

# **Economic, Sociological, and Neighbor Effects in Energy-Efficient Residential Heating and Air Conditioning System Installations: Evidence from the U.S.**

Douglas S. Noonan<sup>1</sup>  
Professor  
Indiana University-Purdue University Indianapolis

Lin-Han Chiang Hsieh  
Assistant Professor  
Chung Yuan Christian University

Daniel Matisoff  
Assistant Professor  
Georgia Institute of Technology

<sup>1</sup>Corresponding Author:  
Douglas S. Noonan  
School of Public and Environmental Affairs  
Indiana University-Purdue University Indianapolis  
801 W. Michigan St.  
Indianapolis, IN 46202  
USA  
NoonanD@iupui.edu

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2 **Heating and Air Conditioning System Installations: Evidence from the U.S.**  
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6

7 **Abstract**

8 This study identifies factors that affect the adoption behavior for residential Heating,  
9 Ventilating, and Air Conditioning (HVAC) systems, including a spatial and temporal contagion  
10 effect, house characteristics, and other economic and contextual factors. The study draws on a  
11 dataset of house sale records in the greater Chicago area, spanning 1992 to 2004. First-  
12 differenced models and restricting the sample to new construction allow separate identification  
13 of adoption determinants for homeowners and for developers, respectively. We show that  
14 attributes of the building stock and demographics influence adoption decisions of both  
15 homeowners and developers. This includes a strong influence of square footage, a modest spatial  
16 clustering effect for existing homes, a consistent deterrent effect of higher property tax rates, and  
17 a positive influence of neighborhood education levels. Adoption decisions for existing  
18 homeowners appear to be driven by different factors than sellers of newly constructed homes.  
19 Adoption coincided with multi-story homes for developers, and neighbor adoption rates  
20 predicted adoption by existing homeowners but not developers. The results highlight the need for  
21 more research into the social context of energy efficiency investment.

22  
23 keywords: energy efficiency, green buildings, technology adoption, housing  
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# 1 Economic, Sociological, and Neighbor Effects in Energy-Efficient Residential 2 Heating and Air Conditioning System Installations: Evidence from the U.S.

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## 5 1. Introduction

6 Demand for energy and pressures to reduce carbon dioxide emissions continue to grow.  
7 Instead of increasing energy supply to meet demand, many recommend improving energy  
8 efficiency. Gillingham et al. (2004) review a cost-effective collection of energy efficiency  
9 programs that could reduce energy consumption in buildings by 12 percent. In this sense, energy  
10 efficiency can be viewed as a source of supply of energy resources (Paul et al. 2011). Moreover,  
11 Heating, Ventilation, and Air Conditioning (HVAC) consume nearly one-third of building energy  
12 end-use, making this the largest end-use among all residential energy consumption activities  
13 (Kelso 2009). Thus, if the goal is to reduce residential energy consumption by improving energy  
14 efficiency, HVACs should be a top priority. As residential use accounts for 20-30% of total  
15 energy demand globally (Estiri 2015) and rapidly increasing electricity consumption around the  
16 world follows higher economic status (D'Oca et al. 2014), better understanding the human and  
17 social aspects of residential energy efficiency poses a challenge to energy-intensive economies  
18 and those rapidly intensifying.

19 A growing volume of research demonstrates the benefits of adopting energy-efficient or  
20 zoned HVACs, with engineers concluding that substantial energy savings can be achieved  
21 through zoned systems (Burgett et al. 2013, Mathews et al. 2001, Pérez-Lombard et al. 2011,  
22 Meyers et al. 2010, Ardehali and Smith 1996). Zoned HVAC systems allow the consumer to set  
23 different temperatures for different parts of the house and reduce energy consumption when a

1 room is unoccupied, similar to turning off lights when leaving a room. It is generally accepted  
2 that zoned HVAC systems can substantially reduce the 39 percent of HVAC energy costs that do  
3 not add to increased comfort (Meyers et al. 2010). Ardehali and Smith (1996) report reductions  
4 in energy consumption exceeding 50 percent for zoned HVAC systems and simulate a 65 percent  
5 energy cost savings for a typical residential building in Des Moines, Iowa. Mathews et al. (2001)  
6 find similar simulated savings. While our data do not measure energy consumption or savings in  
7 individual houses, understanding the factors that drive technological adoption and choices about  
8 housing characteristics can inform our understanding of the energy efficiency gap and  
9 households' indirect effects on energy consumption (Estiri 2015).

10 Research focusing on the adoption behavior for these systems, however, is relatively  
11 limited. Evidence indicates that adopting energy efficient technologies benefits homeowners, but  
12 homeowners frequently forgo the adoption of cost-effective technologies, creating an energy  
13 efficiency “paradox” or “gap” (Hassett and Metcalf 1994, Jaffe and Stavins 1994, Allcott and  
14 Greenstone 2012). Factors affecting homeowners' decision-making – either the possible  
15 motivations or barriers to the adoption of energy efficient HVACs – merit additional research  
16 (Allcott and Mullainathan 2010). From a policy perspective, an improved understanding of  
17 adoption behavior enables better policies to enhance the diffusion of energy-efficient HVACs or  
18 lower the barriers to adoption. Higher energy prices, for example, should result in more energy-  
19 efficient HVAC adoption. Yet prices are not consumers' sole consideration, and they cannot  
20 explain the variation in adoption behavior among homeowners in the same market, facing  
21 identical energy prices and building codes. Identifying the determinants of adoption can guide  
22 the design of appropriate policies to stimulate the diffusion of energy-efficient HVACs.

