ARE BUILDING CODES EFFECTIVE AT SAVING ENERGY? EVIDENCE FROM RESIDENTIAL BILLING DATA IN FLORIDA

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Abstract—We evaluate the effect of a change in the energy code applied to buildings using residential billing data on electricity and natural gas, combined with data on observable characteristics of each residence. The study is based on comparisons between residences constructed just before and after an increase in the stringency of Florida's energy code in 2002. We find that the code change is associated with a decrease in the consumption of electricity by 4% and natural gas by 6%. We estimate average social and private payback periods that range between 3.5 and 6.4 years.

I. Introduction

IMPROVING energy efficiency is an increasingly important component of energy policy in the United States. In addition to longstanding concerns about resource scarcity and national security, recognition of climate change and the need to reduce greenhouse gas emissions has further elevated the importance of energy efficiency. Much attention is focused on improving efficiency in the built environment, as buildings account for roughly 72% of electricity consumption, 39% of all energy use, and 38% of carbon dioxide emissions in the United States (U.S. Department of Energy, 2008). Building energy codes (which we will refer to as just "energy codes") are the primary policy instrument for influencing the energy efficiency of newly constructed and renovated buildings. The vast majority of states have statewide energy codes for both commercial and residential buildings (U.S. Department of Energy, 2009a), and increasing the stringency of energy codes has been a priority of the U.S. Department of Energy for decades.

The policy relevance of energy codes has increased markedly with their inclusion in pending legislation for a national policy to address climate change. The Waxman-Markey climate bill (H.R. 2454) that recently passed in the U.S. House of Representatives requires that all states enact residential building codes by 2014 that are 30% more stringent than the 2006 International Energy Conservation Code Standard, and the target increases to 50% more efficient in 2017. Thereafter, the bill calls for a 5% increase every three years until 2029. Though less explicit, the Boxer-Kerry bill in the Senate (S. 1733) also includes provisions for increased stringency of energy codes. It states that the U.S. Department of Energy shall promulgate regulations establishing building code energy-efficiency targets beginning not later than January 1, 2014. Moreover, in terms of energy codes themselves, the bill states that such regulations shall be sufficient to meet the national building code energy-efficiency targets in the most cost-effective manner and may include provisions for state adoption of a national building code standard.

Despite proposals for such sweeping changes to residential energy codes, surprisingly little is known about how energy codes affect residential energy consumption in practice. Evaluations are typically based on engineering simulations that compare energy use of a baseline residence before the code change to that of one after the code change.[1] While this approach is useful in many respects, particularly for making ex ante predictions, it has a number of potential limitations. First, changes in energy codes may not affect building infrastructure if the codes are not effectively enforced or are not stringent enough to be binding. Evidence at the state level suggests, for example, that energy codes for the thermal resistance of household insulation had no significant influence on actual levels of insulation (Jaffe & Stavins, 1995). More generally, Jaffe and Stavins conclude that their analysis "does not suggest that building codes made any significant difference to observed building practices in the decade 1979–1988" (p. S61). Second, even if energy codes are effective at changing infrastructure, engineering simulations take no account of potential behavioral responses. For instance, improvements in energy efficiency decrease the effective price of energy-related services, such as air-conditioning, which may stimulate demand and produce a so-called rebound effect.[2] Third, if the assumptions that engineering models are based on are not accurate, then realized energy savings will be different from the predicted energy savings. Metcalf and Hassett (1999), for example, find that the realized returns of attic insulation differ significantly from those predicted by an engineering model. Where as a simulation model predicts an annual savings of 50%, the realized returns are substantially lower, at only 9%.

The concerns we describe parallel those discussed in the early 1990s about energy efficiency in "The Great Nega-

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[1] DOE-2 and EnergyGauge are two common software programs used to conduct simulation models on the effect of energy code changes on energy use. Examples of two government-commissioned evaluations of residential energy code changes are Fairey and Sonne (2007) for the Florida Department of Community Affairs and Lucas (2007) for the U.S. Department of Energy. The former studies real policy changes in Florida, and the latter predicts what might happen with policy changes in the Gulf Coast region. Both conclude that residential energy code changes can result in substantial energy savings. Links to a number of other studies can be found through the U.S. Department of Energy's Building Energy Codes Program at www.energycodes.gov/implement/tech_assist_reports.stm.

[2] Greening, Greene, and Difiglio (2000) survey the literature on rebound effects and find implied residential elasticities of 0.1 to 0.3 for space heating, 0 to 0.5 for space cooling, 0.05 to 0.12 for water heating, and 0.1 to 0.4 for lighting.

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watts Debate" between Amory Lovins (1994) and Paul Joskow (1994; see also Joskow & Marron, 1993). Highlighting the importance of going beyond engineering approaches, Joskow (1994) writes, "Technical potential studies of the kind that Lovins relies on may be useful to this process [promoting efficiency], but standing alone they are not very meaningful because they don't even purport to measure actual behavior and performance of real institutions" (p. 50).

In this paper, we employ a different methodology to evaluate whether energy codes affect residential energy consumption. Rather than conduct simulations, we take advantage of utility billing data to directly compare energy consumption of households built under different energy code regimes. Because the approach is based on actual changes in both the building code and energy consumption, the approach accounts for changes in construction practices, or lack thereof, and for potential behavioral responses. Such ex post analyses based on field data are needed to more fully evaluate the effects of energy codes.

The paper makes several contributions by providing (1) the first study that uses residential billing data to evaluate the effect of an increase in the stringency of an energy code on both electricity and natural gas consumption, (2) evidence that energy codes can in fact reduce energy consumption with magnitudes relatively close to simulation estimates, (3) a cost-benefit analysis to derive both private and social payback periods, and (4) a template for how similar studies can be carried out in other areas.

The analysis is based on a change in Florida's statewide energy code that came into effect in 2002. We obtained residential billing data on electricity and natural gas in the city of Gainesville that are combined with appraiser data for a set of observable characteristics for each residence. Indeed, a unique feature of our data, which is central to the empirical strategy, is that we have monthly billing data from the utility company combined with characteristics of each residence. Our evaluation of the impact on energy consumption is based on comparisons between residences constructed within three years before and three years after the energy code change was implemented. Using monthly utility bills for all residences in the years after the code change, we employ two empirical strategies to evaluate how energy code changes affect both electricity and natural gas consumption. The first is an analysis of consumption levels after controlling for differences in observable characteristics. The second is difference-in-differences estimates of the responsiveness of energy consumption to variability in weather.

The first approach produces our main results: the energy code appears to have caused a 4% decrease in annual electricity consumption and a 6% decrease in annual natural gas consumption. Moreover, the differences in the energy savings by month and weather variability are consistent with reduced consumption of electricity for air-conditioning and reduced consumption of natural gas for heating, the two main end uses that energy codes target. Finally, we consider the costs and benefits of the energy code change on a per residence basis. The costs consist of increased compliance costs, while the benefits consist of lower expenditures on utility bills and avoided social costs of air pollution emissions. We find that under the best-case scenario, the private payback period is 6.4 years, and the social payback period ranges between 3.5 and 5.3 years, depending on whether avoided damages from carbon dioxide are included.

In terms of related studies that explicitly evaluate the effect of energy codes, we are aware of only one that uses a research design similar to our first strategy. Horowitz and Haeri (1990) conducted a cross-sectional analysis of annual electricity consumption for electrically heated residences built before and after conservation standards for these homes were implemented in Tacoma, Washington. They find with a relatively small sample size that the standards are consistent with a 13.7% decrease in electricity consumption. In contrast to their study, we consider the effects of strengthening an existing code rather than implementing a new one, the former being the more policy-relevant question at a time when the majority of states have already implemented codes and are considering increasing their stringency. We also consider both electricity and natural gas consumption for all residences and not just electricity consumption for residences with electric heat. Finally, unlike Horowitz and Haeri (1990), we have monthly observations for repeated years, and this proves central to our second empirical strategy that allows us to control for residence fixed effects.

Two recent working papers also address questions about the effectiveness of building codes, though both employ methodologies that differ from the ones we use here. Arroonruengsawat, Auffhammer, and Sanstad (2009), using per capita electricity consumption in 48 U.S. states to investigate the impact of residential building codes, find decreases in per capita consumption between 3% and 5% in states that have adapted codes and experienced significant amounts of new construction. Costa and Kahn (2010) use household-level data in Sacramento, California, and find that after controlling for the price of electricity, decreases in consumption after 1983-vintage residences appear consistent with implementation of California's residential building codes. While both of these studies contribute much-needed evidence on the effectiveness of energy codes, our study makes a different contribution because we use microdata on both electricity and natural gas, make explicit comparisons to engineering simulations, and calculate private and social payback periods. The trade-off, of course, is potential concern about the external validity of a study based on one policy in one location. As we discuss, however, the usefulness of our results for making predictions about the effectiveness of codes in other areas is aided by the fact that most state building codes, including Florida's, are based on the same underlying structure, the International Energy Conservation Code (IECC). Moreover, Florida is representative of many states with respect to the stringency of its code, its level of enforcement and compliance, and the way changes in the stringency of its code typically follow changes to the IECC (American Council for an Energy-Efficient Economy, 2010).

The remainder of the paper is organized as follows. Section II describes the empirical setting of our study along with the methods of data collection. Section III reports the results of the main empirical analysis. Section IV provides estimates of the costs, benefits, and payback periods. Section V discusses the results and compares them to those of an engineering simulation model. Section VI concludes with a summary and remarks about the generalizability of our results.

