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Abstract

In 1978, California adopted building codes designed to reduce the energy used for heating and cooling. Using a rich dataset of hourly electricity consumption for 158,112 California houses, we estimate that the average house built just after 1978 uses 13% less electricity for cooling than a similar house built just before 1978. Comparing the estimated savings to the policy's projected cost, we conclude that the policy comfortably passes a cost-benefit test. In settings where market failures prevent energy costs from being completely passed through to home prices, building codes can serve as a cost-effective tool for improving residential energy efficiency.

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1 Introduction

Following the 1973 energy crisis, U.S. policymakers sought to reduce fossil fuel consumption by mandating improvements in energy efficiency. In 1975, the federal government established minimum fuel efficiency (CAFE) standards for new vehicles. In 1978, California adopted the nation's first state-level energy building codes, establishing minimum energy efficiency requirements for new 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 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, each of which would allow more flexibility in compliance and would raise prices, creating an incentive to reduce consumption. Anderson and Sallee (2016) and Jacobsen (2013) highlight 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 as a cost-effective policy for reducing emissions. Similarly, Bushnell et al. (2017) document the inefficiency of rate standards in the electricity 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 Kotchen (2013), and Kotchen (2017) present ex-post estimates of the impact of build-

[1]The U.S. DOE's Building Energy Codes Program 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.

ing 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]

In this paper, we reexamine how Title 24, the policy that established California's residential energy efficiency building standards, has affected electricity consumption. Our results suggest that not only have the building codes resulted in sizable electricity savings, the policy also comfortably passes a cost-benefit test. 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 during 2012 and 2013, cover 158,112 single-family homes constructed from 1960 through 2011 in Sacramento County, California. To determine if Title 24 provided electricity savings, we test whether the level of electricity used for cooling during 2012 and 2013 discontinuously drops in houses built immediately after 1978 versus those built immediately before 1978. To do so, we first estimate the quantity of electricity used for cooling in each premise. Examining the premise-level predicted cooling, 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 corresponds to a 2.6% reduction in total electricity use. 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 afternoon and evening hours, precisely when demand for cooling is at it highest levels in the region.[4]

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, bed-

[3]This finding is consistent with the results presented by Chong (2012).

[4]We focus on cooling because we do not observe household natural gas consumption. Most houses in Sacramento County are heated using natural gas.

rooms). 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 homes of different vintages. Similarly, no discontinuous changes in electricity rates or natural gas prices occurred around the adoption of Title 24 that could account for energy efficiency improvements in post-Title 24 homes. 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.

It is important to stress that, although we observe electricity consumption for a large number of houses, they are all located in the Sacramento area. Therefore, our estimates of the energy saved apply specifically to this region. However, rather than being a weakness of the data, we view this as a key advantage. 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 homogeneous weather experienced by the houses in our sample enables us to credibly estimate Title-24's effect in this area.

To compare our estimates of the benefits provided by Title 24 to the cost of imposing the policy, 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 – a point that has been overlooked in cost-benefit analyses presented in the previous empirical work. Precise estimates are elusive, 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 estimates of the compliance costs and potential energy savings (CEC, 1980*c*), we estimate that Title 24 increased the average cost of building a Sacramento house by $782 (in 1980 dollars) and was projected to reduce electricity consumed for cooling by 20%. Even if this projection correctly predicted the energy savings that occurred immediately after the adoption of Title 24, the realized difference between pre- and post-1978 houses in 2012-13 would likely 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. The CEC's ex-ante predictions suggested that the natural gas cost savings from reduced space heating would exceed the electricity cost savings by a factor of nine, so our results support the conclusion that Title 24 comfortably passes 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)). However, market imperfections may render the typical first-best price policies inefficient in the market for new houses. A home buyer typically cannot (costlessly) observe the energy efficiency of a house, so the additional costs of using more energy efficient materials may not be fully priced in. As a result, there is little incentive for the builder to incur extra costs to improve energy efficiency (e.g., Jaffe and Stavins (1994), Howarth and Andersson (1993), Howarth and

Sanstad (1995)).

In the presence of such imperfect information, simply pricing the negative externalities (e.g., local pollution, greenhouse gas emissions) may not create a strong enough incentive to induce efficient investment in residential energy efficiency. We examine 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 during this period. This finding suggests that, by itself, a price policy may not work well at inducing investment in energy efficiency. In such an environment, well-designed building codes can serve as a complement to price-based policies, cost-effectively improving energy efficiency.

The remainder of the paper proceeds as follows. Section 2 discusses California's building codes and the data. Section 3 presents estimates from a regression discontinuity approach to quantify the reduction in cooling-driven electricity consumption caused by the building codes. Section 4 analyzes whether we confound the impact of a house's vintage on consumption with the impact of a house's age. Section 5 discusses the policy implications, and Section 6 concludes.

2 Background and Data Sources

2.1 Residential Building Codes

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, building codes have become the primary policy tool used to reduce energy use. California's building energy codes, known as Title 24, were adopted in 1977. Although the codes 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.[5] Therefore, Title 24 was fully effective for all 1980-built houses, but not all 1978 and 1979-built houses. Following California's lead, 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.

Title 24 was primarily intended to reduce the energy required for indoor temperature control.[6] In particular, the codes specified minimum 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.[7] Table 1 shows that the codes were expected to add $1,565 to the cost of building a 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. The 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.

[5] Moreover, Title 24 placed significant 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*). Therefore, initial enforcement of the codes may have been lax.

[6] 1982 updates to the codes also regulate water heating systems and lighting.

[7] 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.

It is important to account for the fact that many houses would have met or exceeded Title 24 standards even without the regulation in place. 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.[8] 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. Using these percentages, 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.[9]

The remainder of the paper focuses on comparing the preceding ex-ante engineering projections of the average energy savings and the projected compliance costs to ex-post estimates of the realized electricity savings and benefits achieved by the adoption of Title 24.

2.2 Premise-Level Data

We focus exclusively on houses located in the Sacramento Municipal Utility District (SMUD) service area – i.e. Sacramento and the surrounding communities. 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.[10] We also use billing records

[8] 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.

[9] 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 evidence of the presence of measures to reduce air infiltration in pre-1978 houses.

[10] 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

that record the monthly aggregate consumption at each 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. In addition, we focus on houses that rely on natural gas as the primary source for heating, which includes 82% of the single-family premises constructed from 1960 through 2011.[11] All together, our primary analysis focuses on 158,112 single-family premises constructed between 1960 and 2011.

Table 2 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 1.13 kWh/day more than premises constructed from 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 2. For example, houses built from 1980 through 1982 were larger than houses built from 1975 through 1977 by an average of 157 square feet and were 3% more likely to have central air conditioning.

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. We do not observe household-level natural gas consumption. Therefore, we cannot estimate the resulting changes in heating energy use. In California

meter, and as a result, we do not observe hourly consumption from these houses.

[11] Among the single-family homes built from 1975 through 1982, 32% use electricity as their primary energy source for heating. In an Appendix, we examine how heating energy use differs pre- and post-Title 24 within this subset of homes. However, as we note in Appendix C, this analysis may be confounded by the fact that there was a shift away from resistance heating towards early, potentially inefficient, heat pumps.

as a whole, electricity use for space cooling only accounts for 4% of total residential energy use and only 40% of houses have central air conditioning (AC) units.[12] 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 2. Among the households constructed in SMUD's service territory from 1975 though 1982, 95% 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 station that records the hourly temperature at the Sacramento International Airport.[13] 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.[14] The upper right panel of Figure 1 displays the distribution of the daily temperatures from 2012 through 2013.

[12] 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.

[13] 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.

[14] See Appendix Table A2

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 and 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 typical day with an average temperature of 60°F will reach a high of 73°F, and a typical day with an average of 80°F will reach 100°F. When the daily average temperature increases above the $60°F$ to $62°F$ range, 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 on a day with an average temperature of $60°F$. While we are focusing on the homes that do not use electricity as their primary source for heat, it is clear that slightly more electricity is also used when the weather gets cold. This cold-temperature increase in electricity consumption is driven in part the fact that, even in gas-heated houses, some electricity is required to distribute the heat.

The bottom panels of Figure 1 highlight that the impact of temperature on consumption is very heterogeneous across hours of the day. During the early morning hours, temperatures in the region are well below the daily average temperature.[15] 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.

[15] See Appendix Table A2

3 Estimating the Temperature Response Function

3.1 Model Specification

We estimate a separate model for each single-family premise in our sample constructed between 1960 and 2011. We model daily consumption during 2012 and 2013 as a function of the daily average temperature. Estimating a separate model for each premise allows unrestricted heterogeneity across households. Premises may use different amounts of electricity for cooling due to differences in the slope of the temperature response function or due to differences in the temperature at which they begin using air conditioning.

We specify the response function using a restricted cubic spline with knot points at 52°F, 62°F, and 72°F. The cubic spline specifies the temperature response functions as (i) a cubic function between 52°F and 62°F as well as between 62°F and 72°F, (ii) a linear function for temperatures below 52°F and above 72°F, and (3) continuous in the levels, first, and second derivatives.

Figure 2 provides a graphical representation of the model. By specifying cubic polynomials for temperatures between 52°F and 72°F, we allow the temperature where average consumption is minimized ($Temp_i^{min}$) to vary flexibly over this range. On a day when the average temperature exceeds $Temp_i^{min}$ (e.g., $Temp'$ in the diagram), premise i's consumption of electricity for cooling can be estimated as the difference between $Cons'$ and $Cons_i^{min}$. We estimate a premise's annual electricity used for cooling by summing this difference across all days when the average temperature exceeds $Temp_i^{min}$.

The model can be written as:

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

$Cons_{i,d}$ represents household i's total electricity consumption (kWh) on day d, Temp_d is the daily temperature (°F), and variable S_d is specified as follows:

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

where $(x)_+$ equals x if $x > 0$ and zero otherwise. We fit this model for each household using electricity consumption data for each day during the two years spanning January 1, 2012 through December 31, 2013.

If Title 24 improved the thermal insulation of houses, then there are two outcomes we may expect to observe. First, we would expect to see a reduction in the average use of electricity for cooling in the homes built after Title 24 was adopted. Second, we may also expect the post-adoption vintage houses to 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.

3.2 Premise-Specific Estimates

Using the premise-specific estimates of Eq. (1), we predict average annual electricity used for cooling ($\widehat{\text{Cooling}}_i$) during 2012 and 2013. Specifically, we compute

$$\widehat{\text{Cooling}}_i = 0.5 \sum_{d \in \{2012, 2013\}} \left(\widehat{\alpha}_i + \widehat{\beta}_{1,i} \cdot \text{Temp}_d + \widehat{\beta}_{2,i} \cdot S_d - \widehat{Cons}_i^{min} \right)_+, \quad (3)$$

where $\widehat{Cons}_i^{min}$ is predicted consumption at the minimum consumption temperature (see Figure 2). For 95% of the premises in our sample, we estimate a minimum consumption temperature between 52°F and 72°F.[16] For another 1.4% of the premises, we estimate a monotonically decreasing temperature response function. We assume that zero electricity is used for cooling in these houses. For the remaining 3.7% of premises, we estimate a monotonically increasing temperature response function. We drop these premises because we are unable to estimate the electricity used for cooling.[17]

[16] Appendix Figure A1 displays the distribution of the predicted minimum consumption temperatures ($\widehat{Temp}_i^{min}$) for these premises.

[17] By dropping this subset of premises that 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.

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

$$\widehat{\text{Cooling}}_i = \sum_t \Big(\gamma_t \cdot \text{Vintage}_{i,t}\Big) + \boldsymbol{\theta} \cdot \mathbf{X}_i + \varepsilon_i, \qquad (4)$$

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, $\mathbf{X}_i$ 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). To define the baseline house, we exclude the indicator for three bedroom, single story houses with 1,600 to 1,750 square feet.

The estimates of γ_t represent average electricity used annually for cooling in baseline houses constructed during year t. The top panel of Figure 3 presents the estimates of γ_t from Eq. (4), as well as the corresponding 95% confidence intervals. 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. The gray line in the top panel of Figure 3 shows the unconditional means of the predicted cooling by vintage (i.e., estimates of γ_t from a model that excludes $\mathbf{X}_i$).

If Title 24 resulted in an improvement in thermal insulation, then we would expect that the average minimum consumption temperature ($\widehat{Temp}_i^{min}$) would be higher in post-Title 24 houses. To explore whether this is the case, we re-estimate the model specified by Eq. (4) using the premise-specific estimates of $\widehat{Temp}_i^{min}$ as the dependent variable.[18] The bottom panel of Figure 3 presents the estimates of γ_t, which represent the average minimum-consumption temperature in a baseline house by year of construction.

Focusing on the years surrounding 1978, the top panel of Figure 3 reveals a clear decrease in the quantity of electricity used for cooling after Title 24

[18] For this regression, we use 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 $Temp_i^{min}$.

was implemented. The difference in cooling-driven consumption between the 1977 and 1980 vintages stands out for two reasons. First, it is larger than any three year changes observed across houses constructed from 1960 through the mid-1990s. Second, it is the only decrease over a three year range of vintages from 1960 through the mid-1990s. Similarly, the bottom panel of Figure 3 reveals a pronounced increase in the average temperature at which cooling begins between 1977 and 1980 vintages.