23 This study offers several contributions to the literature regarding energy efficiency

1 technology adoption behavior. First, we use market data on major investments at the house level.  
2 This represents an improvement over many existing studies, which typically rely on potentially  
3 biased survey (Wilson et al. 2015) or aggregated data. Second, this study allows for spatio-  
4 temporal spillovers in household behavior, which measures the diffusion of technology change.  
5 Third, this study adds new empirical tests of the relationships between the factors expected to  
6 impact HVAC adoptions and observed adoptions. This study also contributes to Estiri's (2015)  
7 new approach to understanding residential energy use by providing more evidence about housing  
8 choice behaviors that impact energy consumption.

9 In addition to identifying the relationships between HVAC adoption and microeconomic  
10 determinants that ought to affect HVAC adoption (e.g., tax rates, age of the house, size of the  
11 house), suggestive evidence about a "spatial contagion" is offered. That is, our model  
12 construction allows us to test for peer effects and the impact that energy efficient technology  
13 adoption behavior at the house level has on nearby house adoption behavior. Policymakers and  
14 economists appear increasingly interested in the diffusion of energy-efficient technologies among  
15 houses. Early adopters can influence later adopters through sharing knowledge, "keeping up with  
16 the Joneses" copycatting, "green signaling," "competitive altruism," or "conspicuous  
17 conservation" (Bollinger and Gillingham 2011, Sexton and Sexton 2014). We examine a spatial  
18 contagion effect for HVAC technology adoption in a large panel dataset of home sales that reveal  
19 housing choices across the Chicago suburbs.

20 The empirical analysis here directly addresses the shortcomings of the "physical-technical-  
21 economic model" (PTEM) of energy efficiency adoption, with its "very little consideration of  
22 social systems, consumers as social actors, or other non-engineering/non-economic social  
23 considerations" (Lutzenhiser 2014, 143). We explicitly introduce neighborhood effects and

1 allowing for more heterogeneity by decision-makers, all while controlling for many PTEM  
2 concerns either by explicit controls (e.g., structural characteristics) or by holding those  
3 conditions fixed within the data (e.g., climate, regional policies). Broadening the adoption model  
4 to include factors beyond financial attributes like technology costs and energy prices lends  
5 insight into the contextual factors as well as more rarely analyzed personal influences (Wilson et  
6 al. 2015) and peer effects (McCoy and Lyons 2014).

## 7 **2. Background**

### 8 2.1 Related Work

9 An “energy efficiency gap,” where decision-makers forgo seemingly cost-effective energy  
10 efficiency technologies, has recently attracted renewed interest by economists (Gillingham et al.  
11 2009). Economists have raised concerns that engineering estimates of energy efficiency overstate  
12 real-world gains, in part, by overlooking behavioral components (e.g., Jacobsen and Kotchen  
13 2013, Brounen et al. 2012, Allcott and Greenstone 2012, Metcalf and Hassett 1999, Greening et  
14 al. 2000, Jaffe and Stavins 1994). The question of who adopts efficiency technologies remains  
15 critical. A handful of recent studies have explored these questions with respect to household  
16 technologies, both large (Kahn and Vaughn 2009, Metcalf and Hassett 1999, Jaffe and Stavins  
17 1995) and small (Mills and Schleich 2010). Nevertheless, investigations of single-family  
18 household-level adoption behavior for energy efficient large appliances like HVAC systems  
19 remain rare.

20 To date, studies that focus on homeowners’ adoption of zoned HVAC systems are limited.  
21 The handful of studies addressing homeowners’ adoption of energy-efficient heating and cooling  
22 systems tend to use case studies (e.g., Mlecnik 2010) or surveys (e.g., Nair et al. 2010, Niemeyer  
23 2010). Niemeyer’s (2010) survey of 800 households in Nebraska finds variables that impact

1 adoption choices such as knowledge of existing technologies, budget constraints, obstacles to  
2 making changes, demographics, and attitudes. Nair et al. (2010) survey 3,000 Swedish  
3 homeowners to discover that personal attributes, such as income and education, and contextual  
4 factors, such as age of the house and perceived energy cost, influence homeowners' choices  
5 regarding energy efficiency improvements (which could include major investments like new  
6 heating systems). Of course, increases in resale price (Dinan and Miranowski 1989, Fuerst and  
7 McAllister 2011) might also motivate adoption. Wilson et al.'s (2015) lengthier review of the  
8 literature modeling renovation decisions highlights the dominance of choice experiments and  
9 surveys. Our analysis of actual market data complements this previous household-level adoption  
10 literature.

11 In a broader context, our work stems from Griliches' (1957) work on technology diffusion  
12 theory, which has received recent attention in green building and other energy efficiency  
13 technology adoption studies. Ioannides and Zabel (2003) show considerable evidence of a  
14 powerful "keeping up with the Joneses" effect in home maintenance decisions. More recently,  
15 Helms (2012) finds evidence of neighborhood effects in residential renovations. Kahn and  
16 Vaughn (2009) discuss the idea of contagion among neighbors' hybrid vehicle purchases, and  
17 work by Costa and Kahn (2010) and others (see, e.g., Allcott and Mullainathan 2010, Sexton and  
18 Sexton 2014, Bollinger and Gillingham 2011) frequently point to social pressure involved in  
19 energy consumption decisions. The influence of neighbor characteristics is also evident in  
20 Dastrup et al. (2012), who identify larger price premiums for homes with solar panels in  
21 communities with high education levels. Keeping up with the Joneses may include major  
22 decisions like upgrading HVAC systems, although these interior investments are not as visible as  
23 the distinctive Prius or exterior solar paneling. Network effects, via personal communication

1 among neighbors or shared real estate agents or contractors, may promote information sharing,  
2 increased demand, and diffusion of new technologies (Galster 2008, Axsen et al. 2009, Axsen  
3 and Kurani 2011).<sup>1</sup> Social interaction can promote energy efficiency improvements as recently  
4 shown with survey data (Southwell and Murphy 2014) and simulations (McCoy and Lyons  
5 2014).