II. Empirical Setting and Data Collection

Residential construction in Florida has been regulated under a statewide energy code since 1978. Like the energy codes in most other states, Florida's residential code sets a minimum energy-efficiency standard for space heating, space cooling, and water heating. The code is performance based, which means that the overall efficiency of a new home is considered rather than its specific design features. In effect, the energy code designates points for different design features of a residence based on how important they are considered for energy efficiency. In order to comply with the code, which is required to obtain a building permit, a newly constructed residence must receive a number of points for its design features that exceed the number based on the design features of a model home. While certain components of the newly constructed home can be less efficient than the model home, it is only the overall efficiency rating (i.e., its number of points) that matters. Specifications of the model home thus determine the overall stringency of the energy code, and these characteristics have changed over time in Florida.

This paper considers the effect of changes adopted by the Florida Building Commission for the 2001 Building Code that were implemented on March 1, 2002. At the time, three major changes were made to the energy code. First, for the central and south Florida climate regions, the baseline heating system was changed from electric strip resistance with a heating season performance factor (HSPF) of 3.4 to an electric heat pump with an HSPF of 6.8. The more stringent HSPF was already in place in the northern climate region. Second, the assumed air distribution system of the baseline home was changed from "leak free" to "leaky." This effectively relaxed one aspect of the code because homes determined to be leak free could now earn points for having an improved air duct system.[3] Third, the solar heat gain coefficient (SHGC), which is the amount of solar heat that passes through a window compared to how much strikes it on the outside, was reduced from 0.61 to 0.4. This change was the most substantial and expected to have a large impact for all three of Florida's climate regions.

These three major changes to the energy code were designed to bring the 2001 Florida Building Code into alignment with the IECC, which also provides the basis for residential energy codes in most other U.S. states (American Council for an Energy-Efficient Economy, 2010). Together, the changes to Florida's code led to a substantial increase in the stringency of Florida's regulation.[4] According to EnergyGauge (2002), the authorized code compliance software for Florida, the estimated increase in stringency was 4%, 15%, and 10% for the northern, central, and southern regions, respectively. These predicted changes in stringency, however, apply only to energy used for space heating, space cooling, and water heating.

We focus in this paper on how changes in the residential energy code translate into changes in actual energy consumption. In particular, we focus on the changes to Florida's energy code that applied in the northern climate region. We obtained residential utility data for households in the city of Gainesville, which is located in the northern part of the state. The data were downloaded from Gainesville-Green.com, a website designed to encourage energy conservation through provision of publicly available information on household energy consumption.[5] Included in the data set are monthly billing records for electricity and natural gas consumption for residential households. At the time we downloaded the data, Gainesville-Green included data only for residences with 12 months of electricity service in 2006 and the meter matching a single building on its parcel. While the complete set of monthly billing data spans 2000 through 2006, we use data only from 2004 through 2006, the period that includes residences built before and after the energy code change.[6] Also included in the data is detailed information on housing characteristics, including information on zip code, square footage, number of bathrooms, number of bedrooms, number of stories, air-conditioning, roof type, and effective year built.[7]

[3] "Leak free" in the Florida energy code is defined as air leakage less than 5% of the rated air handler flow at a pressure of 25 Pascal (0.1 inches water gauge). The energy credit for qualifying as leak free is substantial, ranging between 13% and 15% of heating and cooling energy.

[4] Smaller changes were also made to the code that might have an impact on compliance under certain circumstances: (1) energy credits for certain white roofing products, (2) a greater penalty for air-handler units located in attics, (3) updated multipliers for attic insulation, (4) inclusion of multipliers for interior radiation control coatings, and (5) credits for factory-sealed air handlers. Further details about all changes in Florida's 2001 energy code are available online, along with the official compliance software (EnergyGauge, 2002).

[5] Gainesville-Green.com is a cooperative effort among the City of Gainesville, Gainesville Regional Utilities, the University of Florida's Institute for Food and Agricultural Sciences, the International Carbon Bank and Exchange, and Acceleration.net. The first version of Gainesville Green appeared online in 2008.

[6] We also conduct analyses that incorporate the data for the years 2000 through 2003, though we do not report them here. But as will become clear, the earlier data add nothing to identification of the energy code effects, because post code-change residences were not constructed yet. Nevertheless, as might be expected, the results are robust to models that include the additional data.

[7] Not included in the data set are variables from which to identify changes in tenancy at each residence and an indicator of the residence's billing cycle, which determines the day in each month when a residence's electric meter is read. The fact that these variables are not included in the data set does not create problems for our empirical strategy.

The housing characteristic of primary interest is effective year built (EYB) because it enables us to determine when a residence was constructed and, in particular, whether it was subject to the energy code regime before or after the 2001 changes came into effect. EYB typically indicates the year when construction was completed (i.e., year of the final inspection), but it can also indicate the year when the last major remodeling occurred. In order to focus on residences for which EYB indicates the year when initial construction was completed, which we use to determine the corresponding energy code regime, we drop any residence in the data with a utility bill on record prior to its EYB, as this suggests EYB indicates a remodeling year.

Using EYB to categorize the remaining residences as being constructed pre- or postcode change, we must also take account of the fact that Florida's energy code is enforced when building permits are issued, not when final inspections take place. Evidence suggests that the average time between initial permitting and final inspection is about six months for residential construction (Bashford, Walsh, & Sawhney, 2005; Burk, 2008). We thus categorize residences as pre- or postcode change, which took effect in March 2002, as follows: EYB of 2001 or earlier designates a residence as precode change, EYB of 2003 or later designates a residence as postcode change, and EYB of 2002 designates a residence as indeterminate because the corresponding building code regime is unclear. We thus drop from the analysis, unless otherwise indicated, all residences with an EYB of 2002.[8] We also exclude from the analysis all residences with an EYB of 1998 or earlier. These observations are excluded for two reasons. First, Florida's energy code also changed in November 1997. This means that all residences with an EYB up to and including 1997, and some of the residences with an EYB of 1998 (because of the lag between permitting and final inspection), were subject to a different energy code regime than those with an EYB of 1999 through 2001.[9] Second, and more important, our empirical strategy is based on a comparison of residences built before and after the energy code change. The best comparison is based on residences built just before and just after the code change, as this minimizes the possibility that some unobservable time trend in housing construction will bias the analysis. The basic idea is that residences constructed at more similar points in time are likely to be more similar in terms of both their observed and unobservable characteristics.

A few more steps are necessary to clean and prepare the data. To address partial occupation of new construction, we exclude the first 12 months of utility billing data for new residences. The pattern of partial occupation for newly constructed homes is clearly seen in the data. For example, mean electricity use is 45% less in the first month than in the thirteenth month. While the pattern becomes less pronounced in subsequent months, until it levels off around month 8, we conservatively drop the first 12 months. One implication is the exclusion of all 47 residences with an EYB of 2006, and thus the newest residences in the data have an EYB of 2005. We also drop residences recorded as having less than one story, monthly electricity observations with a negative or zero quantity, and monthly natural gas observations with a negative quantity. These drops account for 3,130 observations, 256 observations, and 375 observations, respectively, or 5.8% of the complete data set, for a total of 64,471 observations.

Finally, we collect weather data from the National Climatic Data Center for the Gainesville area and merge these with the monthly utility data. We download daily weather data from a single weather station located at the Gainesville regional airport.[10] Two weather variables are of interest for our analysis: average heating degree days (AHDD) and average cooling degree days (ACDD). Using standard practice, the reference point for calculating degree days is 65°F. When average daily temperature falls below 65°F, the difference is the number of heating degrees in a day. When average daily temperature exceeds 65°F, the difference is the number of cooling degrees in a day.

We then merge the daily weather data with the monthly utility data. Because we do not know the billing cycle of each residence (i.e., the start and end date of each bill), we cannot match the daily weather data to the exact days of each utility bill. But we do know that the billing cycles across residences are uniformly distributed on business days throughout the month. Thus, in order to maximize the probability of overlap between daily weather and the associated billing days, we calculate averages for the weather data from the 15th to the 15th of adjacent months (or the 14th in the case of February). We then merge these averages with the monthly billing data when the meter was read to the later fifteen days over which the weather average was taken. For example, all utility bills that were read in June are

[8] While it is possible that some residences with an EYB of 2003 were also constructed under the precode regime, categorizing them as we do might be a concern only because of the potential for attenuation bias.

[9] Including residences with an EYB of 1998 or earlier would therefore require consideration of more than one change to the state's energy code. While in principle our empirical strategy would enable us to study Florida's 1997 code change, it is complicated by the fact that the change actually made the overall code less stringent. Moreover, it appears that Florida's building code was not well enforced during the 1990s. The Alachua County website reports, "during the early 1990's a series of natural disasters, together with the increasing complexity of building construction regulation in vastly changed markets precipitated the comprehensive review of the state building code system. The study revealed that building code adoption and enforcement was inconsistent throughout the state and those local codes thought to be the strongest proved inadequate when tested by major hurricane events. The consequences were devastation to lives and economies and a statewide property insurance crisis. The response was reform of the state building construction system, which placed emphasis on uniformity and accountability" (Alachua County, 2009). For this reason, and because we are interested primarily in the effect of increasing the stringency of energy codes (which is not likely to be symmetric with relaxing energy codes), this paper focuses on the 2001 code change alone.

[10] We use station number 083362 in the National Weather Service's Cooperative Station Network. This station is the closest one to our study area that was running continuously over the period for which we have utility data. The data can be downloaded at http://www.ncdc.noaa.gov/oa/climate/climateinventories.html.