Observing a decline in cooling-driven consumption between the 1977 and 1980 vintages of homes does not necessarily imply that Title 24 resulted in energy savings. Instead, it is possible that other determinants of cooling could differ between the pre and post-Title 24 vintages. Indeed, Figure 3 reveals that, apart from the decline between 1977 and 1980, cooling consumption trends upwards for vintages between the late 1960s through the early 1990s. Similarly, with the exception of the increase between 1978 and 1980, average $\widehat{Temp}_i^{min}$ shows a downward trend over the same vintages. The trends persist after we control for square footage, stories, and bedrooms, suggesting that changes in those characteristics do not explain the trends. Therefore, unobserved factors affecting cooling consumption must be varying across vintages.

There are several potential explanations for these trends. For example, ceiling heights could be changing over this time period, resulting in higher energy requirements for cooling. Another important physical feature we do not observe at the premise-level is the amount of exposure a premise has to sunlight. One clear possibility is that older houses may be surrounded by older, larger trees. As a result, the older vintages of homes may be shaded to a larger extent and, as a result, require less electricity for cooling.[19] In Appendix A, we present evidence of a strong, negative relationship at the zip code level between the average age of houses and a unique measure of the exposure of buildings to solar radiation. Importantly, although a negative correlation between solar exposure and house age could explain an upward

[19]Donovan and Butry (2009), focusing specifically on houses in Sacramento 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).

trend in cooling across vintages, it cannot explain the discontinuous decrease in cooling between 1977-1980 homes.

In addition to physical differences in the premises, households sorting into houses may result in demographic trends across vintages. For example, studying Census Block Group level data in Appendix A, we present evidence that households 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. Again, the analysis presented in Appendix A fails to uncover evidence that the pattern of sorting by income discontinuously changes across homes built around the adoption of Title 24.

Of course, we cannot rule out that households may be discontinuously sorting into homes along dimensions other than income. For example, households with strong preferences for cool temperatures may sort into the more energy efficient, post-Title 24 homes. Given that preferences for cooling are unobserved, we cannot rule out this pattern of sorting. However, it is important to note that if households with higher demands for cooling discontinuously sort into post-Title 24 homes, then our estimate of the energy savings achieved by Title 24 would understate the actual energy savings.

Another possibility is that market forces, as opposed to direct regulation (Title 24), lead to the sudden improvement in the energy efficiency of homes built after 1977. For example, during 1978, there was a large increase in the price of oil. However, oil was not directly used as a source of energy by homes constructed in the region. Instead, the premises we examine relied on natural gas and electricity. The real price per kWh in SMUD's service territory was flat around the time of Title 24's adoption while natural gas prices steadily began increasing from 1973 through 1983.[20] Therefore, there was no discontinuous energy price changes that could explain the break in cooling-driven consumption between the 1977-1980 vintages of houses.[21]

[20] Appendix Figure A6 shows historical real SMUD electricity rates and natural gas prices.

[21] It is also important to note that, in contrast to the period surrounding the 1978 oil price shock, there was no large decline in cooling-driven consumption in homes constructed around the time of the oil price shock that occurred in 1973.

Ultimately, the results presented in Figure 3, combined with the lack of a competing explanation for the discontinuous decline in cooling, provide strong support for the conclusion that the adoption of Title 24 reduced the quantity of electricity used for cooling. In the next section, we use a regression discontinuity approach to quantify the changes around this discontinuity.

3.3 Discontinuity in Predicted Cooling

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

$$\widehat{\text{Cooling}}_i = \delta \cdot Post_i + \beta_1 \cdot \Big(\text{Year}_i - 1978\Big)_- + \beta_2 \cdot \Big(\text{Year}_i - 1978\Big)_+ + \boldsymbol{\theta} \cdot \mathbf{X}_i + \varepsilon_i, \quad (5)$$

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 implemented. 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, $\mathbf{X}_i$ includes the same set of saturated controls for stories, square footage, and bedrooms as in Eq. (4). 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. (5) 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 3 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.[22] Therefore, our primary estimates of Eq. (5) are based on the houses constructed from 1968 through 1989. Given that the Title 24 building

[22] Appendix Table A3 in the appendix presents estimates of the discontinuity in cooling for different ranges of years and for linear and quadratic trends. The estimated post-Title 24 reduction in cooling is stable across the alternative specifications.

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. (5), we allow the predicted annual cooling to change discontinuously in 1978, the year Title 24 was 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.

Table 3 presents the estimates of Eq. (5). The first column displays the estimates of the baseline model, without the inclusion of income controls or spatial fixed effects, and the top panel of Figure 4 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 of 257 kWh/year (13%) in cooling energy used. The second and third columns of Table 3 reveal that the predicted reduction in cooling is effectively unchanged by the inclusion of Census Block Group level income controls.[23] Finally, the last three columns of Table 3 present the estimates of discontinuity in cooling consumption with the inclusion of spatial fixed effects. Although the point estimates of δ are closer to zero, 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 the adoption of Title 24, we re-estimate the model specified

[23] With the inclusion of income controls, the upward trends in cooling across vintages decrease only 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.

by Eq. (5) using $\widehat{Temp}_i^{min}$ as the dependent variable. The bottom panel of Figure 4 displays the predicted trends and the discontinuity in the minimum consumption temperatures across the 1968 through 1989 vintages of houses.[24] 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.

3.4 Robustness and Comparison to Previous Literature

In the preceding analysis, we exploit our high-frequency data to estimate household-specific daily temperature response functions. This approach allows unrestricted heterogeneity across premises at the potential cost of a loss in precision. Previous papers in this literature estimated models that pool across premises (e.g., Jacobsen and Kotchen (2013), Levinson (2016)). To facilitate comparison with previous papers, we report results from pooled models. These estimates also allow us to demonstrate the robustness of our results to an alternative specification and to validate our results by showing that the estimated reductions occur in the hottest parts of the day.

We summarize the results here and provide details in Appendix B. To focus on a relatively homogeneous set of houses, we use those built in the years 1975-1982. To maximize the number of premises, we include those that use either natural gas or electricity for heating. Using the resulting 39,913 houses, we estimate the following model:

$$\text{Cons}_{i,d} = \alpha_i + \sum_j \left(\boldsymbol{\beta}_j \cdot \mathbf{T}_d \cdot \text{Vintage}_{i,j} \right) + \boldsymbol{\theta} \cdot \mathbf{T}_d \cdot \mathbf{X}_i + \varepsilon_{i,d}, \tag{6}$$

where i indexes each individual premise, d indexes each day during the two year sample, and j indexes three vintages—pre-adoption (1975-77), adoption (1978-79), post-adoption (1980-82). 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). We include a premise fixed effect and we allow the slopes of each segment of

[24] Appendix Table A4 presents the estimates of Eq. (5) for the minimum temperature.

the temperature response function to vary with observed premise-level physical characteristics by interacting the temperature spline with a vector of premise characteristics. $\mathbf{X}_i$ includes indicator variables for the number of bedrooms $(1, 2, ..., 6+)$, whether the house is single versus multi-story, the square footage (twelve bins ranging from $< 1,000$ square feet to $> 2,500$ square feet), and an indicator variable for premises with electric heat.

The left panel of Figure 5 displays the estimated daily consumption of electricity for cooling and heating for houses constructed during 1975-77 and 1980-82.[25] As before, the figure refers to a baseline house with three bedrooms, a single story, gas heat, and 1,600 to 1,750 square feet. The right panel displays the difference in the predicted daily electricity used for heating and cooling between the 1980-82 houses and the 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. Using Eq. (3), we estimate that the 1975-77 house consumed 1,814 kWh per year for cooling whereas the 1980-82 house consumed 1,644 kWh per year, which represents a 9.4% reduction in electricity used for cooling. This estimate is smaller than the 13% we estimated in Section 3.3 because it is the average difference between 1980-82 and 1977-79 vintage houses, so it does not account for the increasing trends shown in Figure 3.[26]

If our results represent a reduction in the use of electricity for temperature control, then 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. (6) separately for each hour of the day. Instead of using 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.

Figure 6 plots the predicted change in electricity used for cooling by hour-of-day for two different average daily temperatures.[27] The results reveal that,

[25]For the parameter estimates, see Appendix Table A7.

[26]Differences could also arise because the premise-specific and pooled models imply different weighted averages of the data.

[27]Appendix Figure A4 presents the estimates of the changes in the temperature response

on hot days, houses constructed during 1980-82 consume significantly less electricity for cooling compared to houses constructed during 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). In contrast, during the cool early morning hours, electricity consumed for temperature control does not vary significantly across the two vintages of houses. The pattern displayed by the predicted changes in cooling provides strong evidence that the 1980-82 era houses were constructed with superior thermal insulation.

Levinson (2016) uses monthly data from around California to estimate that electricity use became more responsive to hot temperatures immediately after Title 24, albeit by a statistically insignificant amount.[28] In contrast, we find a statistically significant decrease in the responsiveness. To understand why our findings differ, we replicated Levinson's analysis and compared it directly to the same model estimated using our data. Levinson uses heating and cooling degree days (HDD and CDD) rather than a spline to measure the outdoor temperature, so we use these temperature variables rather in this section.[29]

Figure 7 shows estimates of the coefficients on CDD interacted with vintage. We use 1977 as the base year, so negative values indicate a decline in the response of electricity use to temperatures above 65°F, which is what we expect if the building codes reduce electricity use. Consistent with the results in Figures 3 and 4, applying Levinson's specification to the SMUD data shows less responsiveness to hot temperatures after Title 24. The Levinson data show the same result, although the estimates are much less precise. Thus, it appears that our results differ from Levinson's in large part because his data doesn't allow precise identification of the effect.

Figure 7 also highlights the perils of grouping across vintages in the presence of trends. The 1975 houses in Levinson's sample pull down the average

function slopes from the 1980-82 era houses relative to the 1975-77 era houses.

[28]See his Table 4, Appendix Table A5, and Figure 6

[29]This specification is akin to a V-shaped function for temperature response, with a minimum consumption point at 65°F. See Appendix B.3 for details of our replication.

response to temperature in the pre-adoption period. The 1982 houses pull the average post-adoption response up. As a result, the average 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 Vintage Versus Age Effects

The preceding estimates reveal that houses constructed immediately after the adoption of Title 24 consume less energy for cooling than houses built immediately prior to Title 24's adoption. Although this pattern suggests that Title 24 did result in energy savings, there is another important point to address. As both Levinson (2016) and Kotchen (2017) note, by comparing energy consumption in houses built before versus after the adoption of building codes, we run the risk of confounding the impact of a house's vintage on consumption with the impact of a house's age. Houses built during the early 1980's are newer than the houses constructed during the late 1970's. By observing that the cooling-driven energy consumption is lower in the post-adoption vintage of houses, are we uncovering evidence that the building codes reduce energy consumption or are we simply uncovering evidence that, compared to people in houses that have aged, people in newer houses use less energy for cooling?

Before directly examining how the age of a house impacts cooling, it is useful to reexamine the estimates of the annual electricity used for cooling across different vintages of houses (top panel of Figure 3). If the reduction in cooling-driven electricity consumption in the houses constructed after the adoption of Title 24 is driven by the fact that the post-adoption vintage of houses are newer, then we would expect to see a general downward trend in the quantity of electricity used for cooling across the different years of construction. However, that is not the case. With the exception of the break that occurs between 1977 and 1980, cooling-driven electricity consumption shows a very consistent upward trend across houses constructed from the late 1960s through the early 1990s. This suggests that the estimated reduction in consumption between the pre and post-adoption vintage of houses is not being caused by differences in the age of the houses.

To explore how building 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. To do so, we use data from monthly bills, from which we observe the monthly aggregate electricity consumed at each premise from 2008 through 2013. If aging makes houses of a specific vintage use more energy for cooling, 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 as in Section 3.2 – 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:

$$\overline{\text{Cons}}_{i,m} = \alpha_i + \sum_y \left(\boldsymbol{\beta}_y \cdot \overline{\mathbf{T}}_{i,m} \cdot \text{Vintage}_{i,y} \right) + \varepsilon_{i,m}, \tag{7}$$

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 on premises constructed from 1960 through 2004.[30]

Similar to Eq. (6), 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 elements of the temperature spline ($\mathbf{T}_d$) for each day included in the 2008 through 2013 billing data.[31] For each observed monthly bill, we then calculate the average daily

[30] To increase the likelihood that the 2008 monthly bills reflect the consumption of occupied premises, we exclude houses constructed after 2004.

[31] The daily average temperature is again calculated from the Sacramento Airport NOAA

values of the temperature spline across each of the $N_{i,m}$ days during billing cycle m for household i as $\overline{\mathbf{T}}_{i,m} = N_{i,m}^{-1} \cdot \sum_{d \in m} \mathbf{T}_d$.

To quantify how aging impacts cooling energy used, 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 assume that, regardless of a house's age or vintage, zero electricity is used for cooling when the average daily temperature is 62°F. The left panel of Figure 8 plots the predictions of the average annual electricity consumed for cooling by vintage using the two estimated temperature response functions.[32] The right panel of Figure 8 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. 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 other potential explanations for the differences displayed in Figure 8. In particular, the time period over which we examine the monthly bills

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, to preserve degrees of freedom the estimates of temperature response functions do not condition on the observed house characteristics. Therefore, unlike the results displayed in Figure 3, the estimates of the annual cooling-driven electricity consumption in Figure 8 do not compare similar houses across vintages.