6 The emerging literature on green building diffusion demonstrates similar trends. Kok et al.  
7 (2011) analyze the metropolitan-level diffusion of green building certifications. Professional  
8 networks predict more adoptions (Kok et al. 2011), and local policies that require green building  
9 certification promote networks that generate positive spillovers to neighboring cities (Simcoe  
10 and Toffel 2011, Cidell 2009). Brounen and Kok (2011) find significant effects of neighborhood-  
11 level characteristics rather than buildings' thermal characteristics (e.g., insulation) in predicting  
12 household participation in an energy efficiency certification program. Dastrup et al. (2012) also  
13 find an important role for neighborhood demographics in their study of residential solar panel  
14 installations.

## 15 2.2 Determinants of Technology Adoption

16 Our analysis builds on the previous literature by exploring the house characteristics and  
17 contextual factors that might influence the adoption of energy efficient “zoned” HVACs by  
18 homeowners. A cost-benefit calculus for homeowners and developers to predict adoption  
19 includes a variety of costs and expected benefits. While we cannot precisely estimate a net-  
20 present value calculation for each house, zoned system design elements and prior literature, what  
21 Wilson et al. (2015) term as applied behavioral research, lead us to expect several house

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<sup>1</sup> In addition, economic circumstances of some neighbors that lead to adoption may also attract localized efforts to market the technology to others in the neighborhood. This economic development spillover, in Galster's terms, functions equivalently to a social network effect although it does not require direct ties between neighbors but rather a more indirect spillover of merely attracting businesses to the area.



1 characteristics to predict people's decisions to undertake energy efficiency upgrades. On the cost  
2 side, the vintage, stories, and rooms of the house are expected to reflect the cost of adoption. The  
3 ultimate impact of HVAC energy efficiency improvements depends on a well-sealed thermal  
4 envelope for the building and its overall footprint, whereas the ease of installation depends on  
5 details like attic access and preexisting systems. For zoned systems, home designs that lend  
6 themselves to partitioning into zones (e.g., many rooms, multiple stories) make for good  
7 candidates for zoned systems. High tax and interest rates are also expected to deter the adoption  
8 decisions of purchases involving high capital costs (Parente and Prescott 1994, Lawrence et al.  
9 2005). The square footage and lot size of the house are employed to predict the expected benefits  
10 of zoned systems, due to larger houses.

11       The diffusion and efficiency gap literatures indicate that more than structural characteristics  
12 influence adoption decisions. Contextual or neighborhood-level socioeconomic characteristics,  
13 such as distance to a central business district (CBD), median household income, median house  
14 value, population density, housing vacancy rate, percent renters, and percent of the population  
15 that are college graduates might affect adoption decisions (Baerenklau 2005, Noonan et al.  
16 2013). These neighborhood attributes might affect the benefits of adoption (Dastrup et al. 2012),  
17 either by increasing the expected returns to investment, or by spatial clustering households with  
18 higher demand for energy efficiency. Neighborhood attributes might also affect costs, perhaps  
19 because low-cost installers market to that area or because knowledge is shared locally and thus  
20 search costs or providing inspiration (McCoy and Lyons 2014, Schelly 2014). Neighborhood  
21 demographic variables (e.g., median household income level, median house value, population  
22 density, percent vacant units, and percent who graduated college) might affect the adoption of  
23 energy efficiency improvements.

### 1 **3. Data and Methodology**

2 We measure a dichotomous dependent variable for energy-efficient HVAC adoption, based  
3 on the sales records of Chicago-area homes. This study uses *zoned heating* and *zoned air*  
4 *conditioning systems* to understand the technological adoption of more energy-efficient HVACs.  
5 Actual energy savings of zoned HVAC systems depend on the size and design of the house, the  
6 efficiency of the individual systems, and many other factors. House sales data contain  
7 systematic measures, collected independently of this research, of house attributes and thus  
8 implicitly reflect human behavior that constructed, selected, and sometimes renovated the  
9 housing.

10 This study employs a dataset on home sales in over 160 municipalities in the greater  
11 Chicago area, originally containing over 340,000 sale records (of roughly 260,000 unique  
12 houses) from January 1, 1992 to June 30, 2004. The property data, including address, vintage,  
13 stories, number of rooms, type of HVAC, architectural style, etc., are from the Multiple Listing  
14 Service (MLS) of Northern Illinois, an information clearinghouse for most residential property  
15 sales in that area. Realtors and others in the residential real estate market routinely create and  
16 search MLS records for homes listed for sale. All the records are for single-family houses from  
17 counties surrounding the city of Chicago (i.e., Cook, DuPage, Kane, Lake, McHenry, and Will  
18 counties). (The City of Chicago is not included in order to keep the population of suburban areas  
19 with single-family homes more comparable.) The demographic information is from the 1990 and  
20 2000 Censuses. Unlike the sales record data, which are household level, these demographic data  
21 are available at the block-group level using the GeoLytics database.<sup>2</sup> Using GIS tools, the

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<sup>2</sup> Using the demographic data from GeoLytics, Inc. (East Brunswick, NJ) provides the 1990 Census data in geographic boundaries consistent with 2000 boundaries. Demographic values are linearly interpolated based on 1990 and 2000 values for years other than 2000.