Table 1.—Summary Statistics

Variable	Mean	S.D.	Minimum	Maximum
Electricity (kWh)	1,146.352	736.230	1	9,138
Natural gas (therms)	23.633	30.353	0	661
Effective year built (EYB)	2,000.931	1.895	1999	2005
Square feet	2,072.541	764.191	784	7,465
Bathrooms	2.279	0.574	1	6
Bedrooms	3.359	0.621	2	5
Stories	1.126	0.335	1	3
Central air-conditioning	0.997	0.058	0	1
Shingled roof	0.993	0.085	0	1
Billing year	2,005.130	0.807	2004	2006
Billing month	6.658	3.427	1	12
Average cooling degree days (ACDD)	7.648	6.588	0.000	17.581
Average heating degree days (AHDD)	3.208	4.055	0.000	11.813

Summary statistics are based on 64,471 observations.

Table 2.—Energy Consumption and Residential Characteristics of Residences Built before and after the Code Change

Variable	Before Code Change	After Code Change	Difference	*t*-statistic
Electricity (kWh)	1,149.851	1,104.998	−44.853	1.793
	(616.784)	(537.390)		
Natural gas (therms)	23.224	17.450	−5.774	7.977
	(16.436)	(17.554)		
Square feet	2,084.917	1,990.758	−94.159	2.939
	(785.889)	(694.664)		
Bathrooms	2.276	2.266	−0.010	0.404
	(0.577)	(0.537)		
Bedrooms	3.360	3.329	−0.032	1.202
	(0.628)	(0.597)		
Stories	1.132	1.104	−0.029	2.043
	(0.343)	(0.305)		
Central air-conditioning	0.998	0.993	−0.006	2.163
	(0.039)	(0.086)		
Shingled roof	0.995	0.990	−0.004	1.138
	(0.073)	(0.097)		

The data include 1,293 residences built before the code change and 946 residences built after the code change. Standard deviations are reported in parentheses.

matched with weather data averaged between May 15 and June 15 of the same year. Because the billing cycles are uniformly distributed, this procedure maximizes the number of weather data days that are likely to correspond with the days of each utility bill. In effect, the number of correctly corresponding days ranges from a minimum of 50% to a maximum of 100% for each monthly bill.[11]

The complete data set that we use for the analysis contains 2,239 residences among the 64,471 monthly observations. Table 1 reports basic summary statistics. Mean electricity consumption is 1,146 kilowatt-hours (kWh) per month. Mean natural gas consumption is approximately 24 therms per month. The average residence is 2,072 square feet in size, and it has 2.3 bathrooms, 3.4 bedrooms, and 1.1 stories. Nearly all residences have central air-conditioning and a shingled roof. The mean of ACDD is 7.6, the mean of AHDD is 3.2, and both of these numbers are the average degree-days per month averaged over all observations of the sample.

Among the residences, 1,293 were built before the energy code change, and 946 were built after the change. Table 2 compares the energy consumption and residential characteristics of residences built before and after the code change. Residences built after the code change use less electricity and less natural gas. While these differences are consistent with the energy code having resulted in an energy savings, regression analysis of the type we perform in the next section is necessary to control for observable characteristics of the residences and for the fact that not all residences are observed for the same number of months (e.g., postcode-change residences are more likely to be observed toward the end of the sample period). The other residential characteristics in table 2 are quite similar between groups, with the notable exception that those built after the energy code change are smaller by 94 square feet on average, or roughly 4.5%. The other housing characteristics with statistically significant differences are the number of stories and central air-conditioning, but the magnitudes of the differences are exceedingly small.

III. Empirical Analysis

The change in Florida's 2001 energy code combined with the Gainesville data on residential characteristics and utility

[11] In contrast, if we were to match monthly bills with weather data averaged from the first to the last day of each month, some bills would be matched with weather data that applied for only one day of the billing cycle. Despite the shortcoming of this approach, we did run models with weather matched accordingly, and it has no meaningful effect on the results that we present.

consumption provides an opportunity to examine the effect of energy codes on actual electricity and natural gas consumption. This section describes our empirical strategy and results. We first conduct pre- and postcode change comparisons to estimate annual and monthly differences in energy consumption between residences subject to the before-and-after energy code regimes. We then conduct a difference-in-differences analysis based on weather variability that tests whether the effect of the code is greater when demand for space heating and cooling is greatest. Because Florida's energy code regulates energy efficiency only related to space heating, space cooling, and water heating, we expect that the effect of the code, if it exists, will be greatest during months when the demand for heating and cooling makes up a relatively greater share of a household's energy demand. For electricity, we expect that the effect of the code change will be greatest in the summer months when electricity demand for air-conditioning is at its peak. For natural gas, we expect that the effect of the code change will be greatest in the winter months when demand for natural gas–based heating is at its peak.

A. *Pre- and Postcode Change Comparisons*

We begin the before-and-after comparisons with linear regression models of the form

$$Y_{it} = \delta CodeChange_i + \boldsymbol{\beta X}_i + \nu_t + \varepsilon_{it}, \tag{1}$$

where the dependent variable Y_{it} is either monthly electricity consumption (kWh) or monthly natural gas consumption (therms), depending on the model; i indexes residences; t indexes the month and year of the billing record; $CodeChange_i$ is an indicator variable for whether the residence was constructed after the energy code change; $\boldsymbol{X}_i$ is a vector of explanatory variables, including the natural log of the residence's square feet, indicator variables for central air-conditioning and shingled roofing, and dummy variables for the number of bathrooms, bedrooms, stories, and zip code (there are nine in the data set); ν_t is a month-year-specific intercept that controls for month-to-month effects common to all residences, such as weather fluctuations or changes in the price of electricity or natural gas; and ε_{it} is a normally distributed error term. The estimate of δ is of primary interest, as it captures the average difference in either electricity or natural gas consumption between households built before and after the energy code change. An estimate of δ less than 0 would, for example, be consistent with the energy code change causing a decrease in energy consumption.

We estimate the parameters of specification (1) using ordinary least squares (OLS). To account for potential serial correlation of the error terms, we report standard errors that are clustered at the residence level. We also test for robustness with alternative specifications. In a more flexible specification, we allow the month-year effects to differ by each zip code, which we accomplish by interacting ν_t with each of the zip code dummies. We also estimate log-linear specifications of the model—and all other models discussed throughout the paper—but do not report the results for several reasons other than brevity. First, the qualitative results are very similar to the estimates that we do report based on levels. Second, the log-linear specifications tend not to fit the data as well in many cases. Finally, the estimate of δ in a log-linear specification cannot be precisely extrapolated to an overall annual effect because of the nonlinearity and the fact that consumption differs substantially between months of the year.[12]

Table 3 reports the estimates of specification (1) for electricity and natural gas (columns 1 and 3), along with the additional specifications that allow the time effects to differ by each zip code (columns 2 and 4). Focusing first on the electricity results, we find that the models fit the data well, explaining roughly 50% of the variation in residential electricity consumption. The coefficient estimates are very similar between the two specifications—one with a single set of month-year dummies and one with zip-code-by-month-year dummies. Based on the two models, we find, after controlling for observables, that households built after the energy code change consume approximately 48 kWh per month less than households built before the change, and the result is statistically significant at the 95% level. In terms of a percentage difference, the estimates suggest that the energy code changes result in a 4% decrease in residential electricity consumption. Not surprisingly, we also find that larger residences consume more electricity, and the result is statistically significant. In particular, the coefficient estimates are interpreted such that, for example, a 10% increase in the square footage of a residence is associated with an increase of 96 kWh, or an increase of 8.3% in monthly electricity consumption.

The qualitative pattern of results is very similar for natural gas. The models fit the data reasonably well, and the coefficient estimates are very stable between specifications. The coefficient estimates on the effect of the energy code change are again negative and statistically significant at the 95% level. We find that residences constructed after the code change consume approximately 1.5 therms per month less, which translates into a 6.4% reduction in the consumption of natural gas. Larger residences also consume more natural gas, whereby a 10% increase in square footage is associated with an increase of 2.9 therms per month, or a 1.2% increase in natural gas consumption. We also find

[12] The results of alternative specifications are available on request. In particular, we estimated models with various polynomial specifications for the square footage of a residence and nonparametric specifications in which square footage is binned into categories. In all cases, the estimated effect of the energy code change is very similar. We also evaluated whether the effectiveness of the code varied with the size of the residence. In particular, we reestimated specification (1) with the inclusion of an interaction of *CodeChange* and *ln(squarefeet)*. The coefficient on the interaction term was small in magnitude and statistically insignificant for both electricity and natural gas.

Table 3.—Comparisons of Pre- and Postcode-Change for Electricity and Natural Gas Consumption

	Electricity (mean = 1,146.4 kWh)		Natural Gas (mean = 23.6 therms)	
	(1)	(2)	(3)	(4)
Code Change	−47.617**	−48.922**	−1.446**	−1.572**
	(20.140)	(20.295)	(0.701)	(0.704)
ln(Square feet)	958.940***	961.065***	29.779***	29.846***
	(54.670)	(54.928)	(1.880)	(1.874)
Central air-conditioning	−79.674	−80.463	−2.509*	−2.362*
	(142.365)	(143.622)	(1.282)	(1.408)
Shingled roof	165.682	164.447	6.946*	7.196*
	(115.582)	(115.827)	(3.876)	(3.887)
Bathroom dummies	Yes	Yes	Yes	Yes
Bedroom dummies	Yes	Yes	Yes	Yes
Stories dummies	Yes	Yes	Yes	Yes
Zip code dummies	Yes	Yes	Yes	Yes
Month-year dummies	Yes	Yes	Yes	Yes
Zip code × month-year dummies	No	Yes	No	Yes
R^2 (unadjusted)	0.499	0.514	0.452	0.481
Observations	64,471	64,471	64,471	64,471

Standard errors are reported in parentheses and are clustered at the residence level. One, two, and three asterisks indicate significance at the $p < 0.10$, $p < 0.05$, and $p < 0.01$ level, respectively.

some evidence that central air-conditioning and a shingled roof affect natural gas consumption, but the statistical significance of the results is weaker, and perhaps questionable, as identification comes from exceedingly few observations.

