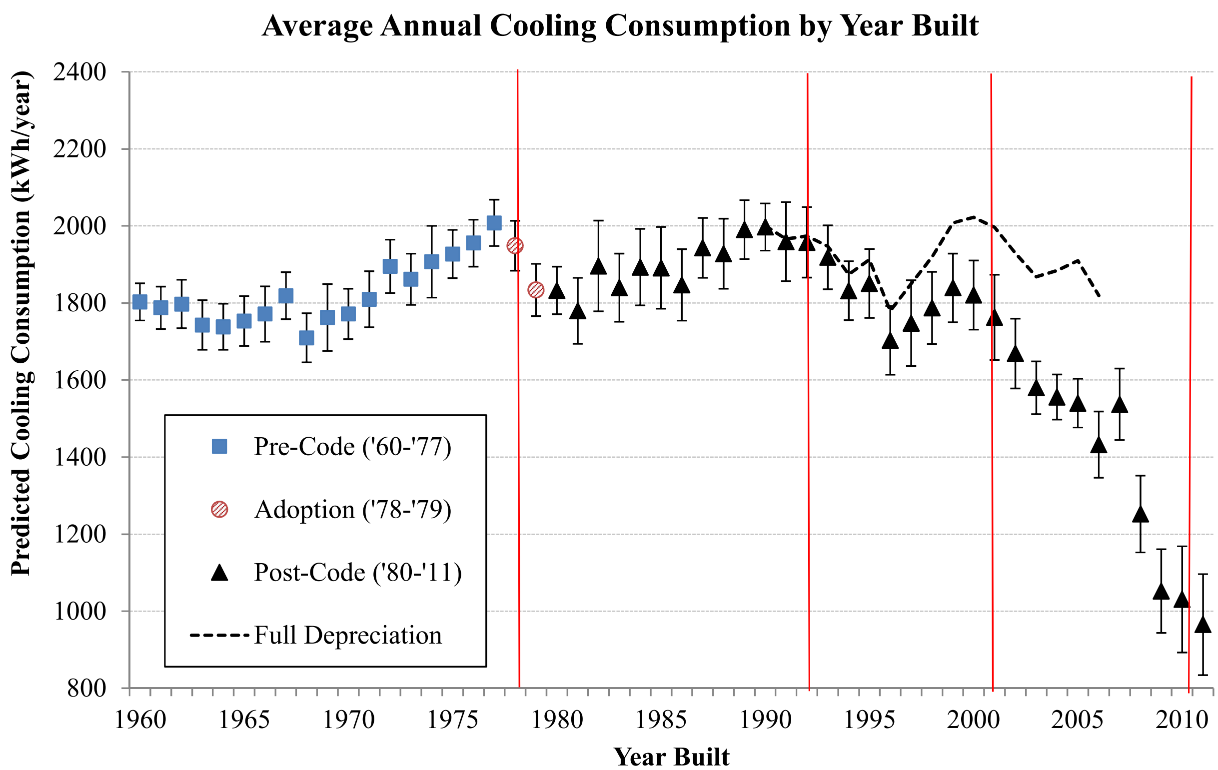


Figure A5: Note:

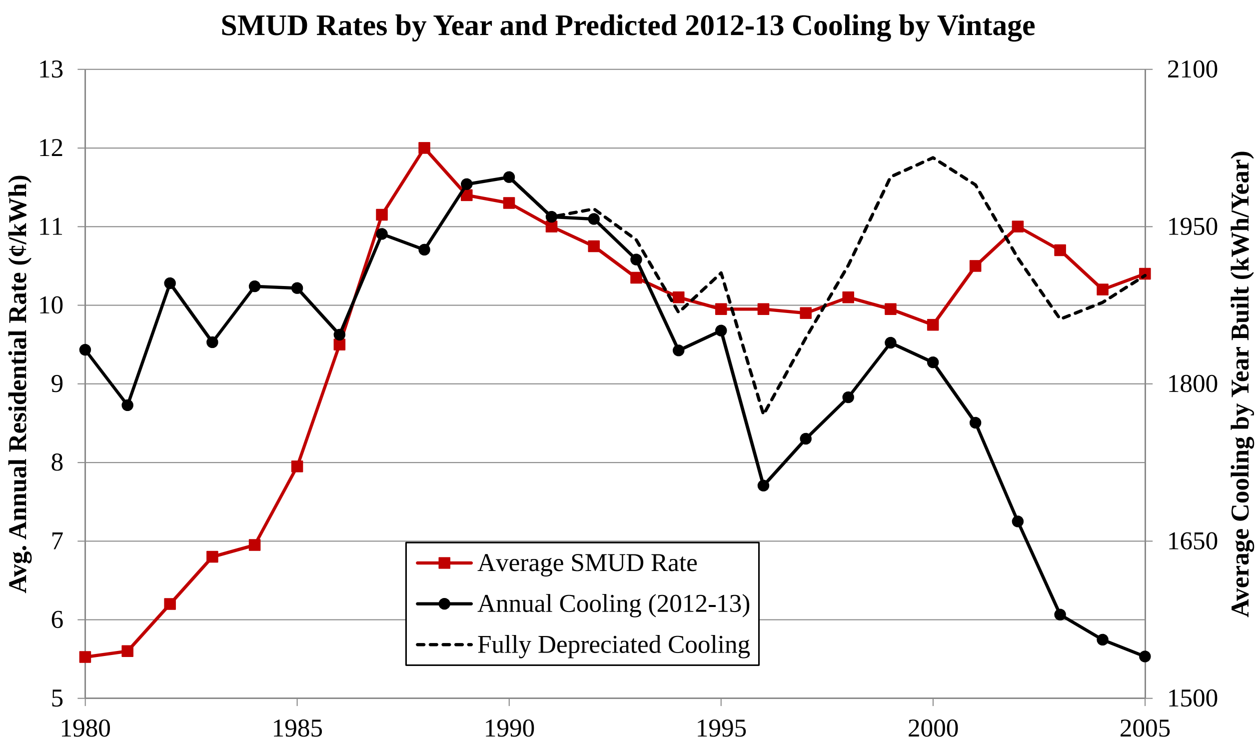


Figure A6: Note:

Table A1: Projected Costs and Savings from 1978 Title 24 Building Codes
1,384 sq.ft. detached single family house in Sacramento

	Compliance			Differences		Approx.
	None	Partial	Full			Ave.
	(1)	(2)	(3)	(3)-(1)	(3)-(2)	Diff.
House Construction Costs (1980$)						
Ceiling insulation	-	536	536	536	-	166
Wall insulation	-	-	386	386	386	224
Windows	879	879	879	-	-	-
Infiltration control	-	-	555	555	555	322
Thermostat	82	82	82	-	-	-
Heating system	1,360	1,360	1,360	-	-	-
Cooling system	1,129	965	965	-164	-	-51
Total building envelope	$3,450	$3,822	$4,763	$1,313	$941	$661
Space conditioning energy used (kBTU)						
Heating	113,695	84,202	37,216	-76,479	-46,986	-36,395
Cooling	27,182	19,058	16,359	-10,823	-2,699	-4,084
Heating + Cooling	140,877	103,260	53,575	-87,302	-49,685	-40,479
Heating and cooling energy saved				*62%*	*48%*	*43%*
Space cooling energy used (kWh)						
Cooling	2,655	1,861	1,597	-1,058	-264	-399
Cooling energy saved				*40%*	*14%*	*20%*

For a median-sized 1,384 square feet single-story detached single family Sacramento house. As long as the window area was less than 16% of the gross floor area of the building, the standard imposed no glazing requirements on windows for Sacramento houses, although it did impose such requirements in colder areas. Infiltration control implies that windows, doors, joints, and other openings in the building envelope that are potential sources of air leakage are caulked, gasketed, weatherstripped, or otherwise sealed to limit infiltration and exfiltration. The codes also did not require programmable thermostats or more efficient heating or cooling systems, but the CEC's cost effectiveness study assumed that non-compliant houses would have an oversized air conditioner. Cooling energy in kBTU is 10.24 times cooling energy in kWh. A kWh is equivalent to 3.41 kBTU of energy, and the CEC assumes a 1/3 efficiency ratio for electricity generation and transmission, i.e. 10.24=3.413*3. To obtain the estimated average differences we assume that, in the absence of building codes, there would be 31% non-compliance, 27% partial compliance and 42% full compliance (see text). Sources: CEC (1980*c*), CEC (1980*a*), OTA (1979).