1 corresponding demographic data is assigned to each sales record based on the block group in  
2 which each house is located.

3 In our dataset, more than 88 percent of households use forced-air heating systems, and 90  
4 percent of households use natural gas as the energy source for heating. The majority of A/C  
5 systems is central air, which is used in over 80 percent of homes. Only 2 percent of sales records  
6 indicate zoned HVACs.

7 The empirical model considered here takes the form:

$$8 \quad y_{igt} = \ln \left[ \frac{P_{igt}}{1-P_{igt}} \right] = \alpha_{igt} + X'_{igt}\beta_t + Z'_{ig}\gamma_t + \theta_{igt} \quad (1)$$

9 where  $y = 1$  to indicate a zoned system is installed and a 0 otherwise,  $P_{igt} / (1-P_{igt})$  is defined as  
10 the probability of a house  $i$  in block group  $g$  and sold in year  $t$  adopting an energy efficient  
11 HVAC system;  $X$  and  $Z$  are time-varying and time-invariant vectors of control variables,  $\alpha_{igt}$  is  
12 an intercept and  $\theta$  is an error term. Random-effects logit models are estimated, where local  
13 neighborhoods (i.e., block groups) are given individual error terms (i.e.,  $\theta_{igt} = \mu_g + \varepsilon_{igt}$ ), due to  
14 concern that might result from uneven sampling or measurement consistency across these areas,  
15 as well as to alleviate concerns regarding block level heterogeneity. (The results from ordinary  
16 logit analyses are substantively similar, differing largely in the size of standard errors.

17 Not all of the 340,000 sales records are appropriate for this study. Because the data do not  
18 include timing of adoption or installation for HVAC systems, and because building maintenance  
19 and other important attributes may be unobserved in the data, care is taken to construct final  
20 datasets that mitigate these problems and offer the cleanest interpretation of results. Accordingly,  
21 we create three samples from the data: a new construction sample, a renovation sample, and a  
22 new-installation sample. The first concerns developers' (i.e., those who sell new construction)  
23 adoption decisions, while the second two concern adoption decisions of homeowners (i.e., those

1 who resell houses). We use equation (1) to estimate developers' adoption decisions; equation (2),  
2 discussed below, is used to estimate homeowners' decisions.

3 First, the **new-construction sample** focuses the analysis on adoption decisions by housing  
4 developers. The new-construction sample includes only sales records that are labeled in the MLS  
5 sales record as new construction (approximately 7,000), thus minimizing the problem of  
6 unobservable equipment age and maintenance. Decisions by housing developers have not yet  
7 been examined in prior literature related to residential energy efficiency adoption in the U.S., yet  
8 developers and new construction clearly play major roles in the prospects for altering the carbon  
9 footprint and energy efficiency the U.S. residential building sector (Costa and Kahn 2011, Chong  
10 2012). Deng and Wu's (2014) analysis of price premiums reveals that energy efficiency  
11 investments may be treated very differently for new and resold homes. We estimate adoptions  
12 with the new construction sample using equation (1).

13 Second, we examine only homes that sold multiple times in the dataset in order to observe  
14 homeowner decisions, mitigate problems related to static but unobservable characteristics of  
15 houses, and control for unobserved timing in adoption. We use the multiple sales to isolate the  
16 impact of changes of house and neighborhood characteristics on changes in HVAC decisions and  
17 avoid the bias of omitting many housing characteristics that do not change over time. Looking at  
18 homes' HVAC systems at two points in time amounts to predicting renovations between sales.  
19 The **renovations sample** consists of houses that had a non-zoned heating (or A/C) system at  
20 their initial sale (approximately 18,000 observations), and may potentially renovate to install a  
21 zoned system.<sup>3</sup> The other type of households that might adopt are homes that had no heating (or  
22 A/C) system at their initial sale. This **new-installation sample** (2,700 observations) includes

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<sup>3</sup> Houses with multiple heating (or A/C) systems at the time of initial sale are also dropped, as they might be seen to already operate a de facto zoned system.

1 houses not coded in the MLS data as “new” homes but still lacking an HVAC system. This  
 2 smaller sample of predominantly very young houses, possibly not yet owner-occupied, lacks a  
 3 technological lock-in and may involve different adoption behavior than in the renovations  
 4 sample. Comparing the results from the renovation and new-installation samples with the new-  
 5 construction sample will highlight the differences in decision criteria for homeowners reselling  
 6 houses and house developers selling new construction.<sup>4</sup>

7 These constructions essentially function like first-differenced models, where *changes* in  
 8 house HVAC technology are predicted by changes in key factors (e.g., square footage, tax rates)  
 9 as well as initial home attributes, while differencing out unobserved static heterogeneity.<sup>5</sup>  
 10 Predicting changes in installed technology between the first and last sales in the dataset reduces  
 11 the sample size to roughly 18,000 observations.<sup>6</sup> The resulting model is a modification of  
 12 equation (1):

$$13 \quad \Delta y_{igt} = \ln \left[ \frac{P_{igt}}{1-P_{igt}} \right] = \Delta \mathbf{X}'_{ig} \boldsymbol{\beta}_s + \mathbf{X}'_{igt} \Delta \boldsymbol{\beta} + \mathbf{Z}'_{ig} \Delta \boldsymbol{\gamma}_t + \Delta \theta_{igt} \quad (2)$$

14 Zoned HVAC adoption between sales in period *t* and *s* is explained by changes in *X* and changes  
 15 in the effects of the determinants. Time-invariant factors *Z*, observed or unobserved, will  
 16 difference out if their parameters are constant. A logistic regression is estimated for equation (2)  
 17 to identify the determinants of adoption by individual homeowners using the renovation and  
 18 new-installation samples.