While the models presented in table 3 provide an estimate of the code change effects averaged across all months, the effects may differ in important ways among months of the year. Weather varies throughout the year and substantially affects demand for cooling and heating, which are known to have a large influence on demand for electricity and natural gas, respectively. We thus estimate expanded versions of specification (1) for electricity and natural gas as follows:

$$Y_{it} = \boldsymbol{\delta} \boldsymbol{CodeChange}_i \times \boldsymbol{Month}_t + \boldsymbol{\beta} \boldsymbol{X}_i + \nu_t + \varepsilon_{it}, \qquad (2)$$

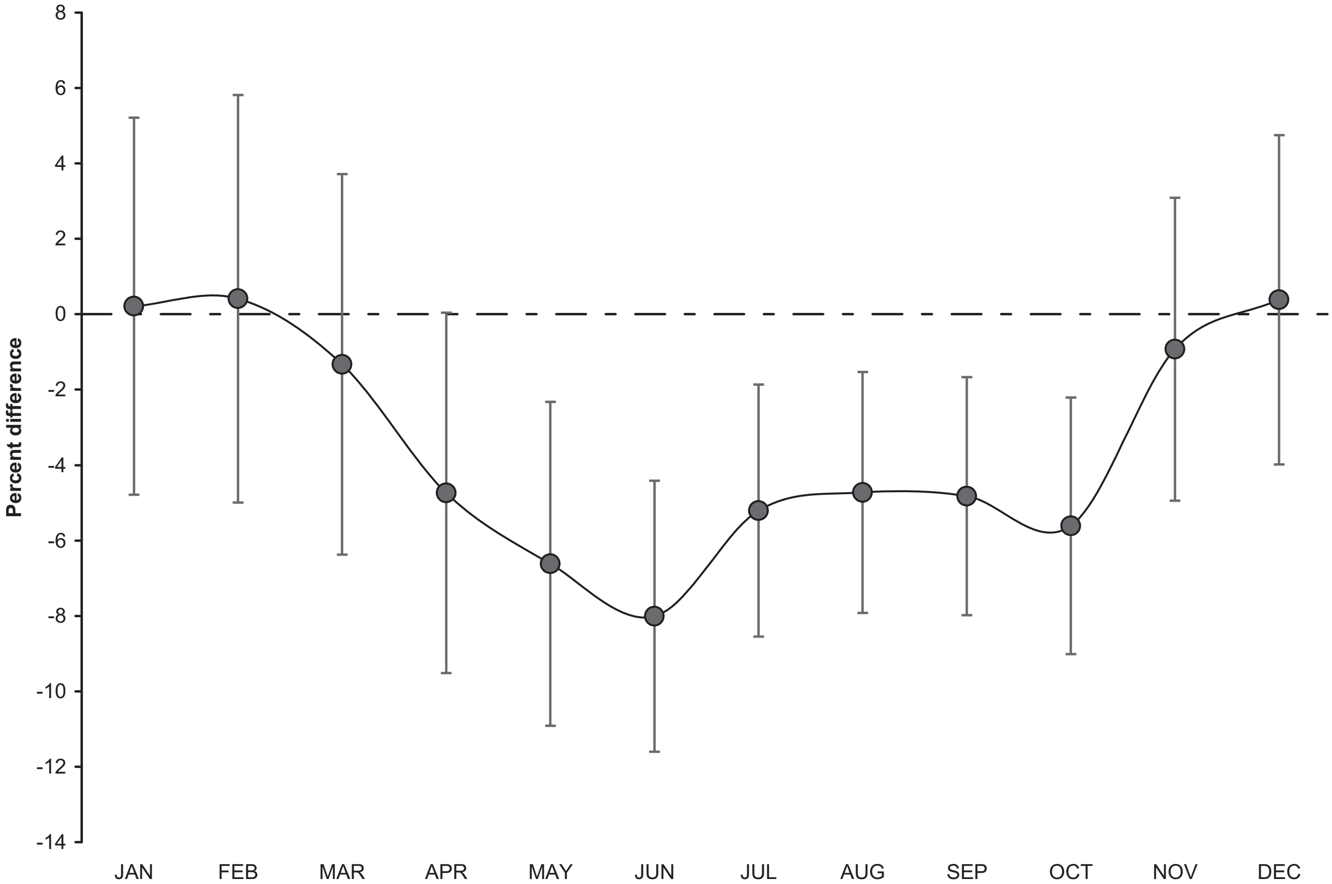
where $\boldsymbol{Month}_t$ is a vector of dummy variables for each of the 12 months in the calendar year. The only difference is that we now estimate the code change effect separately for each month of the year. We estimate models based on specification (2) in the same way: OLS, standard errors clustered at the residence level, uniform time effects, and zip code–specific time effects.

For simplicity and brevity, however, we summarize the main findings with two figures. We take the coefficients of interest in the basic specification (2)—the δ for each month of the year—and report it as the percentage change from average consumption for that particular month. Figure 1 illustrates the electricity results for the average monthly effects along with the 95% confidence intervals. The overall pattern is clear: compared to residences built before the energy code change, those built after consume roughly the same amount of electricity during the colder months but substantially less during the warmer months. Between April and October, all of the point estimates are statistically different from 0 and range between 4% and 8% percent less electricity. The obvious explanation for these results is the impact of energy codes on the efficiency of air-conditioning, which is used during the warmer months of the year. Nearly all households in Gainesville have central air-conditioning, and throughout the South Atlantic region of the United States, air-conditioning accounts for 21% of residential electricity consumption (Energy Information Administration, 2006). Holding other things constant, therefore, changes in the energy code that improve the cooling efficiency of residences would be expected to cause electricity savings during the warmer, and not necessarily the colder, months of the year. The results in figure 1 are consistent with this expectation.

The overall pattern of results for natural gas is nearly the exact opposite, as shown in figure 2. Compared to those built before the energy code change, residences built after consume less during the colder months—December, January, February—when the statistically significant point estimates range between 15% and 25%. But differences between the groups are not statistically significant for any of the other months during the warmer times of year. In this case, the candidate explanation is the impact of energy codes on the efficiency of heating. While the majority of residences in Florida use electric space heating, 26.8% of Gainesville residences heat with natural gas (American Community Survey, 2010), meaning that a substantial portion of natural gas consumption in Gainesville is for heat in the winter. It follows that due to the energy code change, improved energy efficiency with respect to heating would be expected to reduce natural gas consumption during the winter months.

Our analysis thus far builds a case that changes to Florida's energy code have resulted in reduced consumption of both electricity and natural gas. The empirical strategy is based on a comparison of monthly consumption in the years after the code change between residences built within three years before and three years after the code change went into effect. Specification of the empirical models seeks to account for observable characteristics that help explain variation in energy consumption, including square footage, central air-conditioning, shingled roof, and number of bed-

FIGURE 1.—PERCENTAGE DIFFERENCE IN ELECTRICITY CONSUMPTION BETWEEN RESIDENCES CONSTRUCTED BEFORE AND AFTER THE ENERGY CODE CHANGE, BY MONTH



rooms, bathrooms, and stories. Moreover, the inclusion of zip code dummies accounts for unobserved heterogeneity that is common among all residences within the same zip code. A potential limitation of the identification strategy, however, could be the existence of other reasons for a downward trend in residential energy consumption across years of construction that, in our analysis, is falsely attributed to the energy code change. To partially address this potential concern, we have chosen to use residences built within only a few years (before and after) of the energy code change. We have also estimated models with both uniform and zip code–specific time effects. Although the estimates are very similar in both cases, the latter is a useful robustness check because it accounts for spatial differences in time trends that might be correlated with areas of predominantly newer or older construction.

To further address the potential concern about a downward trend in energy consumption not due to the code change, we estimate differences in consumption for each effective year built while controlling for the other observable characteristics. Specifically, we estimate models of the form