[33]Appendix Figure A5 presents the estimates of $\boldsymbol{\beta}_y$ from Eq. (7) for the 2008-10 and 2011-13 time periods.

(2008 through 2013) straddles a large economic downturn. During periods with high unemployment rates, individuals may be home more often and therefore use more electricity, or they may reduce consumption due to reduced income. Although the unemployment rate in the Sacramento region was very similar across these two periods — 10.11% from 2008-10 and 10.26% from 2011-13 — that may not necessarily be true within each vintage of houses.[34]

Even stronger evidence in support of the aging effects is found by comparing the results to the estimates in Figure 3. The apparent impact of age on consumption that begins in the early 1990s houses coincides with the reversals in the upward trend in cooling consumption (top panel of Figure 3) and the downward trend in the minimum consumption temperature (bottom panel of Figure 3). This suggests that the estimated decline in cooling-driven consumption that begins with the houses constructed in the early 1990's cannot be attributed solely to improvements in energy efficiency. Instead, the decline is, at least in part, due to the fact that the houses constructed after 1990 are experiencing energy efficiency declines as they age.[35]

We use the results from our billing analysis to quantify the contribution of the aging effect to cooling energy used. Figure 8 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.[36] 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.[37] A 21% efficiency decline moves this 2004 house from our Figure 3 estimate of 1,556 kWh per year of cooling energy use

[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.

[35]Rather than declines in the efficiency of the building, changes in behavior of the people in the house could also contribute to the aging effect. For example, family size may grow or the occupants may become willing to spend more money on cooling as a house ages.

[36]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%.

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

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.

This does not mean that energy efficiency has not improved since 1980 because many things vary across home vintages; it is impossible to infer the effect of building codes from homes built decades apart.[38] However, these results do imply that differences in age across the pre-Title 24 vintage of houses (1975-77) versus the post-Title 24 vintage (1980-82) cannot explain the decline in cooling-driven electricity consumption that is observed across these houses.

5 Policy Discussion

5.1 Cost Benefit Analysis

The estimates in Table 3 imply that the Title 24 building codes reduced the quantity of electricity used for cooling in 2012-13 by an average of 257 kWh per year per household. This reduction 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 more temperate home, are not observable to us. Here, we argue that the estimated reduction in cooling energy used indicates that the benefits of the 1978 Title 24 codes exceed the costs.

To approximate the social benefits of the cooling energy saved, we make several assumptions. First, we assume the quantity of electricity saved is constant across years. Second, following Borenstein (Forthcoming), we assume the nominal social cost of electricity is \$0.10/kWh in 2016 dollars. To obtain this number, we assume the long-run marginal cost of natural gas generation is \$0.06/kWh 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 occurs during peak hours. Under these assumptions, we estimate that, during 2016, the average nominal savings in a post-Title 24 home was \$25.70. We assume that nominal savings are constant across years

[38]See Appendix D for further discussion of energy efficiency since 1980.

(1980-2016).[39] Deflating the nominal annual savings of $25.70/year back to 1980 dollars, and using a 3% real discount rate, we estimate that from 1980 through 2016, a post-Title 24 premise provided an average total savings of $354 in 1980 dollars.

Table 1 shows that Title 24 had average costs of approximately $782 per household. Thus, the savings from reduced energy used for cooling are approximately 45% of the cost. If the savings in natural gas use for heating and the value of improved comfort were of a similar magnitude, then the benefits would approximately equal the costs. However, Table 1 shows that the projected savings in natural gas were 9 times the projected electricity savings. Thus, it seems clear that the benefits of Title 24 exceed the costs.

5.2 Policy Implications

Of course, finding that the benefits of Title 24 exceed its costs is not sufficient to conclude that Title 24 is a cost-effective policy to address the negative externalities arising from the production and consumption of energy. For example, in the transportation sector, minimum efficiency standards have been shown to be far inferior to price based policies that directly internalize negative externalities (Holland, Hughes and Knittel (2009), Jacobsen (2013)). The efficiency gains from the first-best price policies (e.g., pollution taxes or cap and trade programs) comes from the flexibility in compliance and the reductions in energy use incentivized by an increase in the price to consumers.

In the housing market, however, several market imperfections may render the typical first-best price policies inefficient – or, importantly, inefficient when used in isolation. Perhaps the most relevant market failure is the potential for imperfect information. First, when a new house is being constructed, the builder of the house is a different person than the consumer of the heating and cooling services. Given that the home buyer may not observe the energy

[39] Over the period from 1980 through 2016, the average annual natural gas wellhead (nominal) price was $3.14 per thousand cubic feet. The levelized cost of electricity (LCOE) estimates provided by the Energy Information Administration's "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016" were based on nominal gas prices in the same range.

efficiency of the house, the additional costs of using more energy efficient materials may not be fully priced into the house. As a result, there is little incentive for the builder to incur extra costs to improve energy efficiency.[40] In addition, imperfect information in the housing resale market can also lead to underinvestment in energy efficiency (Howarth and Andersson (1993), Howarth and Sanstad (1995)). Specifically, even if a principal-agent problem does not arise between new home buyers and builders, the new homeowners may have little incentive to initially invest in energy efficiency if prospective buyers cannot (costlessly) observe the level of energy efficiency.[41]

In the presence of imperfect information, simply pricing the negative externalities (e.g., local pollution, greenhouse gas emissions) may not induce efficient investment in residential energy efficiency. The mid to late 1980s provides one example. Electricity prices increased by more than 100% in Sacramento during this period, but Figure 3 shows no visual evidence of a coincident improvement in residential energy efficiency.[42] This pattern suggests that sharp increases in energy prices did not lead to meaningful improvements in energy efficiency, perhaps because of market failures (e.g., imperfect information).

Although price increases driven by pollution taxes or cap and trade programs will likely lead to reductions in energy consumption, the existence of imperfect information may lead to underinvestment in energy efficiency. In the housing market in particular, the potential efficiency costs stemming from underinvestment in the energy efficiency of newly constructed houses may be quite large for two reasons. First, the housing stock is incredibly durable. According to the U.S. Census Bureau's 2013 American Housing Survey, the median house in the U.S. is 40 years old (constructed in the mid-1970s).[43]

[40] Jaffe and Stavins (1994) highlighted the potential for a principal-agent problem to arise in the market for new houses.

[41] Johnson and Kaserman (1983), Dinan and Miranowski (1989), Brounen and Kok (2011), and Myers (2017) present evidence that, to some degree, the energy efficiency of a house is capitalized into the house price. However, it is unknown whether the costs incurred by investing in energy efficiency, and particularly difficult to observe energy efficiency improvements (e.g., wall insulation), are fully capitalized into house prices.

[42] Appendix Figure A6 plots average real electricity rates in SMUD's service territory.

[43] For information on the American Housing Survey, see `https://www.census.gov/programs-surveys/ahs/`.

Almost one third of U.S. houses were constructed prior to 1960. Second, homeowners have proven to be quite reluctant to invest in energy efficiency upgrades once they have moved into a house (e.g., Fowlie, Greenstone and Wolfram (2015), Holladay et al. (2016)). This suggests that houses built with sub-optimal energy efficiency will continue to impose costs on society for long periods of time. In an environment in which market failures (e.g., imperfect information) contribute to underinvestment in energy efficiency, well-designed building codes can serve as a complement to the first-best price policies, playing an important role in inducing investment in energy efficiency.[44]

6 Conclusion

In this paper, we examine the impact of California's building energy codes on residential electricity consumption. The codes, which were initially implemented in 1978, were designed 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 use a rich dataset of hourly, premise-level electricity consumption from 158,112 single-family houses in Sacramento, California. We estimate electricity use for cooling during 2012 and 2013 within each premise. To determine whether California's initial building codes have reduced cooling-driven consumption, we test whether the predicted cooling energy use falls discontinuously in houses built immediately after the adoption of the energy codes in 1978 versus those built immediately before 1978.

Our estimates reveal that the quantity of electricity used for cooling is, on average, 257 kWh/year (13%) lower in the houses built immediately after the codes were adopted. This drop is similar to the savings projected ex

[44] Allcott and Greenstone (2012) highlight that, when there is heterogeneity in the magnitude of the underinvestment, minimum energy efficiency standards can be a cost-effective policy tool to address the investment inefficiencies. The authors stress that the standards should be appropriately targeted to induce energy efficiency investment among the households under-investing in energy efficiency. For example, just as Title 24 mandates, energy efficiency building codes should be stricter in regions with more extreme temperatures. Jacobsen, LaRiviere and Price (2014) highlight a similar result in the presence of heterogeneous preferences for a public good.

ante by the CEC.[45] This discontinuous drop cannot be explained by observed differences in the type of houses built before and after the codes were adopted, by households sorting discontinuously into houses of different vintages, or by discontinuous changes in energy prices. 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.

Using our estimate of the electricity savings, we examine whether these benefits exceeded the costs of complying with the regulation. Imposing assumptions regarding the marginal social cost of the avoided electricity generation, we estimate that the electricity savings alone have recovered nearly half of the upfront cost of complying with the efficiency standards. Given that the natural gas cost savings were predicted to exceed the electricity cost savings by a factor of nine, our results support the conclusion that the efficiency standards would comfortably pass a cost-benefit test.

Our analysis takes advantage of the long-lived nature of the housing stock – we estimate energy savings more than 30 years after the codes were adopted. The durability of the housing stock also underscores the importance of ensuring that society is not underinvesting in the energy efficiency of new houses. Residential energy consumption accounts for over 20% of total energy consumed in the U.S. Given the potential for a variety of market imperfections (e.g., imperfect information, unpriced externalities) to result in sub-optimal investment in the energy efficiency of new houses, residential energy consumption may be inefficiently high. In such a setting, well-designed minimum energy efficiency standards for new houses can be an important complement to first-best price policies such as pollution taxes or cap and trade programs.

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[45]See Appendix E for further discussion.

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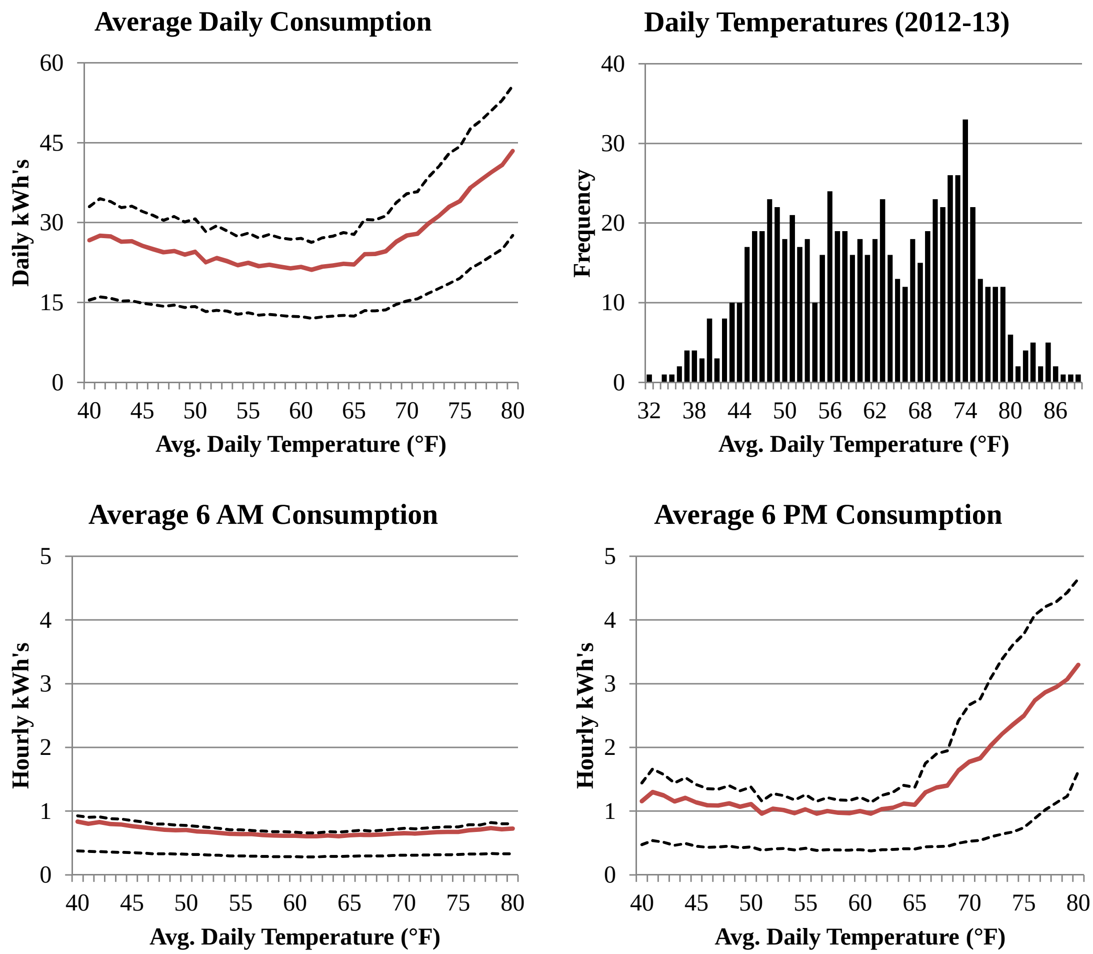


Figure 1: The upper left panel plots the average daily household consumption during 2012 through 2013 by the average daily temperature. The figure includes single-family premises constructed from 1975 through 1982 that do not use electricity as their primary source for heating. The figure also displays 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.