19 The three samples identify different determinants of adoption of energy efficient HVAC

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<sup>4</sup> The distinction between the new-construction and the new-installation samples is that the former is listed as “new construction” in the MLS and only gets sold once in our data, while the latter is not listed as “new construction,” gets sold multiple times, and apparently has no system in place initially.

<sup>5</sup> Including the initial attribute levels or time-invariant attributes (e.g., location) in what is essentially a first-differenced model implies an interaction of these variables and the time variable. Thus, our interpretation of these variables is that they identify a time trend in their effect on adoption.

<sup>6</sup> The much smaller new-installation sample has only 2,700 observations with no initial A/C and 1,300 observations with no initial heating system.

1 systems. For the renovations sample, the coefficients indicate the effect of the regressor on the  
2 likelihood of switching from a non-zoned system to a zoned system between sales. For the new-  
3 installation and new-construction samples, the coefficients indicate the effect of the regressor on  
4 the likelihood of initially installing a zoned system relative not installing such a system. While  
5 zoned systems can be expected to be more energy efficient than conventional systems, houses  
6 with zoned systems are likely to consume more energy than a house with no system.

7 We estimate separate models for adoption of zoned heating systems and of zoned A/C  
8 systems (for each of the three samples). This is done to detect different determinants for the two  
9 systems, although clearly adoption decisions may be very interdependent. Brounen et al.'s  
10 (2012) sample of Dutch homes suggest structural and behavioral factors play different roles in  
11 explaining consumption dependent on whether it is gas or electricity use. Given that ninety  
12 percent of heating is fueled by gas in our sample, we estimate adoptions for heating and cooling  
13 systems separately to account for different sources of fuel cost savings. In addition to these  
14 structural and contextual factors, neighborhood factors may influence adoption differently for  
15 heating and A/C for other social reasons (e.g., residents sort into neighborhoods based partly on  
16 differential demand for better A/C).

17 The definitions and descriptive statistics of all the variables introduced in this study are  
18 listed in Tables 1 and 2, respectively. Estimating similar models improves the comparability  
19 across the three samples. The vector  $X$  includes a host of structural, neighborhood, and other  
20 contextual variables. We include in  $\Delta X$  the differences in square footage, lot size, interest rates,  
21 sale date, and rehab status for the renovation and new-installation samples. Included in  $X$ , as  
22 measured at the time of first sale, are structural characteristics (e.g., vintage, rooms, size),  
23 neighborhood factors (e.g., income, education, vacancies), and tax and interest rates. Following

1 equation (2), these variables capture the changes in parameter values between sales. Year of  
2 (first) sale dummies to allow for time trends (in “green” tastes, in energy prices, in installation  
3 prices, etc.). Seasonal dummies allow tests for whether houses adopting zoned HVAC systems  
4 tend to sell disproportionately in certain seasons, something that might occur if owners upgrade  
5 before selling their home in certain seasons or salience of HVAC systems varies seasonally.  
6 Busse et al. (2012) observe a similar sort of seasonality for hedonic values of central air  
7 conditioning. Differences between renovating and new installation suggest that some factors are  
8 irrelevant to one choice (e.g., vintage for new installations) and others may operate differently  
9 between samples. For instance, the offsetting effects of multi-story houses on renovation  
10 adoptions become largely positive for multi-story new construction, due to fewer structural  
11 barriers to zoned HVAC installation at the time of construction.

12       The *neighborhood adoption* variable is a (spatially and temporally) lagged adoption rate  
13 defined as the share of homes in the block group that have installed zoned HVACs and are sold  
14 within a 5-year window before the sale date of each sales record.<sup>7</sup> In other words, it is the density  
15 of homes sold with zoned HVACs in the block group during the moving 5-year window. We  
16 hypothesize that higher zoned HVAC density will lead to a greater probability of adoption. We  
17 remain agnostic about the mechanism for this interdependence, although certainly social pressure  
18 and norms, social networks, competition, learning, a lowering of transaction and search costs,  
19 and other mechanisms may all be at work (Allcott and Mullainathan 2010, Galster 2008). Insofar  
20 as higher neighborhood adoption rates reduce search costs for homeowners considering installing

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<sup>7</sup> This contagion concept aims to capture the share among neighbors of recent sales that have already adopted the technology. As a practical matter, five years is used to define “recent,” although other windows could readily be selected. A sensitivity check of using one and three years shows that different definition of “recent” generally does not affect other estimators. The contagion effect is stronger as “recent” is defined as a shorter time period. Similarly, different definitions of neighbors (other than being in the same block group) could be used.

1 a zoned HVAC system, renovators can learn from (Southwell and Murphy 2014) and experience  
2 neighbors' prior installations (Wallenborn and Wilhite 2014), and new home developers have  
3 already conducted basic marketing research (Dastrup et al. 2012), we expect neighborhood  
4 adoption to have a stronger effect on renovation decisions than on new construction decisions.

5 <<<insert table 1 about here>>>

6 <<<insert table 2 about here>>>

7

## 8 **4. Results**

### 9 4.1 New-Construction Sample

10 Table 3 provides the results for the random-effects logistic regressions for both zoned heating  
11 systems and zoned air-conditioning systems in the new-construction sample. In the new-  
12 construction sample, multistory and square footage have positive effects on adoption. Unlike  
13 those in the two repeat-observations (i.e., renovations and new-installation) samples, *multistory*  
14 has a positive effect in the new sample, perhaps due to the ease of installing zoned HVAC  
15 systems during new construction, and the logic of designating zones in multistory homes. Like  
16 those in the renovation sample, the property tax rate has a negative effect on the inclusion of  
17 zoned HVAC systems in new construction.