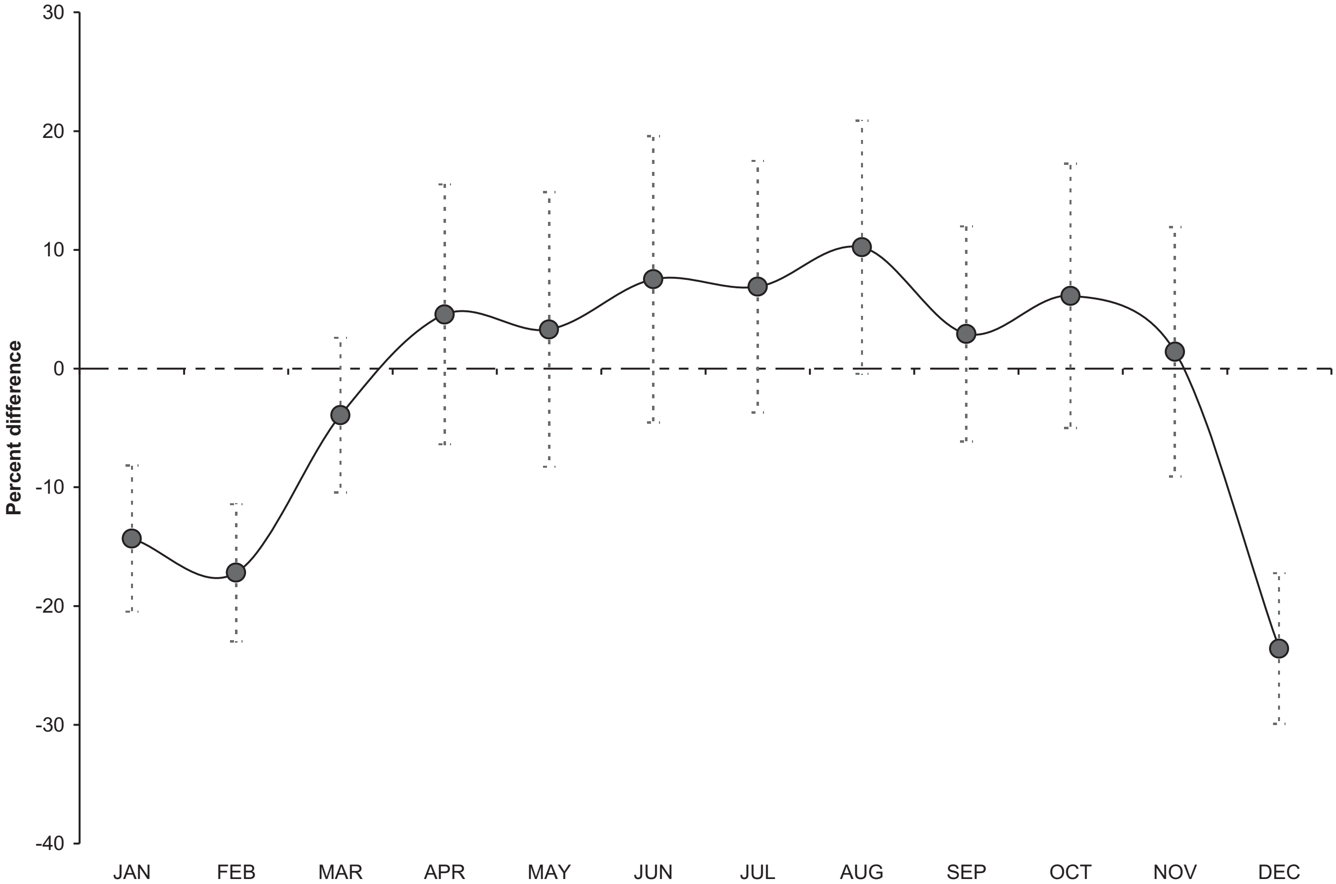
$$Y_{it} = \boldsymbol{\theta}\boldsymbol{EYB}_i + \boldsymbol{\beta}\boldsymbol{X}_i + \nu_t + \varepsilon_{it}, \tag{3}$$

where $\boldsymbol{EYB}_i$ is a categorical variable for the effective year built for each residence. The vector of coefficients $\boldsymbol{\theta}$ provides estimates of the average difference in energy consumption (either electricity or natural gas) for the different years of EYB. When estimating specification (3), we include residences with an EYB of 2002 and use them as the omitted category. Recall that these residences were excluded from the previous models because the lag between building permit issuances and final inspections made it uncertain as to whether they were subject to the before-or-after energy-code change regime. But in terms of exploring a potential time trend independent of the code change, there is no reason to exclude these observations.

Figures 3 and 4 illustrate the coefficients of interest for electricity and natural gas, along with 95% confidence intervals based on clustering at the residence level.[13] Figure 3 shows no clear downward trend in electricity consumption based on the EYB from 1999 to 2005. Moreover, although the estimates for before the code change appear higher than the postcode change estimates, none of the point estimates for any EYB on its own is statistically distinguishable from any other. Turning to figure 4, there does appear to be somewhat of a downward trend in natural gas

[13] As with all other models, we also estimate specification (3) with zip code–specific time effects and a log-linear functional form. We do not report these results in the main text because they follow patterns very similar to those shown in figures 3 and 4.

FIGURE 2.—PERCENTAGE DIFFERENCE IN NATURAL GAS CONSUMPTION BETWEEN RESIDENCES CONSTRUCTED BEFORE AND AFTER THE ENERGY CODE CHANGE, BY MONTH



consumption for EYBs before and after the energy code change, but consumption increases rather than decreases for residences constructed immediately after the change. Just as we find for electricity, however, each of the point estimates shown in figure 4 is not statistically distinguishable from any other. Based on these results—for both electricity and natural gas—we conclude that our estimates of the energy code change on residential energy consumption are not simply capturing an unobserved time trend. Instead, the comparisons for before and after the code change appear to be capturing how the more stringent energy code causes a real decrease in residential electricity and natural gas consumption.[14]

B. *Difference-in-Differences*

We now use a different empirical strategy to investigate the effect of Florida's energy code change on residential energy consumption. In particular, we focus on how weather variability—the primary driver of fluctuations in residential energy consumption—may differentially affect pre- and postcode change residences. Figure 5 illustrates the variability in the primary weather variables—average cooling degree days (ACDD) and average heating degree days (AHDD)—by month-year from 2004 through 2006. The basic pattern, as one might expect, is that ACDD peaks in the summer and comes close to 0 in the winter, while AHDD is 0 during the summer months and peaks during the winter.

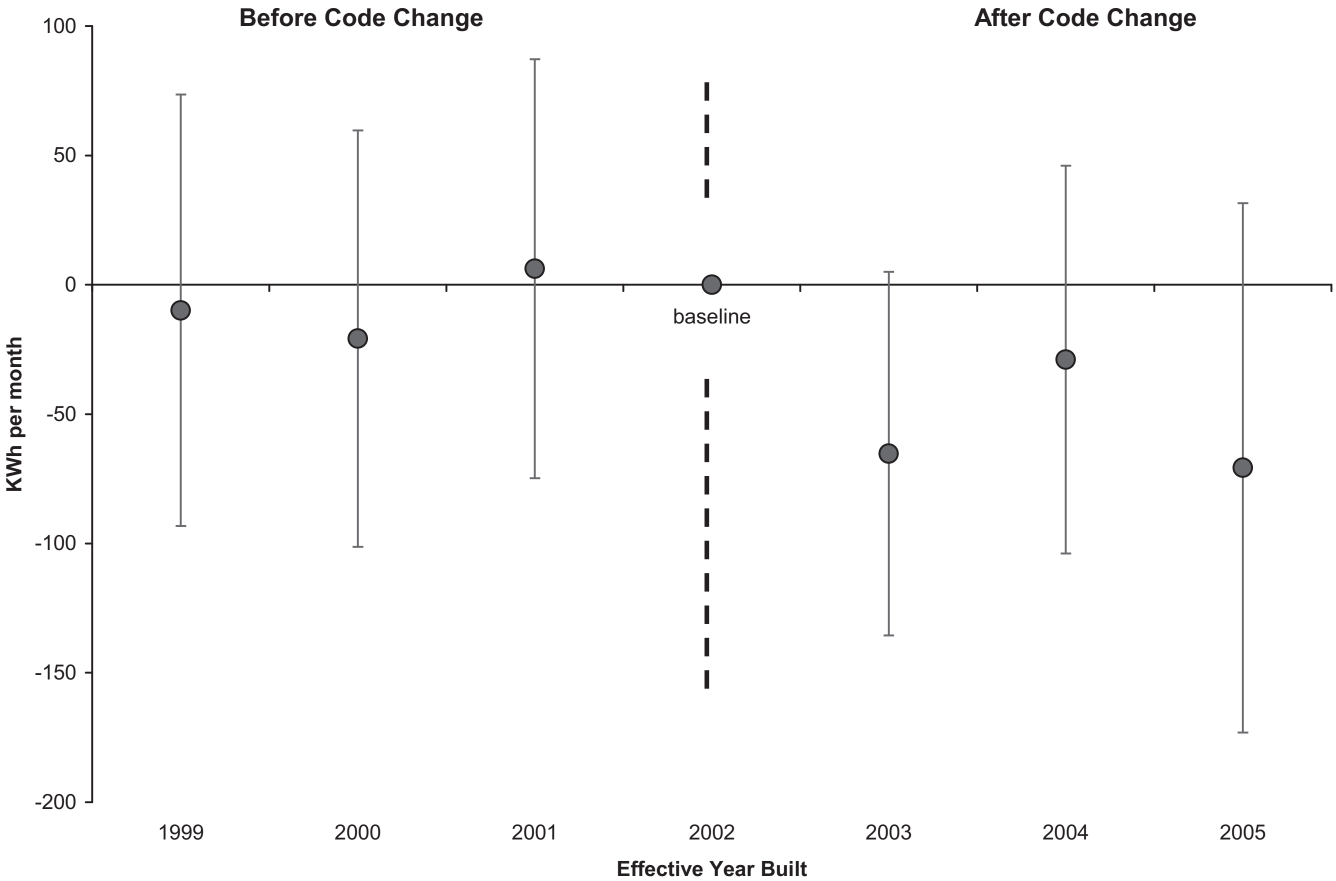
As discussed previously, we combine these weather data with the billing data on electricity and natural gas. With the combined data set, we estimate models for both electricity and natural gas of the form

$$\begin{aligned} Y_{it} = \boldsymbol{\beta}[ACDD_t, AHDD_t] + \boldsymbol{\delta CodeChange}_i \\ \times [ACDD_t, AHDD_t] + Month_t \\ + Year_t + \mu_i + \varepsilon_{it}, \end{aligned} \tag{4}$$

where the indicator variable for whether the residence was constructed after the energy code change is interacted with each of the weather variables; $Month_t$ are month dummies, $Year_t$ are year dummies, and μ_i is a residence-specific intercept. For purposes of comparison, we also estimate a similar specification in which the weather variables themselves,

[14] Beyond the empirically based robustness checks that we report, we also looked into other policy changes or utility programs that might otherwise affect residential energy consumption during the time of our study. We found no evidence of policies or programs of sufficient scale to explain the results that we attribute to the energy code change.