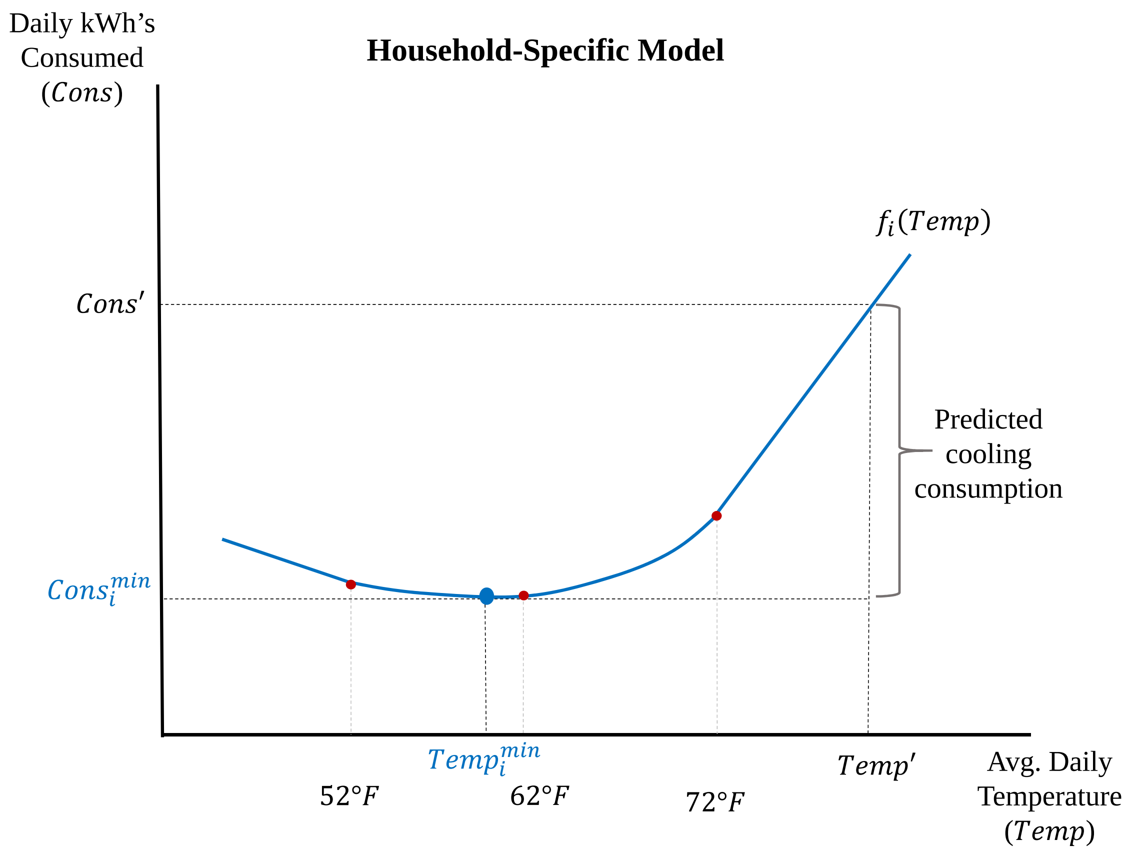


Figure 2: Average daily electricity consumption is modeled as a function of the average temperature using a restricted cubic spline that is linear below 52°F and above 72°F and a cubic function between 52°F and 72°F.

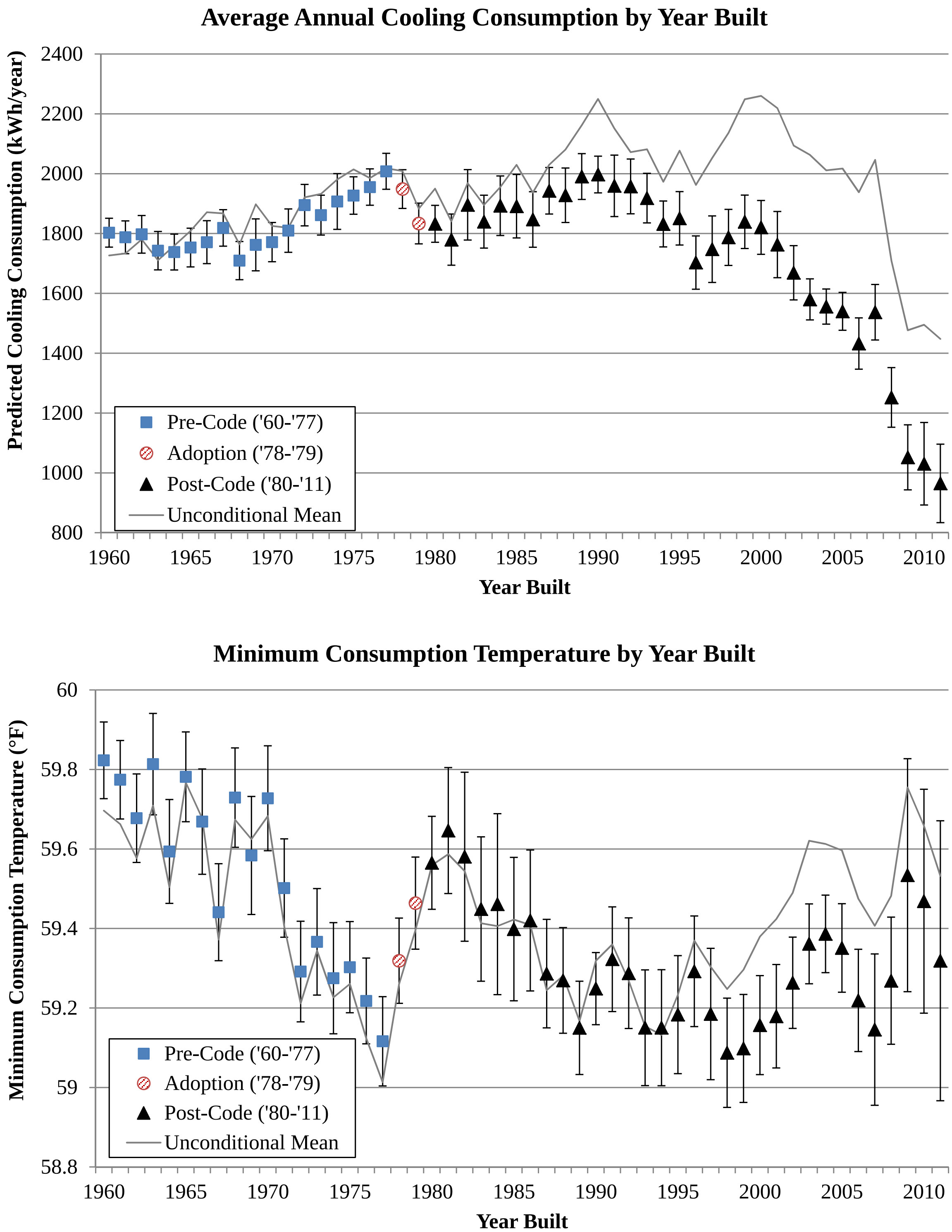
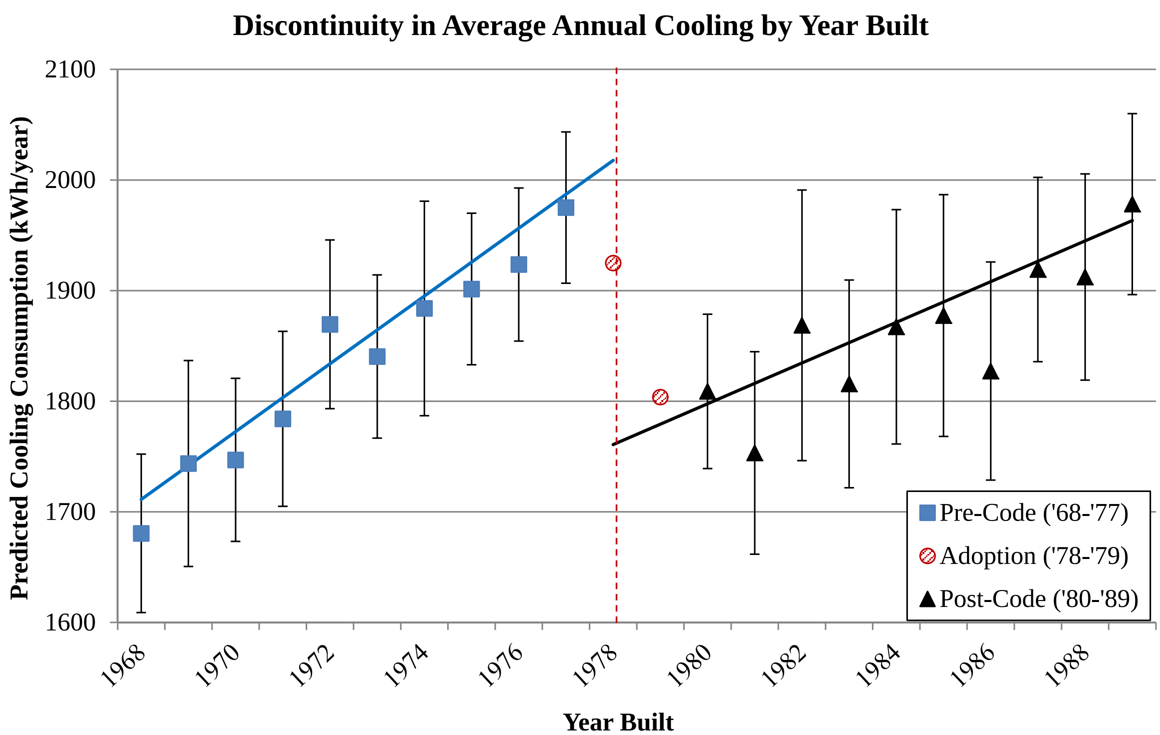


Figure 3: The top panel summarizes the predictions of the premise-specific electricity consumed for cooling during 2012-13. The solid line displays the unconditional average cooling usage by year of construction and the point estimates, and corresponding 95% confidence intervals, summarize the average cooling used by a baseline house (i.e. a house with three bedrooms, a single story, gas heat, and 1,600 to 1,750 square feet). The bottom panel summarizes the estimates of the premise-specific minimum consumption temperatures ($\widehat{Temp_i^{min}}$). The predictions are all based on the estimates of the temperature response function specified by Eq. (1).



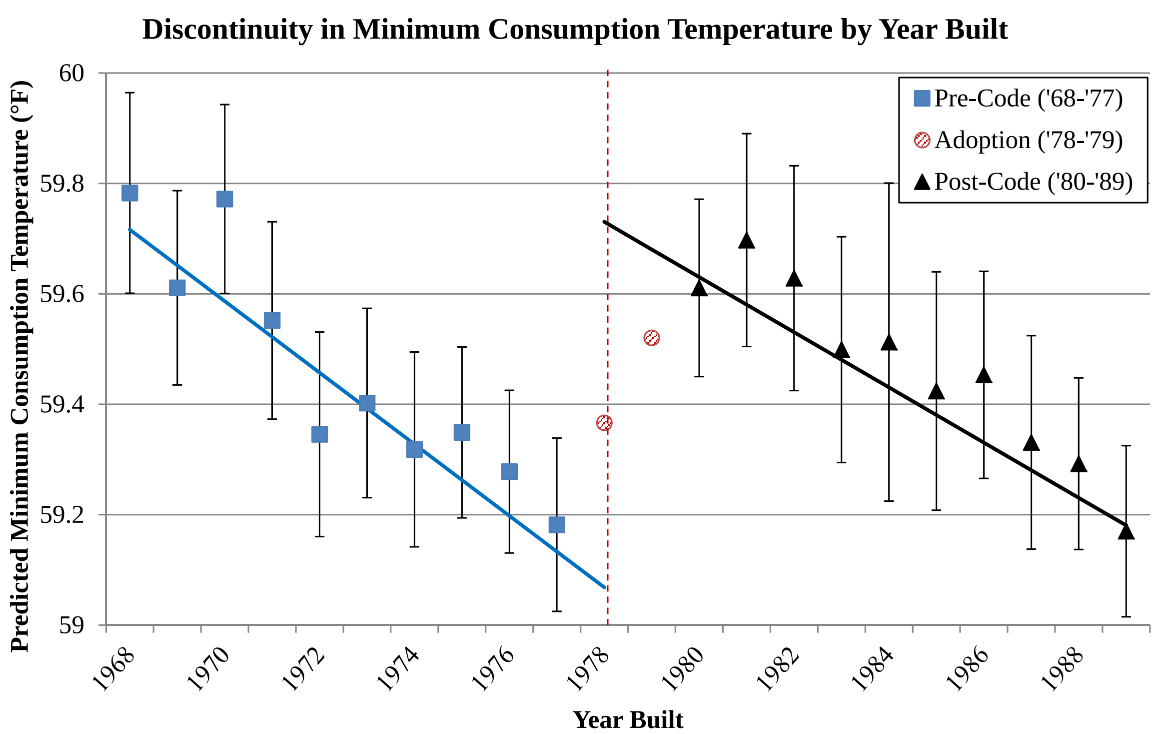


Figure 4: The top panel displays the estimates of the average annual electricity consumed for cooling by houses constructed between 1968-1989. In addition, the top panel displays pre and post-Title 24 linear trend estimates from the model specified by Eq. (5) testing for a discontinuous change in cooling electricity usage between houses constructed pre and post-Title 24. The bottom panel displays the corresponding pre and post-Title 24 linear trend estimates of Eq. (5) testing for a discontinuous change in the predicted minimum consumption temperatures ($\widehat{Temp_i^{min}}$).