18 The prevailing mortgage interest rates do not appear to predict zoned HVAC adoption by  
19 homeowners or developers. Interest rates are inconsistent and only weakly significant for zoned  
20 air conditioning in Table 3, zoned heating in Table 4 and Table 5. Inconsistent findings may  
21 result from similar fixed costs among substitutes or an incentive to construct homes that shift  
22 costs to operating costs as interest rates rise to offset homebuyers' expected higher mortgage  
23 payments.



1 For developers rather than existing homeowners, the effect of neighborhood adoptions is  
2 not significant in either zoned heating or air conditioning systems. This insignificant effect  
3 indicates that social pressure and knowledge sharing may be less likely to occur between  
4 developers and existing owners than among owners of existing stock.<sup>8</sup> It is likely that social  
5 pressure and knowledge sharing have not occurred if new homes are built by new entrants to a  
6 neighborhood.

7 <<<insert table 3 about here>>>

8 Neighborhood variables are generally insignificant, except for distance to CBD for the  
9 adoption of zoned air-conditioning, and median house value and population density for zoned  
10 heating. The percent of college graduates in the neighborhood has positive and significant effects  
11 for both heating and air conditioning. The median house value has a positive effect on the  
12 installation of zoned heating system in the new-construction sample, likely reflecting localized  
13 demand and clustering of higher-value homes. Numerous hedonic studies have demonstrated that  
14 energy efficiency brings a sales premium to a property (Dinan and Miranowski 1989, Eichholtz  
15 et al. 2010b, Fuerst and McAllister 2011) and this premium is even greater in highly educated  
16 communities (Dastrup et al. 2012). Even though neighborhood variables are generally  
17 individually insignificant for new-construction sample, they are jointly significant for both zoned  
18 air-conditioning ( $\chi^2 = 15.48$ ) and heating system ( $\chi^2 = 23.88$ ) models.

## 19 4.2 Renovation Sample

20 Table 4 lists the results of random-effects logistic regressions for the renovation sample.  
21 Two models are reported to show the determinants for two dependent variables: the adoption of  
22 zoned heating systems and the adoption of zoned air conditioning systems. For house

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<sup>8</sup> Instead of defining the lagged adoption as “share of all sales with zoned HVAC in the block group,” if we change the definition to the “share of new construction sales with zoned HVAC,” the results are similar.

1 characteristics, the effect of property vintage is significant for both technologies. The likelihood  
2 of installing a zoned system between sales falls with age until houses are over 50 years old,  
3 beyond which the odds of adoption begin to rise with age. Compared with newer properties (age  
4 under five years), older houses are less likely to adopt zoned HVACs. This may be because  
5 installing zoned HVACs in newer houses is easier due to home design characteristics or greater  
6 rewards to keeping modern homes updated.

7       The effect of square footage is positive and significant. Houses with larger indoor space  
8 have greater benefits from adopting zoned HVAC systems due to greater potential energy  
9 savings. Interestingly, *multistory* and *rooms* do not have significant effects on adoption,  
10 conditional on house size. Gross size (square footage) appears to drive adoption decisions more  
11 than the ease of separating zones in the home (stories, rooms). However, house characteristic is  
12 jointly significant for both heating ( $\chi^2=165.47$ ) and air conditioning ( $\chi^2=42.68$ ).

13       Context matters as well. Effective property tax rates have significant negative effects on the  
14 adoption of energy efficiency. Consistent with the expectation that property taxes reduce the  
15 returns on property investments (Tse and Webb 1999), higher tax rates indeed reduce the odds of  
16 adopting zoned HVAC systems. The weak effect of interest rates likely follows from its poor  
17 measurement. It is a market average rate (rather investor-specific) at the time of sale (rather than  
18 time of installation). The effects of neighborhood adoption are only positive and statistically  
19 significant for zoned heating. In other words, higher adoption rates in the previous five years at  
20 the block group level only affects the adoption of heating, not air conditioning. The effects of  
21 neighborhood quality (i.e., neighborhood attributes listed after *neighborhood adoption* and above  
22 sales year in the table) are inconsistent between two technologies. For air conditioning, a location  
23 closer to the central business district, a higher housing vacancy rate, and a higher proportion of

1 rental units have positive effects on adoption. For heating systems, median household income is  
2 negatively related, while median house value and the percent of college graduates in the  
3 neighborhood are positively related with adoption. These neighborhood quality variables are  
4 jointly significant at the 0.01 level for both heating and air conditioning. Their different roles for  
5 different technologies are expected as demographic correlates of demand and the ways people  
6 experience the systems differ for heating versus cooling.

7 <<<insert table 4 about here>>>

8 The change in square footage between each sales record has a significant positive effect on  
9 the adoption of both zoned air conditioning and heating systems. The effect is even stronger than  
10 the effect of square footage for the first sale. This is as expected. Homes that add square footage  
11 are much more likely to adopt zoned HVAC systems because the estimated savings from  
12 adoption also increases. In addition, the cost to adopt will also likely be lower since a major  
13 renovation is already taking place or the addition to the house may require an additional HVAC  
14 system. As Judson and Maller (2014) observe for efficiency upgrades generally, it is the  
15 expansion of square footage (not any  $\Delta$ rehabilitation) that drives adoption. The changes in lot  
16 size and interest rate also do not influence the probability of adoption. While those results  
17 confirm expectations, the weak effect of *time elapsed* in Table 4 is somewhat surprising in light  
18 of the expectation that more time between sales offers more time for HVAC upgrades to occur.  
19 Apparently the incentive and opportunity to renovate HVACs in homes with rapid turnover (i.e.,  
20 shorter time elapsed) roughly offset the effect having more time to renovate.