FIGURE 3.—DIFFERENCES IN MEAN ELECTRICITY CONSUMPTION BY EFFECTIVE YEAR BUILT BASED ON SPECIFICATION (3)



which come from a single weather station and are aggregated at the monthly level, are absorbed in month-year dummies:

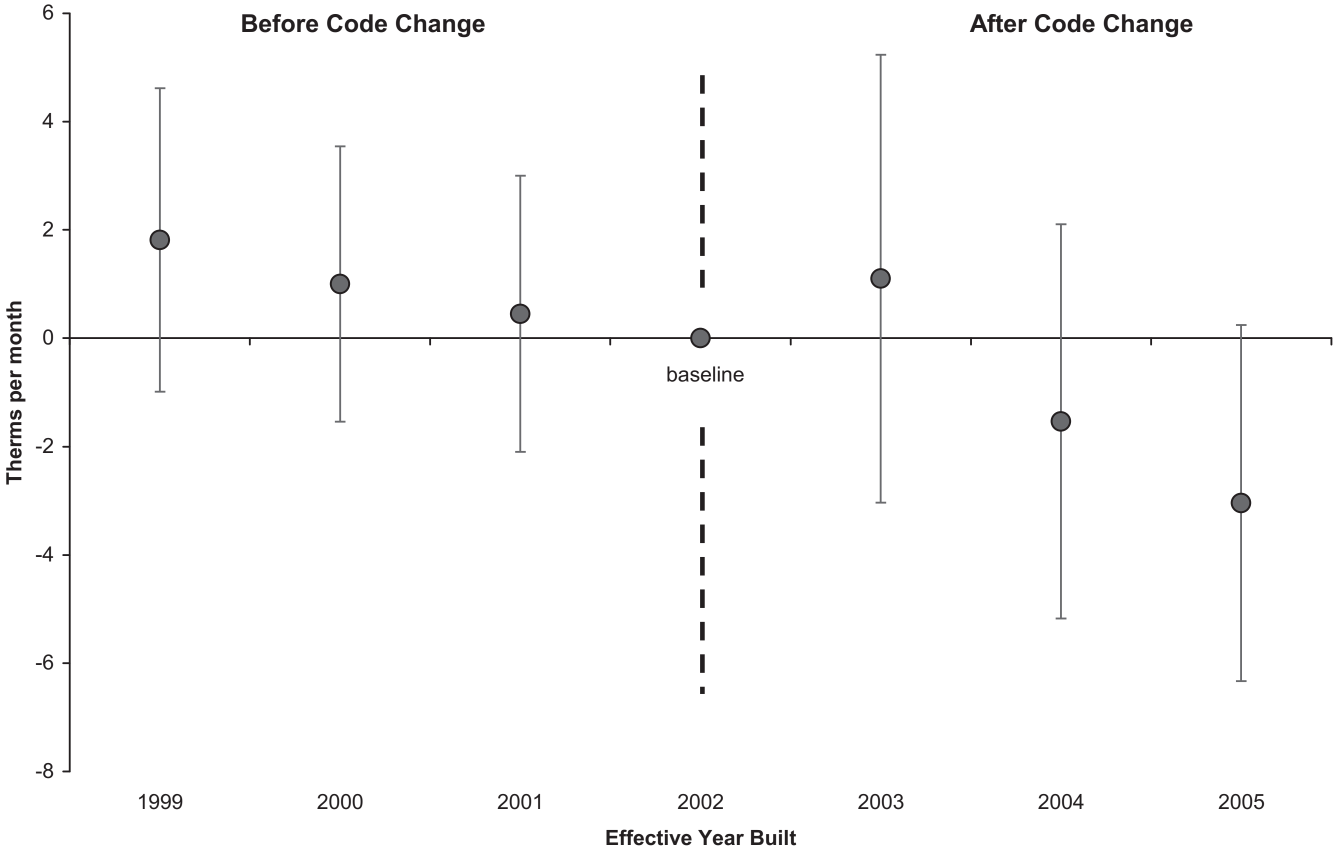
$$Y_{it} = \boldsymbol{\delta CodeChange}_i \times [ACDD_t, AHDD_t]\nu_t + \varepsilon_{it}. \quad (5)$$

We estimate equations (4) and (5) with the fixed-effects estimator and cluster standard errors at the residence level. A key feature of both specifications is the residence-specific intercept (i.e., the fixed effect). This controls for any unobserved, time-invariant heterogeneity among residences. If, for example, there is an unobserved trend in average energy consumption based on EYB, as was a potential concern with our previous estimates, then the fixed effect accounts for the trend with residence-specific intercepts.

The coefficients of interest, the δs on the interactions with ACDD and AHDD, are essentially difference-in-differences estimates of how residences before and after the energy code change differ in their energy consumption responses to changes in weather. If the energy code changes do in fact have an effect, we would expect the before and after residences to differ in their responses given that the code changes were designed to improve energy efficiency and that variability in weather is known to be the primary determinant of changes in residential demand for space heating and cooling, the primary end uses targeted by residential energy codes. Based on both intuition and the results of the monthly before-and-after comparisons, we have strong priors about one of the coefficients in both the electricity and natural gas estimates of specifications (4) and (5). With respect to electricity, if the energy code changes are having the intended effect, we would expect residences constructed after the code change to be less responsive to increases in ACDD. This follows because air-conditioning, which is used more intensely with more ACDD, would be more efficient in the after-code-change residences. With respect to natural gas, we would expect after-code-change residences to be less responsive to increases in AHDD. This follows because natural gas–based heating, which is used more intensely with more AHDD, would be more efficient in the after-code-change residences.

The first two columns of table 4 report the electricity estimates of specifications (4) and (5). Focusing first on the uninteracted weather variables in column 1, which apply to the before-code-change residences, we find that the coefficients have the expected signs. Electricity consumption is increasing in ACDD and AHDD, and these results are all consistent with electricity being the primary energy source for cooling and heating Florida residences. Based on the interaction with *CodeChange,* we find that the electricity consumption of postcode-change residences is less responsive to an increase in ACDD. In particular, the marginal

FIGURE 4.—DIFFERENCES IN MEAN NATURAL GAS CONSUMPTION BY EFFECTIVE YEAR BUILT BASED ON SPECIFICATION (3)



effect of a 1-unit increase in ACDD is 2.5 kWh per month smaller for postcode-change residences, which is a 7.8% decrease in responsiveness to ACDD relative to the response of precode-change residences, which was 32.25 kWh per month. Hence, consistent with our previous monthly results, the increase in the stringency of the energy code appears to have improved residential air-conditioning efficiency. In contrast, the estimated effect with respect to electricity and AHDD suggests that the after-code-change residences are less efficient with respect to electric heating. However, increased response to AHDD is less important because heating degree days are far less frequent in Florida, as shown in figure 5. Overall, the estimates indicate that the electricity consumption of postcode-change residences is less responsive to weather-induced demand shocks than is the consumption of the precode-change residences. The results for specification (5) are similar, though the magnitudes of the differences between pre- and postcode-change residences are even larger.

Turning now to the natural gas results, we find again that the uninteracted weather variables in column 3 have the expected signs. The largest source of variability in natural gas consumption would be due to its use in heating, which explains why consumption is increasing in AHDD and decreasing in ACDD. Based on the interactions with *Code-Change,* the results suggest that postcode-change residences are more efficient with respect to natural gas consumption for heating. When an increase in AHDD causes an increase in natural gas consumption for precode-change residences, the effect is less so for postcode-change residences. In particular, the marginal effect differs by 1.3 therms per month, which is substantial: 58%. When a decrease in ACDD causes an increase in natural gas consumption for precode-change residences, which is likely due to more demand for heating, the increase is more so for postcode-change residences. In this case, the marginal effect differs by 0.1 therms per month, which is roughly 43%. However, this effect is outweighed by the response to AHDD, because natural gas consumption is much more responsive to one additional heating degree day than to one less cooling degree day, as reflected in the magnitude of the point estimates. Overall, the estimates indicate that the natural gas consumption of postcode-change residences is less responsive to weather-induced demand than is the consumption of the precode-change residences. These results are also robust to specification (5), where the coefficient estimates on the interaction terms of interest are very similar.