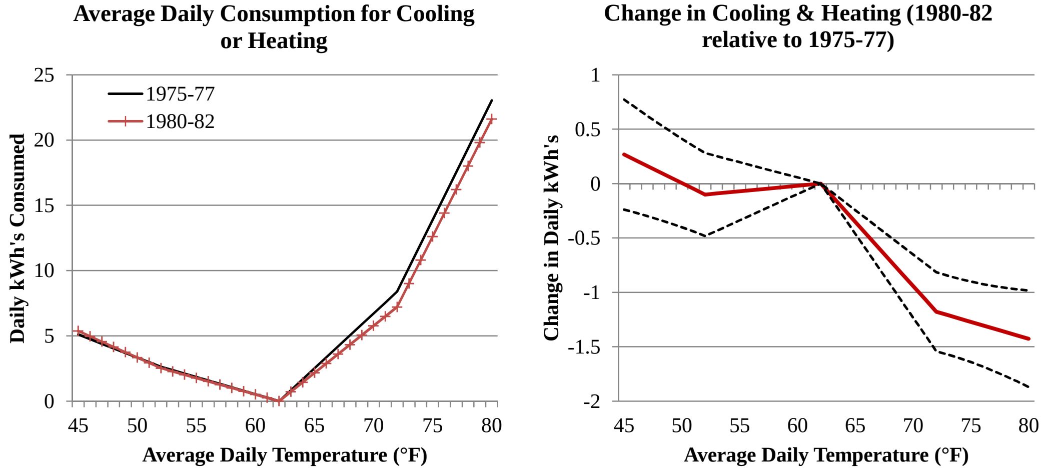


Figure 5: The left panel displays the predicted average daily electricity consumed for heating or cooling among houses built between 1975-77 and 1980-82. The predictions are based on the estimates of the temperature response function specified by Eq. (6). The temperature response functions displayed correspond to a house with three bedrooms, a single story, gas heat, and 1,600 to 1,750 square feet. We assume that, on average, zero electricity is used for temperature control when the average daily temperature is 62°F. The right panel displays the difference between the predicted average daily electricity used for temperature control in 1980-82 vintage houses relative to 1975-77 vintage houses and the corresponding 95% confidence interval, again assuming zero electricity is used for heating and cooling when the temperature is 62°F.

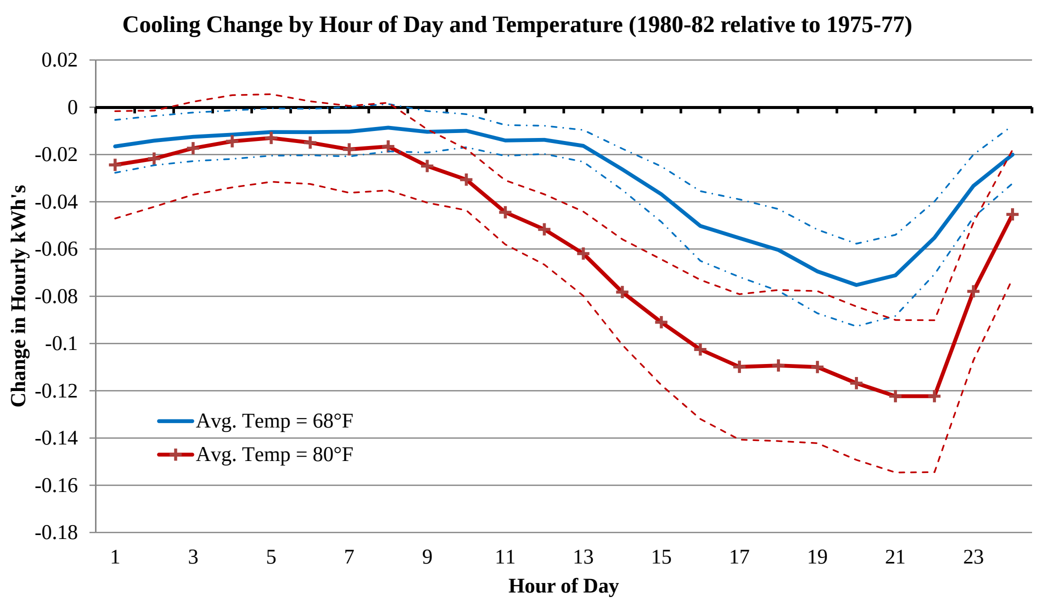


Figure 6: The figure displays the predicted change in hourly electricity used for cooling – in 1980-82 houses relative to 1975-77 houses – by hour-of-day for two different average daily temperatures. The predictions are based on estimates of the temperature response function specified by Eq. (6). In addition, we impose the assumption that, on average, zero electricity is used for heating and cooling, in any hour, on days with an average daily temperature of 62°F.

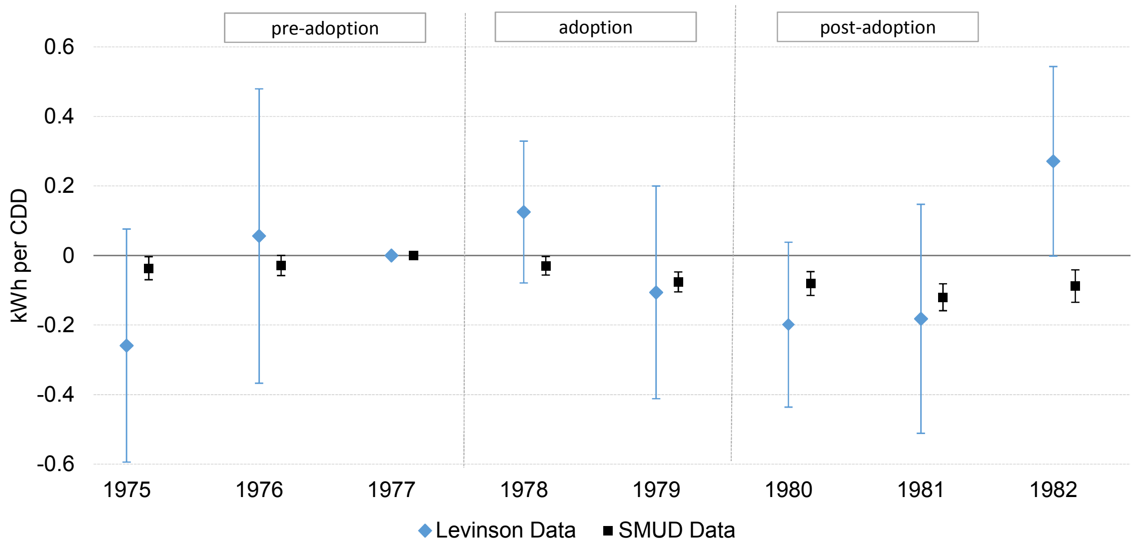


Figure 7: The figure displays the estimates of the change in average daily electricity consumption in response to a 1 degree increase in the cooling degree day (CDD) measure. The estimates are allowed to vary by year of construction and the coefficients are reported as differences with the 1977 houses as the base year. The estimates were made using the houses constructed between 1975-82 from the 2003 RASS data used by Levinson (2016) as well as the SMUD data used in the present analysis.

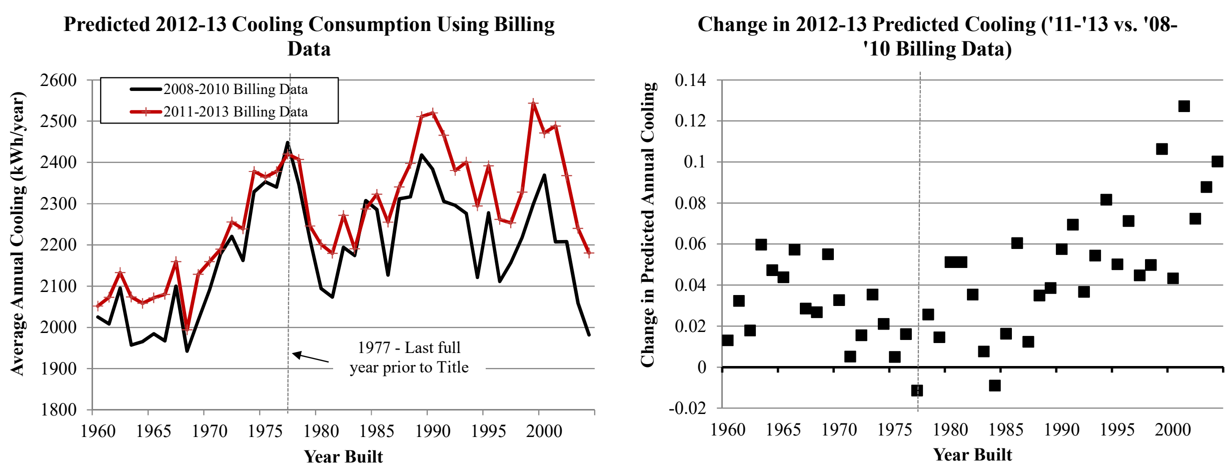


Figure 8: The left panel plots the predictions of the average annual electricity consumed for cooling by vintage during 2012-13. The cooling consumption is predicted using the estimates of the temperature response functions specified by Eq. (7). The estimates are made using monthly billing data over two time periods (2008-10 and 2011-13). The right panel displays the percentage difference between the prediction based on the 2011-13 temperature response functions versus the 2008-10 response functions.

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 (1)	Partial (2)	Full (3)	(3)-(1)	(3)-(2)	Ave. 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: 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	3,500	3,569	5,342	3,874	5,568	3,253	1,600	519	
Daily kWh	27.89	26.66	26.76	27.01	26.38	28.71	26.94	28.69	1.13**
	(14.00)	(13.50)	(14.20)	(13.02)	(14.11)	(15.80)	(15.21)	(15.36)	(0.24)
Square Feet	1,709	1,572	1,525	1,641	1,614	1,796	1,660	1,709	156.89**
	(557)	(462)	(438)	(497)	(441)	(629)	(491)	(507)	(8.46)
Bedrooms	3.53	3.51	3.48	3.51	3.48	3.55	3.48	3.46	0.02
	(0.72)	(0.67)	(0.65)	(0.74)	(0.68)	(0.75)	(0.68)	(0.70)	(0.01)
Stories	1.21	1.21	1.19	1.23	1.20	1.22	1.21	1.24	0.01
	(0.51)	(0.50)	(0.41)	(0.45)	(0.41)	(0.44)	(0.45)	(0.46)	(0.007)
Central AC	0.92	0.91	0.97	0.98	0.99	0.97	0.96	0.96	0.03**
	(0.27)	(0.28)	(0.18)	(0.13)	(0.10)	(0.17)	(0.20)	(0.19)	(0.004)

Table presents the mean daily household electricity consumption, household square footage, number of bedrooms, and number of stories for single family houses, that do not use electricity as their primary source for heat, 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 3: 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 – For Online Publication

A Trends in Cooling

The top panels of Figures 3 and 4 display the estimates of the average annual quantity of electricity used for cooling during 2012-13. With the exception of the discontinuous drop in cooling between 1977 and 1980, there is a clear upward trend in cooling from the 1960s through the early 1990s. Controlling for the physical characteristics of the houses (i.e. square footage, bedrooms, stories), annual cooling increases by roughly 25 kWh/year during this period. This represents approximately a 1.5% increase in annual cooling with each new vintage.

There are several potential factors that can contribute to the upward trend in cooling. In this section, we examine two potential mechanisms: (1) higher income households may sort into newer houses, and (2) newer houses may have less tree shade and are more exposed to the sun. In addition, we examine whether their is any evidence that households with different incomes discontinuously sort into houses of different vintages. Evidence of discontinuous sorting behavior – e.g., a discontinuous increase in income among the households choosing to live the post-Title 24 houses – would pose a clear concern for our identification strategy.

A.1 Sorting by Income

To examine how household income varies with house vintage, we use information on the distribution of household incomes at the Census Block-Group level from the 2010 American Community Survey. We observe consumption from houses in 901 different Block-Groups. Using the 5-year moving average predictions, we estimate the average household income for each of the 901 Census Block-Groups.[46] To explore how household incomes vary with the vintage of the houses, we estimate the following model:

$$\text{Income}_j = \sum_{v=1}^{37} \theta_v \cdot \text{Share}_{v,j} + \varepsilon_j, \tag{A1}$$

[46] The ACS 5-year data provides counts of the number of households in individual income bins ranging from < \$10,000/year to > \$200,000/year. Using the mid-points for each bin, and a value of \$7,500 for the lowest bin and \$225,000 for the highest bin, we calculate the average household income for each Block-Group.

where Income_j represents the average household income in Census Block-Group j and $\text{Share}_{v,j}$ represents the share (0 to 1) of houses in Census Block-Group j that were constructed during vintage bin v. We separate the houses into 37 two-year wide vintage bins: pre-1940, 1940-41, 1942-43,. . . , 2008-2009, post-2009. The coefficient θ_v therefore represents the average household income for houses constructed during vintage bin v.