#### 21 4.3 New-Installations Sample

22 Table 5 lists results for the random-effects logistic regressions for both zoned air-  
23 conditioning systems and zoned heating systems in the new-installations sample. Observations in

1 this smaller sample have no HVAC systems before resale and are virtually all very young houses.  
2 Thus, vintage variables are dropped. Since observations having no air-conditioning system at  
3 previous sale do not necessarily overlap with observations with no heating system, the two  
4 columns of Table 4 are discussed separately.

5 For the new-installation of air-conditioning sample, neighborhood adoptions (block group  
6 zoned HVAC adoption density), square footage, difference in square footage, lot size, and  
7 population density all have positive effects on the adoption. The density and neighborhood  
8 adoption effects might capture more social activity and a greater probability of information  
9 exchange. Except as a possible proxy for owner income, it is unclear why the lot-size effect  
10 remains significant even after controlling for indoor square footage. (The income explanation is  
11 consistent with the insignificant lot-size effect for zoned heating, in any sample, as Brounen et al.  
12 (2012) suggest that A/C use – and hence cost-savings from efficiency upgrades – depends more  
13 on income.)

14 <<<insert table 5 about here>>>

15 Zoned heating systems have different drivers than zoned air-conditioning systems. For  
16 homebuyers installing new heating systems in existing houses, the effects of neighborhood  
17 adoption, lot-size, population density and rental proportions are no longer significant. Instead,  
18 effective tax rates and mortgage rates have weakly negative effects on adoption. Increases of  
19 square footage and difference in square footage remain positively correlated with zoned heating  
20 system adoption, as expected.

21

## 22 **5. Discussion**

### 23 5.1 Comparisons Across Adopter Types

1           The results for homeowners (both renovations and new-installations) and developers are  
2 generally quite consistent, although some interesting differences exist. Out of 14 house and  
3 neighborhood variables shared in Tables 3, 4, and 5, all but a handful of variables exhibit the  
4 same sign or are insignificant in all tables. Only one parameter estimate is statistically significant  
5 with opposite valences for homeowners and developers. The split-incentives (Davis 2010,  
6 Gillingham et al. 2010, Levinson and Niemann 2003) problem facing new construction does not  
7 appear to lead to very different adoption criteria. Moreover, the much higher adoption rates for  
8 new construction noted in Table 2 indicate that the split incentives problem, to the extent it exists  
9 here, may be a bigger problem between current and future homeowners than between developers  
10 and future owners.

11           Both homeowners and developers are responsive to economic characteristics such as tax  
12 rates, physical attributes such as house size, and neighborhood characteristics such as the  
13 percentage of the population that has a college degree. In contrast to homeowners, developers  
14 appear more responsive to structural characteristics, such as whether the house is multi-story.  
15 The effect of neighborhood adoption rates is positive and statistically significant for the  
16 renovations sample (heating), new installations (cooling). For the other homeowner samples, the  
17 effect is positive, though not statistically significant. For new construction, there does not appear  
18 to be a contagion effect. These results confirm the hypothesis that adoption density in the  
19 neighborhood has a positive effect on adoption decisions for homeowners (and less so for  
20 builders, who may not be situated in that neighborhood).

21           Both house characteristics and contextual factors like neighborhood demographic  
22 characteristics influence adoption behavior. Factors beyond financial attributes and those  
23 commonly found in engineering cost models certainly influence adoption. For homeowners

1 (renovations and new-installations samples), neighborhood adoption and house size have  
2 positive effects on the adoption of energy efficiency; the tax rate and house age have negative  
3 effects. For developers (new-construction sample), neighborhood adoption fails to impact  
4 adoption decisions, but having multiple stories, the size of houses, and the percent of college  
5 educated residents in a neighborhood have positive effects on adoption. Similar to the effect on  
6 homeowners, tax rates have a negative effect on the adoption of energy efficiency. Nonetheless,  
7 the overall statistical insignificance of many variables highlights the heterogeneity of individual  
8 actors with regards to energy efficiency investment decisions.

## 9 5.2 Robustness checks and extensions

10 Fixed-effect logit models (available upon request) yield somewhat comparable results but  
11 are not reported here primarily because the tract-level fixed effects soak up much variation in  
12 local neighborhood characteristics. Other specifications (available upon request) take advantage  
13 of the many other covariates in the MLS dataset. This includes indicators for six age categories,  
14 25 architectural styles, 11 structural types, seven exterior materials, and three roof materials. The  
15 new-installation sample is not included in this analysis due to its small sample size. These joint  
16 F-test statistics are reported in Table 6.<sup>9</sup> The significance of the age and roofing categories is  
17 expected, although the collectively weak predictive power of structural styles is somewhat  
18 surprising. Interestingly, architectural styles appear independent of developers' decisions to  
19 install zoned HVAC systems, while exterior materials are closely related.

20 <<<insert table 6 about here>>>

21

## 22 5.3 Comparisons to Prior Work

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<sup>9</sup> The lengthy results of unrestricted logit models that include these dummy variables are available from the authors upon request.