IV. Costs and Benefits

We now consider the costs and benefits of the increased stringency of Florida's residential energy code. Our calcula-

FIGURE 5.—VARIABILITY OF WEATHER VARIABLES BY MONTH AND YEAR, 2004–2006

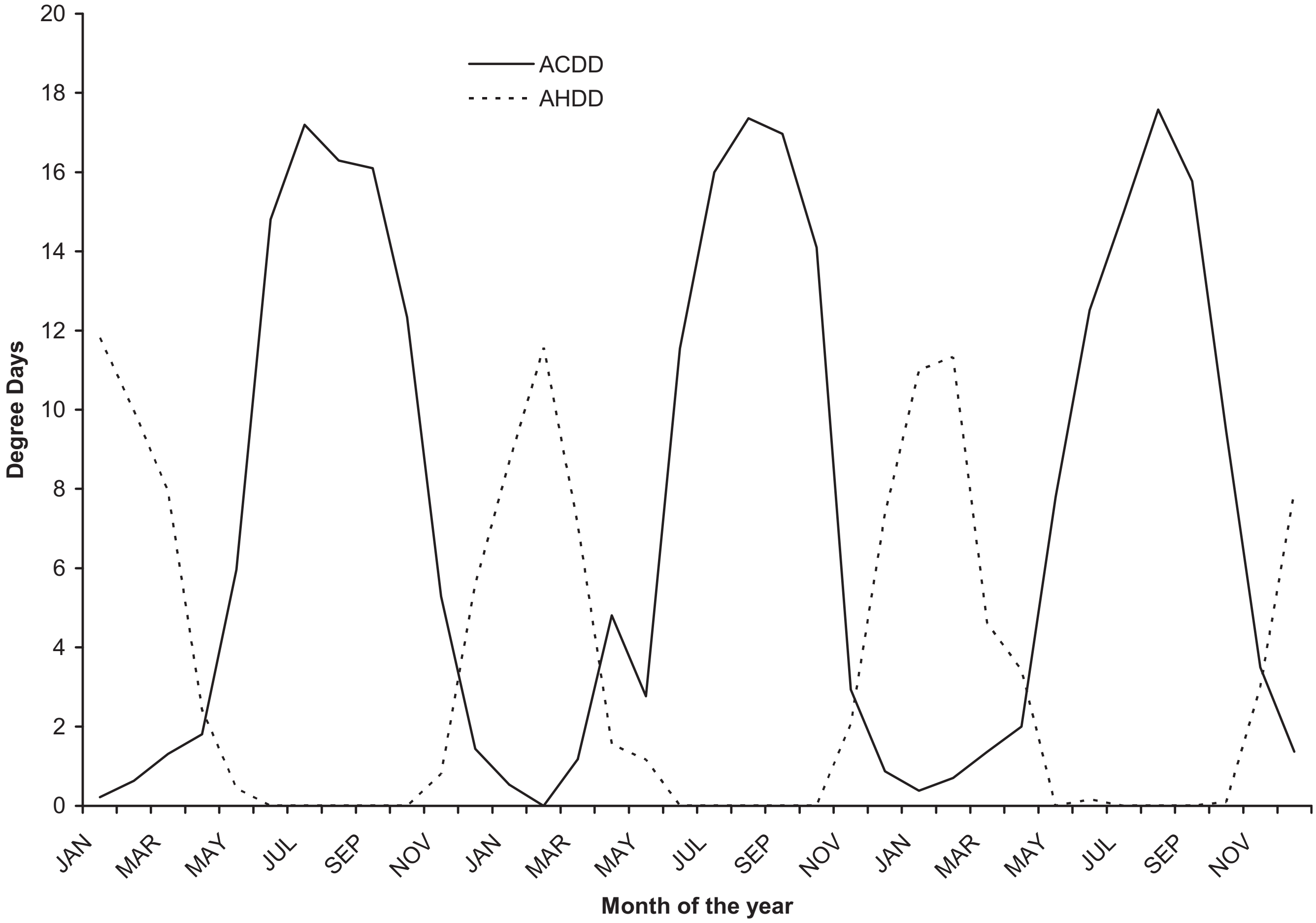


TABLE 4.—DIFFERENCE-IN-DIFFERENCES ESTIMATES FOR ELECTRICITY AND NATURAL GAS CONSUMPTION DUE TO WEATHER VARIABILITY

Dependent Variable	Electricity		Natural Gas	
	(1)	(2)	(3)	(4)
Code Change × ACDD	−2.498**	−3.500***	−0.172***	−0.161***
	(1.187)	(1.223)	(0.051)	(0.053)
Code Change × AHDD	2.446**	3.519**	−1.372***	−1.164***
	(1.377)	(1.379)	(0.154)	(0.155)
ACDD	32.250***	–	−0.268***	–
	(0.961)	–	(0.044)	–
AHDD	6.362***	–	2.326***	–
	(1.287)	–	(0.111)	–
Month dummies	Yes	No	Yes	No
Year dummies	Yes	No	Yes	No
Month-year dummies	No	Yes	No	Yes
Residence fixed-effects	Yes	Yes	Yes	Yes
R^2 (within)	0.522	0.533	0.456	0.462
Observations	64,471	64,471	64,471	64,471

Standard errors are reported in parentheses and are clustered at the residence level. One, two, and three asterisks indicate significance at the $p < 0.10$, $p < 0.05$, and $p < 0.01$ level, respectively.

tions apply directly to the study area of Gainesville. We compare costs and benefits at the level of a single residence. The costs consist of increased compliance costs with the more stringent code, while the benefits consist of lower expenditures on utility bills and avoided social costs of air pollution emissions.

Estimating the increased compliance costs is not straightforward because the policy is a whole-building, performance-based code that does not require specific features of new construction; instead, what matters is the overall efficiency of a residence compared to the baseline home. As explained in section II, the major change to the baseline home that applies in the northern climate region is the reduction in the solar heat gain coefficient (SHGC) on windows from 0.61 to 0.4. For simplicity, we assume that builders meet the new code standard by making the same

Table 5.—Social Benefits of Avoided Emissions from Reduced Electricity and Natural Gas Consumption

	Electricity		Natural Gas		Combined	
	Low $	High $	Low $	High $	Low $	High $
Carbon dioxide	4.37	53.12	0.83	10.12	5.21	63.24
Sulfur dioxide	7.90	19.65	0.00	0.01	7.90	19.66
Nitrous oxide	0.75	1.17	0.09	0.23	0.84	1.40
Particulates	0.20	0.53	0.00	0.01	0.21	0.54
Total	**13.23**	**74.47**	**0.92**	**10.37**	**14.15**	**84.84**

Benefits are reported in 2009 dollars. Methods of derivation and explanations of low and high scenarios are in the main text.

change as that made to the baseline home.[15] In practice, reducing the SHGC on residential windows requires purchasing windows with a low-emissivity (low-E) coating. Windows with a low-E coating typically cost between 10% and 15% more than regular windows (U.S. Department of Energy, 2009b). Following the assumptions of Fairey and Sonne (2007), we assume that a standard Florida home has 400 square feet of windows, which is equivalent to approximately 27 double-hung 60 $\times$ 30-inch windows. Assuming a standard window costs \$250, supplying a house with low-E windows would add between \$675 and \$1,012 to overall construction costs.[16]

To compare against the higher construction costs are the benefits of lower utility bills for both electricity and natural gas. Referring back to table 3, our estimates of the monthly energy savings are approximately 48 kWh and 1.5 therms for electricity and natural gas, respectively. This implies an average annual savings of 576 kWh and 18 therms. Based on GRU's block rate pricing in 2009 and the distribution of monthly consumption levels observed in the data, the average marginal price that Gainesville Regional Utilities (GRU) currently charges consumers is 14.6¢ per kWh, which consists of an 8.6¢ average energy charge plus a 6¢ fuel adjustment charge. These numbers imply that the average household built under the stricter code regime saves \$84.10 per year on its electricity bill. The marginal price of an additional therm of gas is \$1.22, consisting of a 48.3¢ energy charge, a 3.7¢ plant cost recovery fee, and a 70¢ purchased cost adjustment charge. Hence the combined estimated savings on electricity and natural gas utility bills is approximately \$106 per year. It follows that even under the very best-case scenario—a 10% premium for low-E windows and a 0 discount rate—the private payback period is roughly 6.4 years. For purposes of comparison, the average residential ownership tenure in 2006 was approximately 11.5 years in Florida (Stansel, Jackson, & Finch, 2009).

From a social perspective, there are also benefits associated with a reduction in air pollution emissions. We estimate these benefits using a standard benefits-transfer approach for four categories of emissions: carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrous oxide (NO_x), and particulates (PM2.5). With respect to electricity, we calculate emission rates for CO_2, SO_2, and NO_x for GRU using the U.S. Environmental Protection Agency (EPA) eGRIDweb software.[17] Because eGRIDweb does not provide emission rates for PM2.5, we obtain the estimate from Conners et al. (2005), which is a 2002 estimate that applies to Florida more generally.[18] With these emission rates in hand, we calculate the change in emissions using our estimates in table 3 for the reduction in electricity demand. We multiply the estimate of 48 kWh per month by 12 and the emission rate for each pollutant to estimate the annual change in emissions. Finally, we use marginal damage estimates for each of the pollutants to monetize the benefits of avoided damages. For SO_2, NO_x, and PM2.5 emissions, we use high and low estimates specifically for Alachua County, Florida, based on Muller and Mendelsohn's (2007) Air Pollution Emission Experiments and Policy (APEEP) analysis model.[19] For CO_2 emissions, we use low and high estimates of the social cost of carbon from Stern (2007) and Nordhaus (2008), respectively. The results for avoided damages from the reduction in electricity consumption, which range between approximately \$13 and \$74 per residence per year, are reported in the first two columns of table 5.

With respect to natural gas, our estimates in table 3 for the reduction in consumption due to the energy code change are very close to 1.5 therms per month, or 18 therms per year. To monetize the avoided damages for SO_2, NO_x, and PM2.5 emissions, we rely on recent estimates by region for

[15] This approach is the most tractable way to conduct the cost-benefit analysis, but it may lead to an overestimate of the compliance costs, as builders are able to exploit the flexibility of the code to comply with the change at a lower cost. Additionally, if builders tended to overcomply with the initial energy code and only a subset of builders had to take on additional costs to meet the new code, our approach would provide an overestimate of the compliance costs.

[16] As a point of comparison, the least expensive double-hung window on the website of the popular window maker Andersen Corporation is priced at \$271.

[17] The software is available at http://cfpub.epa.gov/egridweb/. Rates are based on the location (operator)-based level of data aggregation for the most recent year of 2005 configured for industry structure through 2007.

[18] The estimate of Conners et al. (2005) is calculated by matching plant-level data on emission totals from the U.S. EPA's National Emissions Inventory database to plant-level data on heat rates from eGrid. We then use this relationship to estimate the average emissions rate for PM2.5 for the entire Florida Reliability Coordinating Council (FRCC) region.