Figure A2 displays the point estimates of $\{\theta_v\}$ for 1950-51 through 2006-07 vintages.[47] Within the oldest houses, the average household income is predicted to be approximately \$50,000/year. In contrast, in the newer houses, the average household income is approximately \$100,000/year. While there is some noise in the point estimates, there is a clear upward trend in the predicted household income with the vintage of the house – i.e. households in newer houses have higher incomes. Assuming cooling is a normal good, this pattern of sorting could certainly contribute to the upward trend in cooling-driving electricity usage seen in Figures 3 and 4.

Importantly, the estimates displayed in Figure A2 do not uncover evidence of a discontinuous change in income between the pre-Title 24 vintage (1976-77) houses and the post-Title 24 vintage (1980-81) houses. This suggests that the drop in cooling-driven consumption that occurs in houses constructed immediately after Title 24 is not being caused by households discontinuously sorting into pre and post-Title 24 houses.

To test for discontinuous sorting by income, we estimate the following model:

$$\text{Income}_j = \delta \cdot \text{Post}_j + \theta_1 \cdot \text{Years Pre}_j + \theta_2 \cdot \text{Years Post}_j + \varepsilon_j, \tag{A2}$$

where Income_j again represents the average household income in Census Block-Group j and Post_j is the share of houses in Census Block-Group j constructed after Title 24's adoption in 1978. The variable Years Pre_j is equal to $min\{0, \overline{\text{Year}}_j - 1978\}$ and Years Post_j is equal to $max\{0, \overline{\text{Year}}_j - 1978\}$, where Year_j is the average year of construction for houses in Census Block-Group j. The model specified by Eq. (A2) allows income to vary linearly with the age of a house. If this pattern discontinuously changes within the houses constructed around the time of Title 24's adoption, then we would expected to see a non-zero value for δ.

Table A5 displays the estimates of the model specified by Eq. (A2). The first

[47] This age range contains approximately 90% of the premises in our sample.

three columns present the estimates using only Census Block-Groups with houses constructed between 1970-87, 1968-89, or 1966-91. By focusing on Block-Groups with houses built in a narrower window of time, the assumption of linear trends in income across pre and post-Title 24 houses is less severe. Across all three subsets of the Census Block-Groups, we find no evidence of a discontinuous change in household income across houses built immediately before and after Title 24. The last three columns of Table A5 present estimates of Eq. (A2) in which we restrict the pre and post trends in household income to be constant (i.e. $\theta_1 = \theta_2$). Again, there is no evidence of a discontinuous change in the pattern of sorting. Moreover, we continue to see evidence that households in newer houses tend to have higher incomes – income increases by approximate $1,500/year with each vintage.[48]

Our analysis of the Census Block-Group household income suggests that the drop in cooling-driven consumption that occurs in the post-Title 24 houses is not the result of households discontinuously sorting into houses based on their incomes. Of course this does not rule out that households may be discontinuously sorting into houses along dimensions other than income. For example, households with strong preferences for cool temperatures (i.e. high demands for cooling) may sort into the more energy efficient, post-Title 24 houses. Given that we do not observe factors that could affect the demand for cooling (other than income), we cannot rule out this pattern of sorting. It is important to note, however, that if households with higher demands for cooling discontinuously sort into post-Title 24 houses, then our estimate of the energy savings achieved by Title 24 would understate the actual energy savings.

A.2 Trends in Shading

In addition to patterns in how households sort into different premises, there may also be trends in the physical characteristics of the houses that can affect the quantity of electricity used for cooling. Although our analysis controlled for some of the key determinants of cooling (e.g., square footage, bedrooms, and stories), one potentially important feature is not observed at the premise-level – the amount of exposure

[48]The average annual household income is approximately $70,000. Therefore, household income increases by roughly 2% with each new vintage. Recall that cooling increases by roughly 1.5% with each new vintage. Therefore, our estimates suggest an income elasticity of cooling of 0.75.

a premise has to sunlight. 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). One clear possibility is that older houses may be surrounded by older, larger trees. As a result, the older vintages of houses may be shaded to a larger extent and, as a result, require less electricity for cooling.

To examine whether trends in shading could potentially explain some of the upward trend in cooling across vintages, we use data from Google's "Project Sunroof".[49] Project Sunroof uses aerial imagery and maps to compute how much sunlight hits the roof of each building. Using the predicted solar exposure, the algorithm can compute the share of buildings in a given zip code that are "solar viable" – i.e. would be exposed to enough solar during a year to produce at least 1,216 kWh per each kW of installed solar PV capacity. While this measure of solar viability is intended to measure solar PV potential, it will certainly be correlated with the amount of exposure buildings have to sunlight, and therefore the energy that would be required for cooling.

In SMUD's service territory, there are 56 5-digit zip codes. Project Sunroof provides estimates of the share of buildings that are solar viable in 45 of these zip codes. Overall, 86.7% of the buildings in these 45 zip codes are solar viable according to Project Sunroof's algorithm. There is however substantial variation across zip codes, with the zip code-level solar viability measure varying between 58% and 99%.

To examine whether newer houses may in fact be exposed to more solar radiation, and therefore, all else equal, require more energy for cooling, we compare the zip code-level measure of solar viability from Project Sunroof to the average year of construction of the residential premises in each of the 45 zip codes. Figure A3 plots the share of buildings that are solar viable in each zip code versus the average year of construction for the residential premises in the zip code. The plot reveals a clear positive correlation – i.e. new houses are exposed to more solar radiation. This relationship suggests that, indeed, newer houses are exposed to greater solar radiation and, therefore, require more electricity for cooling. Importantly, the pattern is not confined to the newest houses which are likely surrounded by the youngest trees. Instead, the pattern persists across the full range of vintages, suggesting that

[49] For a summary of Project Sunroof, see https://www.google.com/get/sunroof/data-explorer/.

the trend in solar exposure may be responsible for some of the upward trend in cooling-driven electricity consumption between the 1960s and 1990s vintages.

B Temperature Response in a Pooled Model

In this section, we provide further details on the pooled models discussed in Section 3.4 of the main text. 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.

B.1 Model Specification

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

$$\text{Cons}_{i,d} = \alpha_i + \sum_j \left(\boldsymbol{\beta}_j \cdot \mathbf{T}_d \cdot \text{Vintage}_{i,j}\right) + \boldsymbol{\theta} \cdot \mathbf{T}_d \cdot \mathbf{X}_i + \varepsilon_{i,d}, \tag{A3}$$

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:

$$\mathbf{T_d} = \begin{bmatrix} min(\text{Temp}_d, 52) \\ min\left(max(\text{Temp}_d - 62, 0), 62 - 52\right) \\ min\left(max(\text{Temp}_d - 72, 0), 72 - 62\right) \\ max(\text{Temp}_d - 72, 0) \end{bmatrix}. \tag{A4}$$

Eq. (A4) 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. (6)) 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.[50] 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. (6) 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.

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

B.2 Pooled Model Estimates

Table A7 reports the point estimates of the temperature response spline, $\boldsymbol{\beta}_j$ from Eq. (A3), for each of the vintages of houses (1975-77, 1978-79, and 1980-82). The reported standard errors are robust to two-way clustering by premise and week-by-year. Table A7 also reports the change in the slope of each segment of the temperature response function relative to the 1975-77 vintage of houses. Table A8 presents estimates of $\boldsymbol{\beta}_j$ from Eq. (A3) allowing the temperature response function to vary by each year of construction.

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.[51] 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 A7 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 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 2, 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

[51] 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 $100°F$.

response function for temperatures below 62°F.[52]

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. (A4) normalized to have a value of zero at a temperature of 62°F.

The left panel of Figure 5 displays the predicted daily consumption of electricity for cooling and heating for a house constructed during 1975-77 and 1980-82. The right 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 left panel of Figure 5 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-adoption era would have consumed 1,644 kWh per year – which represents a 9.4% reduction in electricity used for cooling relative to the 1975-77 vintage house.

B.3 Why do our Results Differ from Levinson (2016)?

Levinson (2016) concludes that (i) Title 24 was ineffective at reducing electricity consumption significantly, and (ii) any reductions that did occur fell far short of

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

projections. Our analysis reaches different conclusions. In particular, we present evidence that Title 24 resulted in significant electricity savings and that the benefits of the policy likely outweigh the costs. In this section, we highlight why our results differ from Levinson's.

First, we estimate that the upfront cost of implementing Title 24 was substantially lower than the cost highlighted in Levinson's analysis. 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%. While these numbers appear in various California Energy Commission (CEC) documents published in 1979-80, 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.[53] However, these standards were not adopted.

The standards implemented in 1978 were expected to be far less costly than the potential policy summarized by Levinson. Table 1 shows that Title 24 had average costs of approximately $782 per household. This average cost takes into consideration the fact that Title 24 was not a binding standard for all houses – i.e. many houses would have met or exceed the minimum efficiency standards regardless of whether the policy was imposed on not.

The second key reason Levinson's conclusions differ from ours is that we arrive at different estimates of the impact of Title 24 on electricity consumption. In his empirical analysis, Levinson uses monthly data from around California to estimate that electricity use became more responsive to 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.[54]

[53]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. See Section 2.1 and Table A11 for further details.

[54]We obtained Levinson's data and code from the additional materials published alongside

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 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 operating an air conditioner on electricity is not proportional to the amount of electricity 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. (6) using our data and these temperature variables rather than a spline with three knots. Specifically, we set

$$\mathbf{T_d} = \begin{bmatrix} HDD_d \\ CDD_d \end{bmatrix} = \begin{bmatrix} max(65 - \text{Temp}_d, 0) \\ max(\text{Temp}_d - 65, 0) \end{bmatrix}. \quad \text{(A5)}$$

We interact $\{HDD_d, CDD_d\}$ with the same set of $\mathbf{X}_i$ variables as in Table 2.

For comparison with our results, we estimate the model in Levinson's Figure 6 making four modifications. First, we use only data for houses built from 1975 through 1982. Second, we use only the 2003 RASS so we can 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.[55] Table A9 shows the estimation

the paper on the *American Economic Review* website.

[55]We also added HDD to the model, which Levinson excludes, and we dropped the average

results with and without these four modifications.

Figure 7 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 2 and A8, 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 Levinson's in large part because his data doesn't allow precise identification of the effect.

Figure 7 also 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.

C 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. (A3) 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. These technologies differ in some very meaningful ways. First, the resistance heat is typically used to heat individual rooms unlike heat pumps, which are designed to heat the entire house. Second, anecdotally, the early heat pumps installed in the region were often quite inefficient. Both of these differences could lead to an outcome in which we underestimate the heating driven energy savings that would be achieved by Title 24-driven improvements in thermal insulations absent any heating technology shifts.

The slope estimates from the temperature response functions are reported in Table A10. Again, we find that electricity consumption in premises constructed after the building codes were adopted (1980-82) are significantly less responsive to

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 Celsius by Levinson.

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 A7 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 A7, 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.

D Effects of Title 24 Updates

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 A11 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.[56] In 2010, the CEC increased the allowable window area by 25% but tightened the glazing standard by 38% to a 0.4 U-factor.[57]

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.[58] The building code components listed in Table A11 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.

As shown in Table A11, notable updates to Title 24 occurred in 1982, 1992,

[56]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.

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

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

2001, and 2010. The 2010 update occurs too late in our sample to infer its effects, but Figure 3 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 relative to a house built prior to 1975 with single-pane windows and no caulking or weather-stripping (last column of Table A11).

The standards that were enacted in 1982 included a stronger ceiling insulation standard and a windows requirement. Figure 3 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 cooling 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 right panel of Figure 8 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 3 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 8 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.[59] Figure 8 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 after the 19^{th} year. Between year 5 and year 19, the figure implies that the depreciation rate declines approximately linearly as the house ages.

Figure A8 provides an illustration of fully depreciated cooling energy use. We construct this estimate by assuming, as in Section 4, that the annual rate of depre-

[59]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 houses 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%.

ciation in cooling energy used decreases linearly from 2.3% in its 5th year to 0 in its 19th year. The dashed line augments our estimates of the average annual cooling driven energy use in a baseline house that has aged at least 19 years. Assuming linearly decreasing depreciation, the figure highlights that a 2004 house in 2012-13 is 21% more efficient than it will be after it is 19 years old.[60] 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. This does not mean that the updates to Title 24 have not been effective because many things vary across house vintages; it is impossible to infer the effect of building codes from houses built decades apart. Looking at the years around the building code changes in Figure A8, 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.

E Accuracy of Ex-Ante Projections

Based on the 1980 CEC projections, a 1,620 square feet Title-24-compliant house was expected to use 1,869 kWh per year for cooling (see Table 1). Figure 3 shows that cooling energy consumption in the early 1980s vintages was remarkably close to the amount. The γ_t coefficients for 1980, 1981, and 1982 are 1,832 kWh, 1,780 kWh, and 1,896 kWh per year, respectively.

The projected cooling energy used for pre-Title 24 houses is somewhat higher than we observe. Table 1 shows that a non-compliant house was expected to use 3,108 kWh and a partially compliant house 2,178 kWh per year. Accounting for the estimated proportion of houses that were non-, partially, and fully compliant prior to 1978, we approximated the pre-Title 24 cooling energy use at 2,336 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 1,927 kWh, 1,955 kWh, and 2,008 kWh per year, respectively.