Table A2: Summary of Sacramento Temperatures (°F) 2012-2013

	Mean	Standard Deviation	Minimum	Maximum	Correlation with Daily Average
Daily Average	61.17	11.91	32	89	-
Daily Maximum	75.37	14.83	42	108	0.97
Hour of Day:					
1	54.45	10.93	27	82	0.95
2	53.46	10.79	25	80	0.95
3	52.52	10.52	26	76	0.94
4	51.49	10.30	21	74	0.93
5	50.65	10.01	24	73	0.92
6	50.04	9.89	23	75	0.91
7	50.10	10.30	23	80	0.92
8	52.21	11.09	25	83	0.94
9	56.41	10.78	30	87	0.97
10	60.65	11.08	33	90	0.98
11	64.46	11.60	35	94	0.98
12	67.79	12.35	37	100	0.97
13	70.55	13.05	40	101	0.97
14	72.74	13.64	41	106	0.96
15	74.05	14.33	42	106	0.96
16	74.60	14.99	42	108	0.96
17	73.73	16.13	35	107	0.97
18	71.61	17.00	33	107	0.98
19	68.66	16.48	32	104	0.98
20	64.89	14.90	29	99	0.98
21	61.49	13.21	29	92	0.98
22	58.99	12.10	28	88	0.97
23	57.03	11.42	26	87	0.96
24	55.52	11.12	27	85	0.96

The table summarizes the temperature readings recorded at the Sacramento International Airport from January 1, 2012 through December 31, 2013. For hours with multiple temperature readings, the hourly temperature is calculated as the simple average of the readings. The minimum and maximum temperatures are rounded to the nearest integer.

Table A3: Pooled Estimates of Temperature Response by Year Built

Slope		Estimate	Std. Err.	Change Relative to 1977	Std. Err.
Temp. < 52°F					
	1975	-0.33**	(0.03)	0.04*	(0.02)
	1976	-0.35**	(0.03)	0.02	(0.01)
	1977	-0.37**	(0.03)	-	-
	1978	-0.35**	(0.03)	0.03*	(0.01)
	1979	-0.36**	(0.03)	0.01	(0.01)
	1980	-0.41**	(0.03)	-0.03*	(0.02)
	1981	-0.41**	(0.04)	-0.04	(0.02)
	1982	-0.40**	(0.04)	-0.03	(0.03)
52° F≤ Temp. < 62°F					
	1975	-0.28**	(0.03)	-0.03	(0.01)
	1976	-0.26**	(0.03)	-0.01	(0.01)
	1977	-0.25**	(0.03)	-	-
	1978	-0.26**	(0.03)	-0.01	(0.01)
	1979	-0.26**	(0.03)	-0.01	(0.01)
	1980	-0.25**	(0.04)	0.002	(0.02)
	1981	-0.26**	(0.04)	-0.01	(0.02)
	1982	-0.23**	(0.04)	0.02	(0.03)
62°F ≤ Temp. < 72°F					
	1975	0.82**	(0.06)	-0.03	(0.02)
	1976	0.83**	(0.06)	-0.02	(0.01)
	1977	0.85**	(0.06)	-	-
	1978	0.82**	(0.06)	-0.03*	(0.01)
	1979	0.77**	(0.06)	-0.08**	(0.01)
	1980	0.73**	(0.06)	-0.12**	(0.02)
	1981	0.70**	(0.06)	-0.15**	(0.02)
	1982	0.74**	(0.06)	-0.11**	(0.02)
Temp. > 72°F					
	1975	1.83**	(0.07)	-0.02	(0.02)
	1976	1.82**	(0.08)	-0.02	(0.01)
	1977	1.84**	(0.07)	-	-
	1978	1.83**	(0.07)	-0.01	(0.01)
	1979	1.80**	(0.07)	-0.05*	(0.02)
	1980	1.82**	(0.07)	-0.02	(0.02)
	1981	1.78**	(0.07)	-0.07**	(0.02)
	1982	1.79**	(0.07)	-0.05*	(0.02)

Model includes premise fixed effects and interactions between temperature spline and indicators for number of bedrooms, electric heat, multi-level houses, and square footage bins. Standard errors are robust to clustering at the premise level and at the year-by-week level. Significant at the 5% level; ** = Significant at the 1% level.