[19] Because sulfer dioxide is regulated under a national cap, one might argue that the emission reductions in Gainesville will be offset by an increase in emissions elsewhere, and the appropriate measure of the benefits is the permit price, which represents the avoided marginal abatement costs. Here, however, the scope of our analysis is Gainesville, and we consider the avoided damages to be the benefits of emission reductions in the region.

the marginal damages of residential natural gas use for heat (National Research Council, 2009). Within the south region of the United States, we use the 25th and 75th percentile estimates of the marginal damages for low and high cases, respectively. For CO_2 emissions, we use NRC's (2009) estimate that burning 1 therm of natural gas generates 0.006 tons of CO_2 combined with the low and high marginal damages described above. The results for avoided damages from the reduction in natural gas consumption are reported in the middle columns of table 5, and considering all four pollutants, the low and high estimates are approximately $1 and $10 per residence per year.

The last two columns of table 5 report the combined avoided social damages for the reductions in both electricity and natural gas consumption. While the overall estimates range between $14 and $85 per residence per year, reductions of CO_2 and SO_2 account for the vast majority of benefits. Under the best-case scenario described above, along with the high estimates for avoided emission damages, the social payback period reduces to about 3.5 years. Nevertheless, one might argue that the benefits associated with lower CO_2 emissions should not be considered in such cost-benefit calculations, as they are likely to occur for the most part outside the policy jurisdiction. Adjusting the payback period to exclude the CO_2 benefits, we find that the best possible social payback period is 5.3 years.

V. Discussion

We are not aware of any other study that uses residential billing data to evaluate the effect of increasing energy code stringency on both electricity and natural gas consumption. Perhaps the reason is that such studies face significant challenges. Among them is the need to find an appropriate set of "control" residences against which to compare "treatment" residences. One option, the standard difference-in-differences approach, is to use residences from a neighboring area that were not subject to the same energy code change and estimate how the before and after energy consumption differs between the two groups. The general concern with this approach, however, is that time trends in important observable and unobservable variables may differ between the two groups for reasons unrelated to the treatment, leaving models susceptible to bias. Another concern, more specific to energy codes, is that nearby treatment and control areas may not be entirely independent. For example, Horowitz (2007) analyzes the effect of state commitments to energy-efficiency programs on residential electricity consumption and finds evidence that spillovers from the programs are rapid and ubiquitous. Hence, energy codes that change construction patterns in one area are likely to produce spillover effects on construction patterns in nearby areas.

This paper estimates the effect of an energy code change based on comparisons between residences in the same area constructed within three years before and three years after the code change, comprising the control and treatment groups, respectively. Using only monthly utility bills for the years after the code change, we employ two empirical strategies for both electricity and natural gas: comparisons of mean energy consumption and differences in the responsiveness of energy consumption to variability in weather. The first approach produces our main results, which are that the energy code change appears to have caused a 4% decrease in annual electricity consumption and a 6% decrease in annual natural gas consumption. Moreover, differences in the savings by month are consistent with reduced consumption of electricity for air-conditioning and reduced consumption of natural gas for heating. The key identification assumptions, however, are that we appropriately control for the observable characteristics of each residence and that no unobservable characteristics differ between the pre- and postcode-change residences in ways that significantly affect energy consumption.

The primary advantage of our second empirical strategy is that we are able to control for unobservable, time-invariant heterogeneity among residences and still test for differences between those constructed before and after the code change. Specifically, the fixed-effects models account for average differences in consumption among residences and test for differences in the response to weather variability, the main driver of fluctuations in energy demand. One interpretation of these models is as a robustness check against the other estimates of monthly differences explained by energy demand due to heating and cooling. If the energy code change increases efficiency, then consistency between approaches would imply that more cooling degree days and heating degree days should be associated with less of an increase in electricity and natural gas consumption, respectively, for the postcode-change residences. This is, in fact, precisely what we find.

Are there any alternative explanations for our empirical findings? One possibility is that a shift from natural gas to electric heating, caused for reasons independent of the code change, is driving some of the results. This could explain, for example, the lower natural gas consumption, especially during cold months, of the postcode-change residences and the downward pattern in the effective year built dummies presented in figure 4. Although this explanation is not consistent with anecdotal evidence about new construction in Florida, it would be ideal to control for this possibility with data on the type of heating of residences within our sample. Unfortunately these data are not available. However, even if there were some shifting from natural gas heating to electric heating, our primary results—that the code change is associated with reduced overall energy consumption—would be unchanged because we estimate annual energy savings for both electricity and natural gas.

How do our results compare to those of an engineering simulation model? According to EnergyGauge (2002), the energy code change in Florida's northern climate region is predicted to cause a 4% increase in energy-efficiency standards for space heating, space cooling, and water heating. But because these sources of energy demand account for only half of the energy demand for a typical Florida residence (Cushman 2008), the change in code stringency translates into a 2% increase in overall energy efficiency. This estimate is not statistically different from our empirical findings of a 4% savings for electricity and a 6% savings for natural gas.

Because of the difference between our point estimate and the engineering predictions, however, we now discuss a few reasons that the empirically estimated effects might plausibly be larger than the simulated predictions. First, energy code changes are likely to generate spillover effects on construction patterns across regions. While our control and treatment groups are from the same area located within Florida's northern climate region, more substantial changes occurred at the same time in the state's central and southern climate regions. It is possible that changes in the other regions caused a general shift in residential construction practices that resulted in more overcompliance with the energy code in the northern climate region. Second, there appears to have been confusion over what exactly the change in Florida's building code meant for builders. Several sources suggest that builders interpreted changes to the code as prescriptive requirements rather than components that could be traded off in the overall performance-based metric.[20] This would, in practice, result in overcompliance with the energy code. Finally, new standards of the National Appliance Energy Conservation Act took effect in July 2001 and increased the efficiency standard for refrigerators. Fairey and Sonne (2001) predict that these new standards decrease electricity demand of a typical Florida residence by 12.5 kWh per month. Applying this adjustment to our estimates would imply a decrease in electricity consumption of 3% which is closer to the simulated prediction of the engineering simulation.

VI. Conclusion

In response to the 1973 oil embargo, combined with some unusually cold winters and high energy prices during the 1970s, many U.S. states began passing building energy codes in order to promote energy efficiency. While the vast majority of states have energy codes in place, policymakers are now attempting to legislate energy codes at the federal level to help address heightened concern about energy and climate change. Despite widespread implementation of energy codes and calls for greater stringency in the future, surprisingly little is known about whether energy codes are an effective way to reduce energy consumption. Engineering simulations provide most of the evidence, but simulated predictions, even if based on sound models, do not account for enforcement, compliance, and behavioral responses. Hence there is an important and timely need for empirical research that uses field data to more fully evaluate the effects of energy codes on energy consumption.

This paper evaluates the impact of a change in Florida's residential energy code using billing data for both electricity and natural gas. Using residences in the city of Gainesville, we find that the code change is associated with a 4% decrease in electricity consumption and a 6% decrease in natural gas consumption. Moreover, the pattern of savings is consistent with reduced consumption of electricity for air-conditioning and reduced consumption of natural gas for heating. Though direct comparison with engineering simulations is challenging, our estimates are reasonably close to those used by the state of Florida and thereby further confidence in the reliability of simulated predictions. We also estimate economic costs and benefits of the energy code change. We estimate that the private payback period for the average residence is 6.4 years. The social payback period, which accounts for the avoided costs of air pollution emissions, ranges between 3.5 and 5.3 years, depending on whether avoided damages from carbon dioxide are included.

Given the policy relevance of understanding the current and potential impact of energy codes, it is worthwhile to conclude with comments about the generalizability of our results. The obvious limitation of the evaluation is that it applies to a particular policy in a particular location. Our selection of Gainesville, and therefore Florida's energy code, is based entirely on data availability that coincides with an energy code change. Nevertheless, our study of Gainesville is informative about the impact of energy codes more generally for several reasons. First, Florida's energy code is based on standards set by the International Energy Conservation Code (IECC), and some version of this standard provides the basis for energy codes in the majority of U.S. states, due in part to encouragement by the U.S. Department of Energy (American Council for an Energy-Efficient Economy, 2010). Second, changes to the IECC typically motivate changes in state codes, and, in fact, the code change that we study in Florida was motivated by a desire to bring Florida's code into alignment with the 2000 IECC. The primary contribution of this paper is the finding that such code changes affect energy consumption. Third, when it comes to enforcement, compliance, and stringency, Florida is rated close to average for energy codes among all U.S. states in according to the energy-efficiency scorecard of the American Council for an Energy-Efficient Economy (2010).

It is also the case that 22% of all U.S. residences are in the same national climate region as Gainesville (Energy Information Administration, 2009), meaning that energy

[20] For example, the National Fenestration Ratings Council published an article in its widely read magazine *NRFC Update* in January reporting that the "Florida prescriptive requirements will require SHGC of 0.40 for all windows in the state effective January 2002." Additionally, a brochure, "The Florida Building Code and the Florida Home Builder," that contained a number of errors regarding the code change was distributed to attendees of the Southeastern Builders Conference held in Orlando in July 2001. The errors were later explained on the EnergyGauge (2002) website, but they demonstrate considerable confusion about energy code requirements that could result in overcompliance.

code effects in Gainesville might be somewhat representative of how energy codes affect more general regions of the county, including all states that border the Gulf of Mexico, as well as parts of Georgia, South Carolina, Arkansas, Oklahoma, southern California, and western Arizona. As for more northern climates, where demands for heating and cooling are substantially different, along with the mix of energy sources, we leave to future research the question of how energy codes affect actual energy consumption. But the methodology outlined in this paper should serve as a useful and replicable template for how studies can be carried out in other areas.

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