One reason that actual use in pre-1978 houses is less than projected is that many of these houses have likely been retrofitted. SMUD has long operated rebate programs that provide incentives for customers to weatherize their houses. In addition,

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

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.

F Appendix Figures and Tables

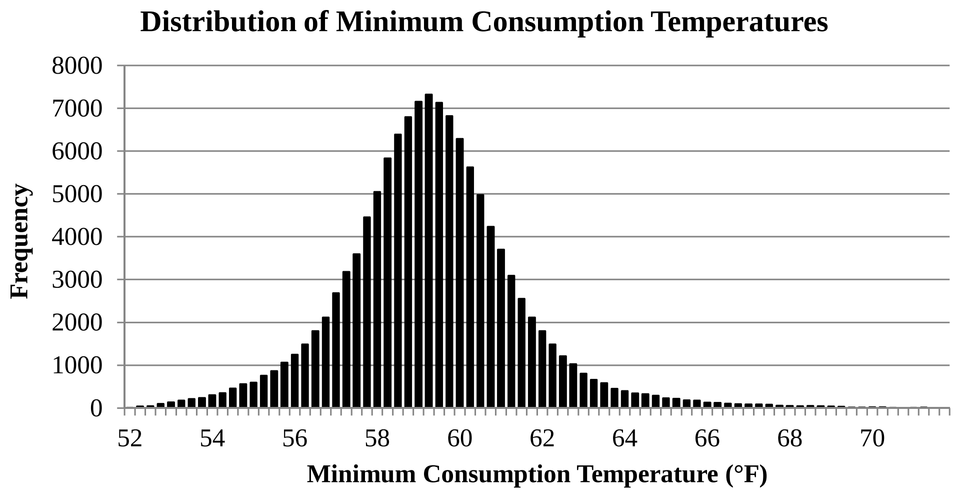


Figure A1: The figure displays the distribution of the predicted premise-specific minimum consumption temperatures ($\widehat{Temp}_i^{min}$) for 95% of the 158,112 premises. $\widehat{Temp}_i^{min}$ is the temperature at which household i's temperature response function, specified by Eq. (1), reaches a global minimum. The 5% of premises excluded from the distribution did not have a well defined estimate for the predicted minimum consumption temperature.

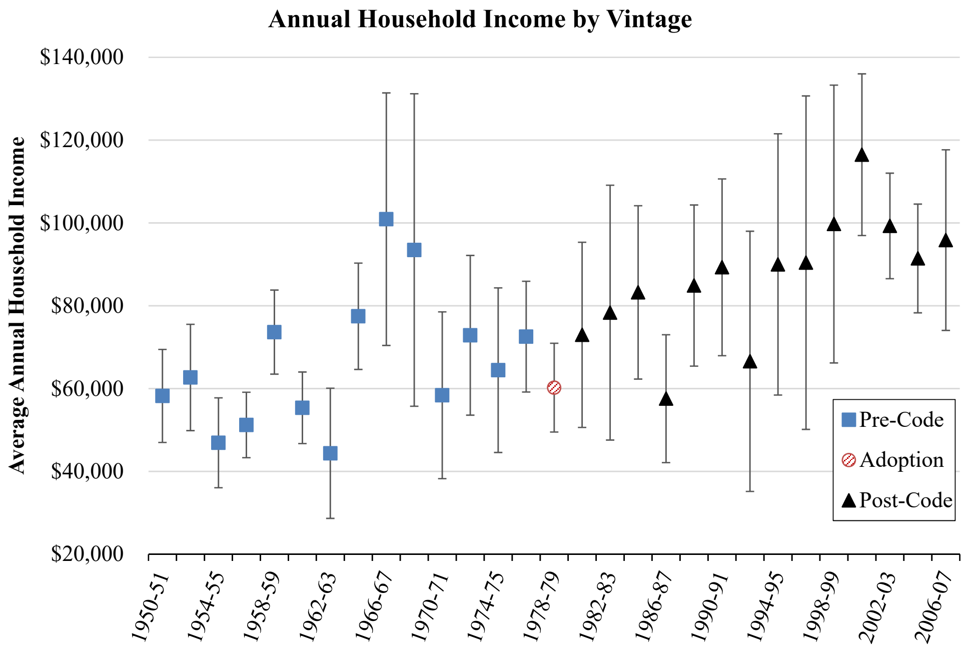


Figure A2: The figure displays the point estimates, and the corresponding 95% confidence intervals, of $\{\theta_v\}$ from Equation A2, the average annual household income, for 1950-51 through 2006-07 vintage houses.

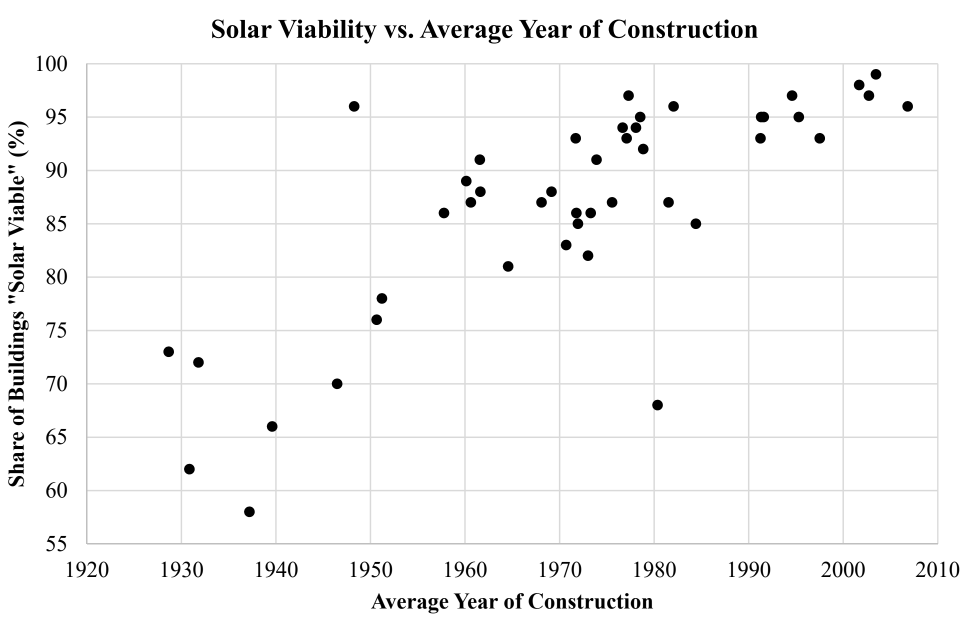


Figure A3: The figure plots the share of buildings at the 9-digit zip code level that are deemed to be "solar viable" by Google's Project Sunroof versus the average year of construction for the houses in the zip code. There are 45 zip codes included in the scatter plot.

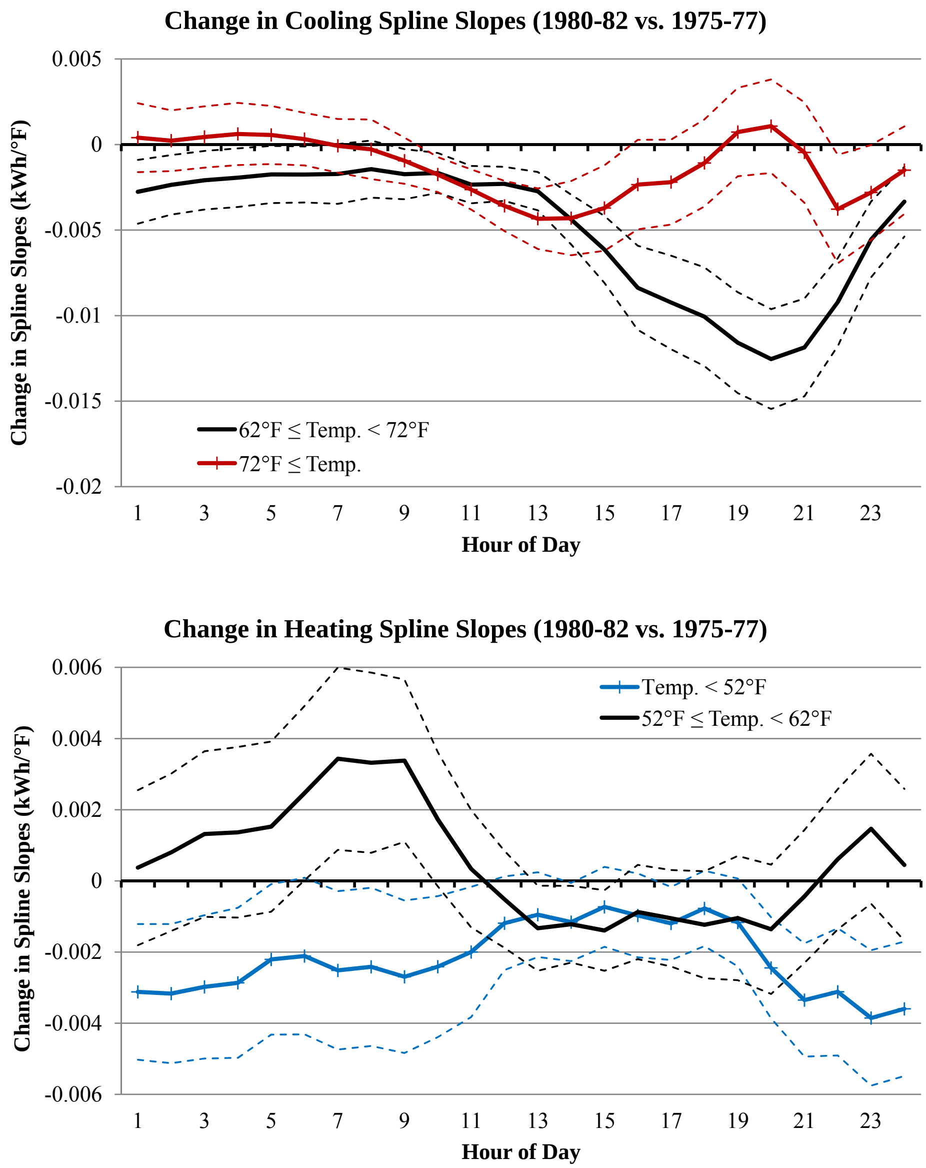


Figure A4: For each hour of the day, the plots display the point estimates, and the corresponding 95% confidence intervals, for the four slope coefficients that define the temperature response function specified by Eq. (6). The top panel displays the slope estimates for temperatures above 62°F. The bottom panel displays the slope estimates for temperatures below 62°F.