Table A4: Pooled Estimates – Households with Electric Heating

Slope		Estimate	Std. Err.	Change Relative to 1975-77	Std. Err.
Temp. < 52°F					
	1975-77	-1.85**	(0.08)	-	-
	1978-79	-1.86**	(0.07)	-0.01	(0.03)
	1980-82	-1.91**	(0.07)	-0.06	(0.04)
52° F≤ Temp. < 62°F					
	1975-77	-1.24**	(0.07)	-	-
	1978-79	-1.18**	(0.07)	0.06*	(0.03)
	1980-82	-1.17**	(0.07)	0.07*	(0.03)
62°F ≤ Temp. < 72°F					
	1975-77	0.66**	(0.06)	-	-
	1978-79	0.67**	(0.06)	0.01	(0.02)
	1980-82	0.56**	(0.06)	-0.09**	(0.02)
Temp. > 72°F					
	1975-77	1.65**	(0.06)	-	-
	1978-79	1.64**	(0.06)	-0.01	(0.02)
	1980-82	1.63**	(0.06)	-0.01	(0.02)

Model includes premise fixed effects and interactions between temperature spline and indicators for number of bedrooms, multi-level houses, and square footage bins. Standard errors are robust to clustering at the premise level and at the year-by-week level. * = Significant at the 5% level; ** = Significant at the 1% level.

Table A5: Comparison to Levinson (2016)

	Levinson Data							SMUD Data	
	Log Full Controls	Levels Full Controls	Drop Avg. CDD	Add Premise FE	Use Only 1975-82	Only 2003 RASS	Yearly Vintage	Group Vintages	Yearly Vintage
CDD	0.00021*	0.14	0.92*	0.98*	0.97*	1.16*	1.21*	1.52*	1.54*
	(0.00009)	(0.08)	(0.09)	(0.05)	(0.06)	(0.08)	(0.12)	(0.05)	(0.05)
Avg Monthly CDD in Zipcode	0.00115*	0.93*							
	(0.00017)	(0.11)							
HDD					0.15*	0.10*	0.10*	0.28*	0.28*
					(0.04)	(0.03)	(0.03)	(0.02)	(0.02)
CDD × built pre-1940	-0.00018	−0.27*	−0.28*	−0.33*					
	(0.0001)	(0.08)	(0.07)	(0.06)					
CDD × built 1940s	0.00008	-0.09	-0.11	−0.22*					
	(0.0001)	(0.07)	(0.07)	(0.05)					
CDD × built 1950s	-0.00007	−0.11*	−0.12*	−0.15*					
	(0.0001)	(0.06)	(0.05)	(0.03)					
CDD × built 1960s	-0.00011	-0.11	-0.12	−0.09*					
	(0.0001)	(0.07)	(0.07)	(0.04)					
CDD × built 1970-74	0.00001	-0.01	-0.02	-0.05					
	(0.0001)	(0.04)	(0.04)	(0.04)					
CDD × built 1978-82	0.00008	0.1	0.1	0.08*	0.09*	0.03		−0.05*	
	(0.0001)	(0.07)	(0.07)	(0.03)	(0.03)	(0.09)		(0.01)	
CDD × built 1983-92	0.00023*	0.21*	0.21*	0.17*					
	(0.0001)	(0.08)	(0.08)	(0.04)					
CDD × built 1993-97	0.00040*	0.35*	0.36*	0.23*					
	(0.0001)	(0.11)	(0.10)	(0.03)					
CDD × built 1998-00	0.00017	0.18*	0.19*	0.19*					
	(0.0001)	(0.06)	(0.06)	(0.05)					
CDD × built 2001-04	0.00037*	0.36*	0.37*	0.24*					
	(0.0001)	(0.13)	(0.13)	(0.05)					

Comparison to Levinson (2016) (cont.)

	Levinson Data							SMUD Data	
	Log Full Controls	Levels Full Controls	Drop Avg. CDD	Add Premise FE	Use Only 1975-82	Only 2003 RASS	Yearly Vintage	Group Vintages	Yearly Vintage
CDD × built 2005-08	0.0002	0.11	0.12	0.10*					
	(0.0001)	(0.08)	(0.08)	(0.05)					
CDD × built 1975							-0.26		−0.04*
							(0.17)		(0.02)
CDD × built 1976							0.06		-0.03
							(0.22)		(0.01)
CDD × built 1978							0.12		−0.03*
							(0.10)		(0.01)
CDD × built 1979							-0.11		−0.08*
							(0.16)		(0.01)
CDD × built 1980							-0.20		−0.08*
							(0.12)		(0.02)
CDD × built 1981							-0.18		−0.12*
							(0.17)		(0.02)
CDD × built 1982							0.27		−0.09*
							(0.14)		(0.02)
Observations	265,599	265,599	265,599	265,599	32,100	15,390	15,390	29,023,229	29,023,229
R-squared	0.37	0.36	0.35	0.85	0.85	0.89	0.89	0.61	0.61
Omitted Group	1975-77	1975-77	1975-77	1975-77	1975-77	1975-77	1977	1975-77	1977

Model includes premise fixed effects and interactions between temperature spline and indicators for number of bedrooms, multi-level houses, and square footage bins. Standard errors are robust to clustering at the premise level and at the year-by-week level. * = Significant at the 5% level.