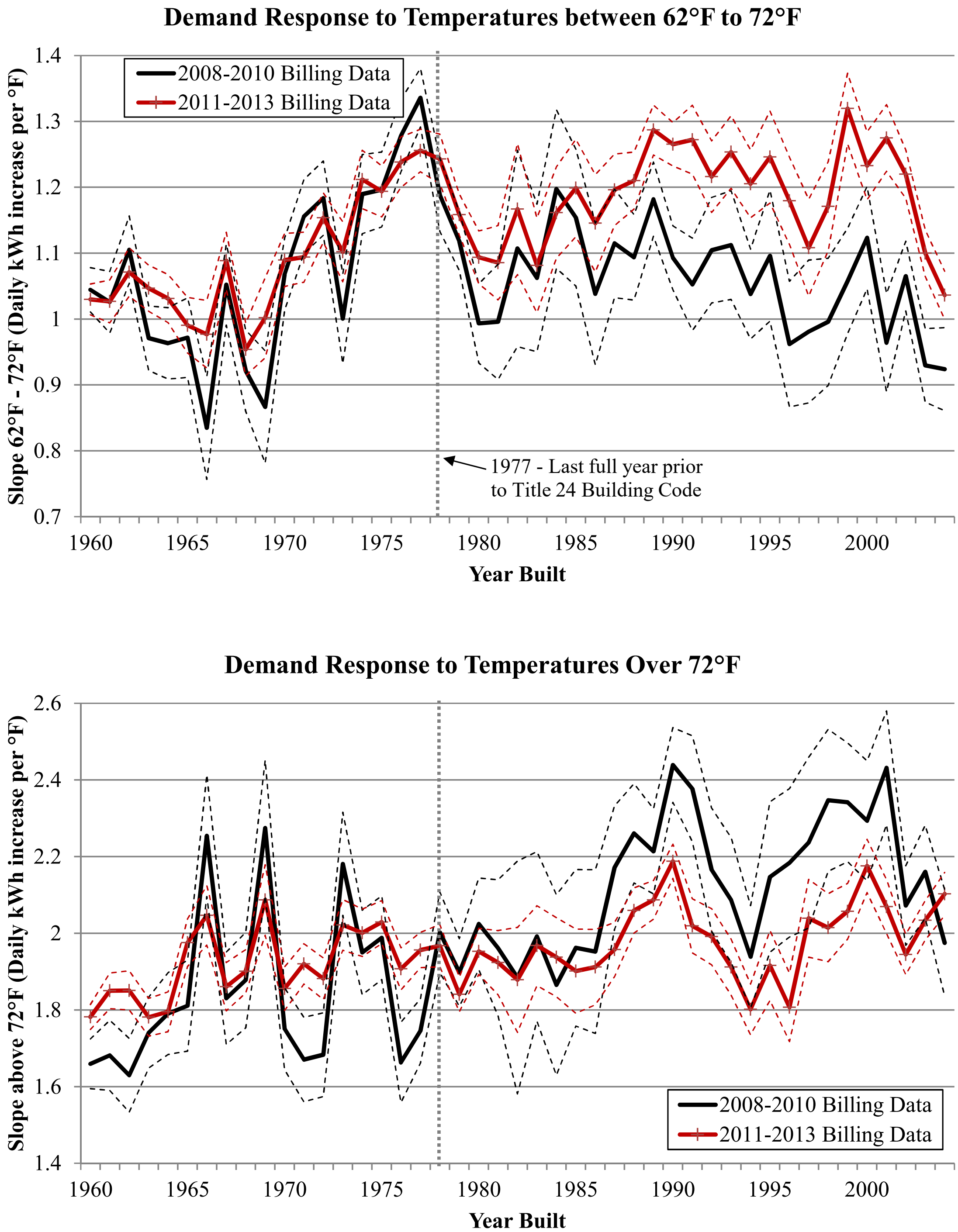
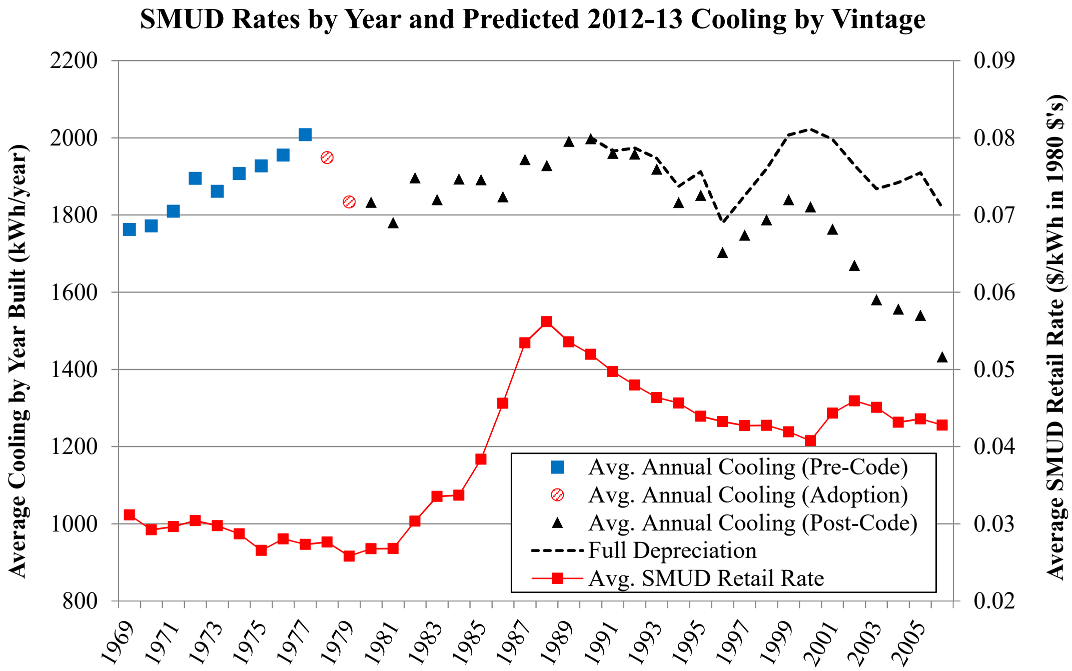


Figure A5: The panels display the point estimates of the temperature response slopes specified by Eq. (7) for each two-year grouping of vintages. For each vintage grouping, two slopes are reported: the slope estimate from the 2008-2010 billing data and the slope estimate from the 2011-2013 billing data. The top panel displays the slope estimates for temperatures between 62°F and 72°F while the bottom panel displays the slope estimates for temperatures above 72°F.



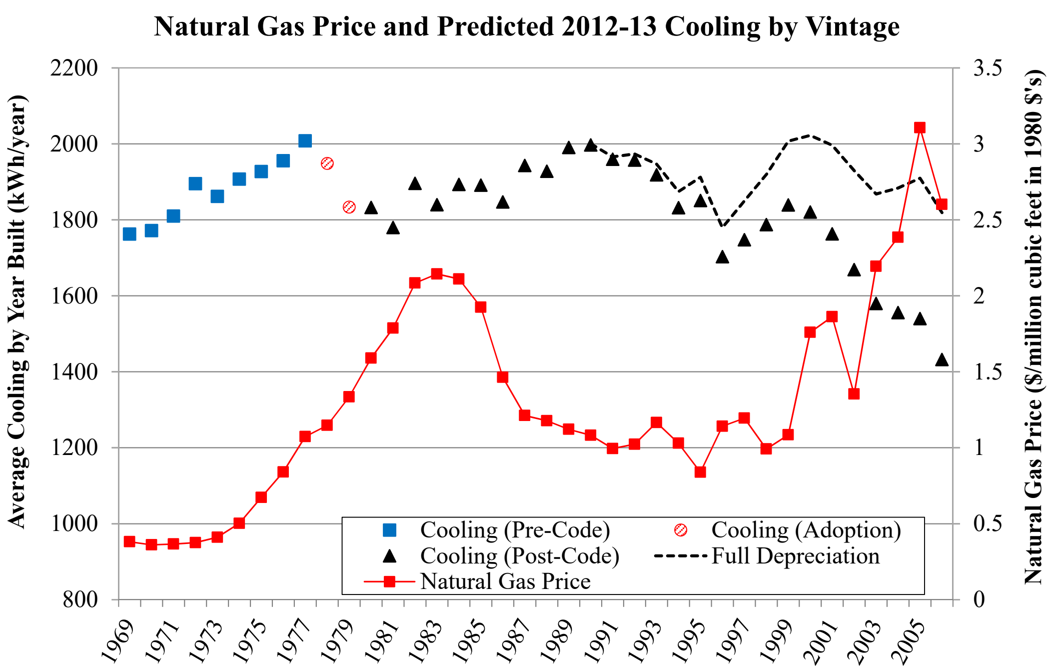


Figure A6: The top panel displays the estimated 2012-2013 average annual cooling by vintage in a baseline house (3 bedrooms, single story, gas heat, 1,600 to 1,750 square feet). In addition, the plot displays the average real retail electricity price paid by SMUD consumers (in 1980 $'s) from 1969 through 2006. The bottom panel again displays the predicted average annual electricity consumed for cooling as well as the real annual wellhead price of natural gas. The natural gas prices are provided by the U.S. Energy Information Administration. Both panels also display an estimate of the "fully depreciated" average annual cooling driven energy consumption – i.e. the cooling usage that would occur if the houses had all aged at least 19 years. Appendix D discusses how these full depreciation estimates are produced.

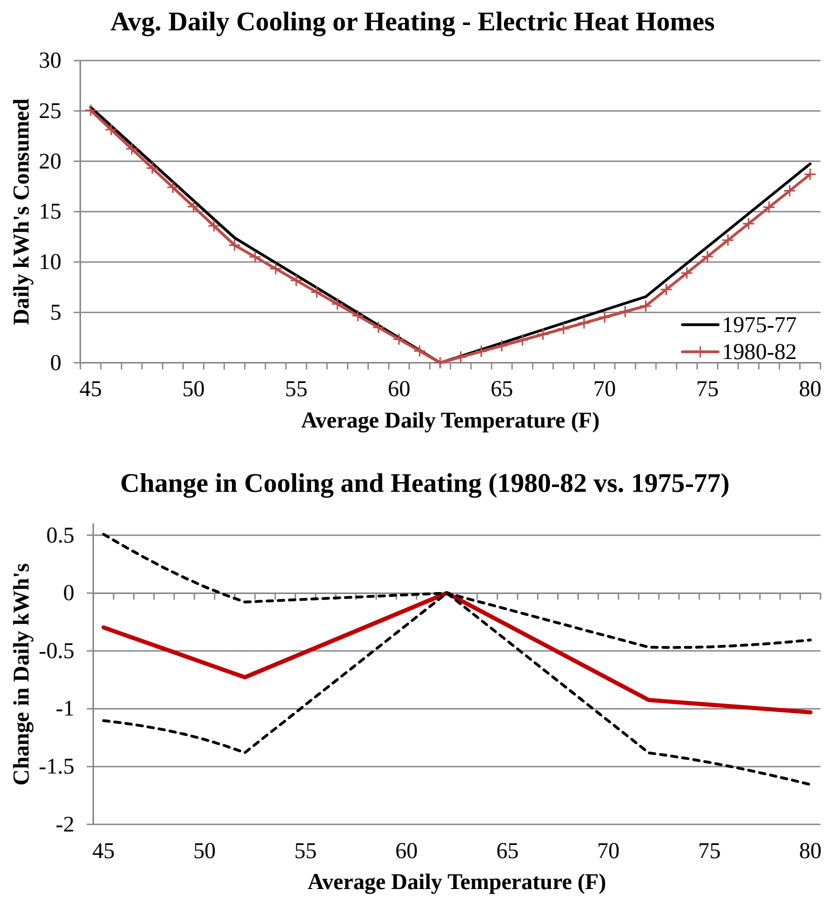


Figure A7: The top panel displays the predicted average daily electricity consumed for heating or cooling among houses built between 1975-77 and 1980-82 that use electricity as the primary source for heat. The predictions are based on the estimates of the temperature response function specified by Eq. (6). The temperature response functions displayed correspond to a house with three bedrooms, a single story, electric heat, and 1,600 to 1,750 square feet. We assume that, on average, zero electricity is used for temperature control when the average daily temperature is 62°F. The bottom panel displays the difference between the predicted average daily electricity used for temperature control in 1980-82 vintage houses relative to 1975-77 vintage houses and the corresponding 95% confidence interval, again assuming zero electricity is used for heating and cooling when the temperature is 62°F.

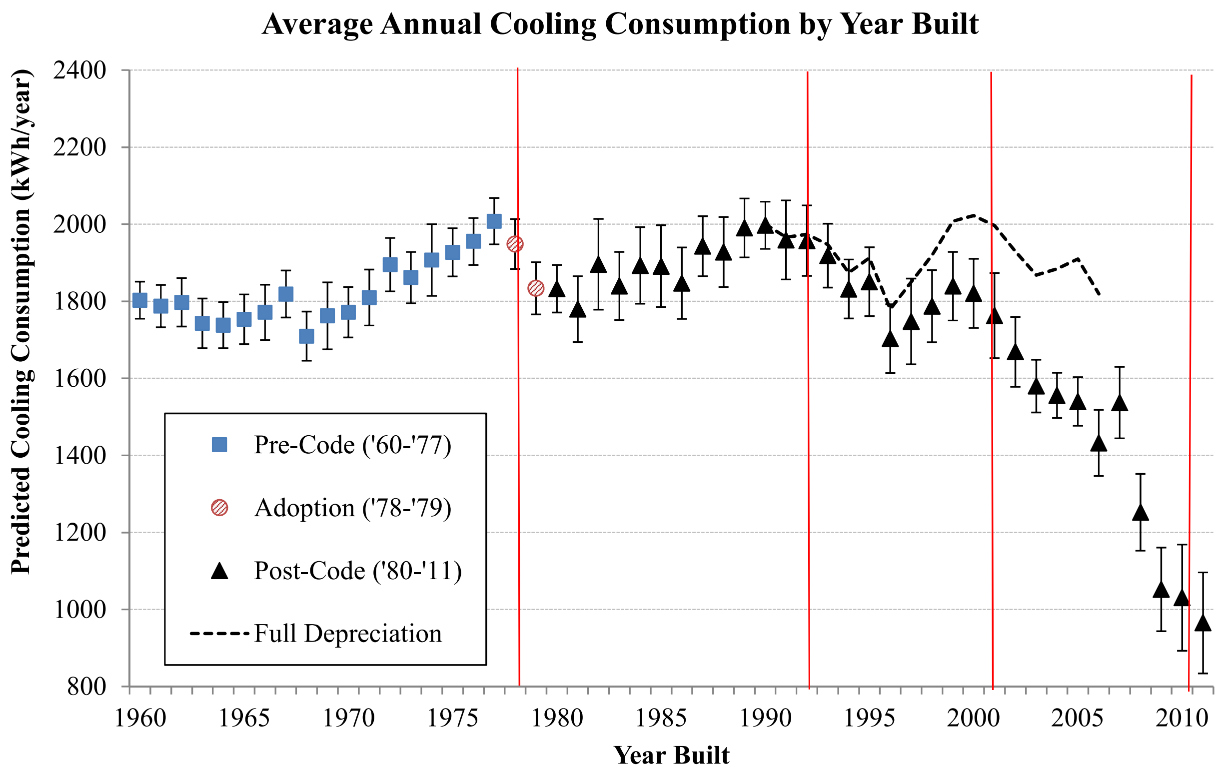


Figure A8: The figure displays the timing of the main post-1978 updates to Title 24 as well as the point estimates of the average annual electricity used for cooling during 2012-13 across each housing vintage. In addition, the dashed line augments the predicted cooling energy consumption among the houses that are newer than 20 years old during 2012. The dashed line represents the "fully depreciated" cooling energy usage – i.e. the cooling energy use that would occur had the houses fully depreciated over the course of 19 years. Appendix D discusses how these full depreciation estimates are produced.

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: 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 A4: 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 A5: 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 A6: 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.

Table A7: 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 A8: 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 A9: 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	0.10	0.10	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

First column replicates Figure 6 in Levinson (2016). Subsequent columns modify the model gradually. SMUD models include 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 A10: 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 A11: 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/`.