Table A6: Discontinuity in Annual Cooling (kWh/year)

	Post-Code Effect	
Years	Linear Trends	Quadratic Trends
1971–1986	-215.3**	-230.7**
	(49.1)	(95.0)
1968–1989	-256.9**	-191.1**
	(42.8)	(75.4)
1965–1992	-217.1**	-286.3**
	(40.4)	(63.5)

Models include saturated set of controls for number of bedrooms, multi-story indicator, and square footage bins. Standard errors are robust to clustering at the Census block group level. ** = Significant at the 1% level.

Table A7: Testing for Discontinuity in Annual Household Income ($'s)

	Pre & Post Trends			Constant Trend		
Coefficient	1970-87	1968-89	1966-91	1970-87	1968-89	1966-91
Share Post-Code	-5,433	9,330	7,384	2,588	3,913	3,125
	(22,012)	(18,832)	(15,023)	(15,495)	(9,890)	(9,861)
Avg. Years Pre-Code	5,246*	2,485	2,393*	-	-	-
	(2,348)	(1,453)	(1,008)			
Avg. Years Post-Code	3,550	519	637	-	-	-
	(3,338)	(2,439)	(1,715)			
Avg. Years Difference	-	-	-	2,542	1,555	1,507*
				(1,810)	(785)	(681)
Constant	60,829**	54,521**	54,598**	51,038**	51,392**	51,128**
	(11,134)	(9,442)	(7,854)	(9,737)	(6,927)	(6,477)
N	19	29	37	19	29	37

Standard errors are robust to heteroskedasticity. * = Significant at the 5% level; ** = Significant at the 1% level.

Table A8: Discontinuity in Minimum Consumption Temperature (°F): 1968–1989 Premises

	Without Spatial FE			With Spatial FE		
	Pre & Post Trends	With Income	Constant Trend	Pre & Post Trends	With Income	Constant Trend
Post	0.662**	0.650**	0.668**	0.505**	0.507**	0.496**
	(0.075)	(0.073)	(0.074)	(0.061)	(0.060)	(0.058)
Pre-Trend	-0.065**	-0.060**	-	-0.051**	-0.048**	-
	(0.008)	(0.008)		(0.005)	(0.005)	
Post-Trend	-0.050**	-0.049**	-	-0.056**	-0.055**	-
	(0.008)	(0.008)		(0.007)	(0.007)	
Trend	-	-	-0.055**	-	-	-0.051**
			(0.005)			(2.9)
Income Controls	N	Y	Y	N	Y	Y
Community FE	N	N	N	Y	Y	Y
N	45,701	45,701	45,701	45,701	45,701	45,701
R^2	0.025	0.028	0.028	0.041	0.042	0.042

Models include saturated set of controls for number of bedrooms, multi-story indicator, and square footage bins. Standard errors are robust to clustering at the Census block group level. ** = Significant at the 1% level.

Table A9: Change in Average Annual Cooling (kWh/year): 1975-77 to 1978-82

	Pre & Post Trends				Without Trends			
	No 1978		With 1978		No 1978		With 1978	
	No FE	FE	No FE	FE	No FE	FE	No FE	FE
Post	-185.2**	-130.0**	-106.8*	-67.8*	-131.0**	-39.0	-97.0**	-25.7
	(54.8)	(46.5)	(42.1)	(34.3)	(28.5)	(24.5)	(25.5)	(21.1)
Income Controls	Y	Y	Y	Y	Y	Y	Y	Y
Community FE	N	Y	N	Y	N	Y	N	Y
N	21,614	21,614	25,201	25,201	21,614	21,614	25,201	25,201
R^2	0.048	0.071	0.047	0.068	0.048	0.071	0.046	0.067

Models include saturated set of controls for number of bedrooms, multi-story indicator, and square footage bins. Standard errors are robust to clustering at the Census block group level. * = Significant at the 5% level; ** = Significant at the 1% level.