1           Comparing results of these models to survey-based studies provides an opportunity to see  
2 how revealed and stated preferences might differ. These differences appear small. Nair et al.  
3 (2010) report similar findings for energy costs and income. They find a positive effect of  
4 building age that differs from our results, where age exhibits a negative and convex relationship  
5 with adoption propensity among homeowners. Our results are less consistent with Niemeyer  
6 (2010), who identifies the most common barriers to energy efficiency as “need financial  
7 assistance or discount on costs,” “need added information,” and “need professional or additional  
8 assistance.” Our findings suggest price effects would need to overcome more powerful income  
9 effects that deterred adoption. Information and professional assistance may be partly supported  
10 by our research in the positive spillover and diffusion impacts observed among existing  
11 homeowners and from block-group education levels.

12           One large advantage of this study is its use of detailed microdata, while many previous  
13 studies use aggregate data on adoption. Noonan et al. (2013) use the same data, aggregated to the  
14 block group level for analysis, and obtain different results. (Helms’ (2012) analysis of renovation  
15 clustering in Chicago also aggregates across time and space, although more modestly.) Serious  
16 problems arise when applying results from aggregated data to individual-level relationships  
17 (Anselin 2002), and this comparison is a prime example of those challenges. The spatial lag  
18 operator is very large and positive in all samples in Noonan et al. (2013), whereas its magnitude  
19 is much smaller here, especially for new construction. The more plausible results here likely  
20 reflect both the modeling at the appropriate scale (the theoretical interdependency is at the  
21 household level, where households are influenced by their neighbors, rather than at the  
22 neighborhood level as if neighborhoods were a decision-maker influenced by nearby  
23 neighborhoods) and the inclusion of the temporal dimension of the spillover. Noonan et al.

1 (2013) aggregate to the block-group level and compress 12 years of data into a single cross-  
2 section. This allows observations from later years to affect preceding years and could inflate the  
3 spatial lag operator. Nonetheless, many results remain consistent, despite the aggregation. For the  
4 repeat-observation sample, both studies indicate that neighborhood adoption rates have positive  
5 effects on adoption. The effects of square footage, lot size, effective property tax rates, and  
6 vacancy rates share the same signs in both studies. It is interesting to note that median household  
7 income has positive effects on adoptions at the block-group level but typically negative effects at  
8 the house level.

9 Our data's advantage over survey data (a large sample reflecting actual behavior) comes  
10 with limitations for the analysis. While our metric of zoned HVAC systems provides insight into  
11 household level energy efficiency technology decisions, we do not directly observe the potential  
12 for zoned HVAC systems to reduce energy consumption in individual households. We assume  
13 that, *ceteris paribus*, zoned HVAC systems are more efficient than non-zoned systems, but we  
14 cannot observe this directly. Second, these sales data have houses, rather than households, as the  
15 unit of observation and shed no light on the specific demographics and attitudes of buyers and  
16 sellers. Moreover, the timing of home sales may correspond poorly with timing of adoption  
17 decisions, bringing noise and possible bias in the analysis. Even the rich MLS sales data lack  
18 detailed information about the quality of installed HVAC technologies, such as their vintage or  
19 efficiency ratings, and actual energy consumption data are unavailable. Our data also exclude the  
20 major rental (apartment, condo) market. Finally, like many case studies and qualitative analyses,  
21 establishing causality of many of the factors here remains a challenge and subject to several  
22 crucial assumptions. Future research would do well to better address these limitations in  
23 explaining adoption behavior.



1           A major advantage of this study’s research design, which controls for many unobserved  
2 economic and regulatory factors by differencing them out and by restricting attention to suburbs  
3 of a single large city, also prevents us from explicitly identifying those factors’ effects on  
4 adoption. Richer data would let us place these more social and contextual factors alongside the  
5 economic and regulatory ones, as small-N studies like Schelly (2014) and Walker et al. (2014)  
6 have done. Future research with data exhibiting substantial exogenous variation in economic  
7 (e.g., installation costs, heating degree days, energy prices) and policy (e.g., subsidies, building  
8 codes) factors would complement these results. Although the more inductive, reduced-form  
9 quantitative approach here has the advantage of making fewer assumptions about the particular  
10 roles of different technical and economic factors in adoption choices, it consequentially is  
11 constrained in shedding light on specific mechanisms through which these factors influence  
12 behavior. A more structural approach or tool based on financial attributes could be developed to  
13 estimate potential gains from adoption, but our findings are not promising for that explaining  
14 much of the variation in adoption within this market (although such an approach might fare  
15 better in explaining variation across markets).

## 16 **6. Conclusion**

17           Adoption of a particular type of technology – one offering substantial gains to energy  
18 efficiency – may be a matter of public interest because homeowners systematically undervalue  
19 energy efficiency upgrades (Gillingham et al. 2009), because energy consumption includes  
20 unpriced negative externalities, because split incentives undermine investment incentives, and  
21 because of other “barriers” to adoption. Promoting adoption of green technology remains a  
22 priority, yet models based on cost-effectiveness criteria or engineering-based approaches predict  
23 more adoption than empirically observed. Nevertheless, adoption does not imply less energy

1 consumption (Estiri 2015). Frequently, these installations accompany renovations, expansions,  
2 or possibly altered behavior that leads to a “rebound effect” (Gillingham et al. 2009). The results  
3 presented here highlight the importance of other *social* factors related to technology adoption,  
4 those not typically included in simple cost-effectiveness or engineering approaches to assessing  
5 the likelihood of energy efficiency adoption. The evidence here supports a broader sense of cost-  
6 effectiveness criteria in analyzing adoption because clearly social context plays a role at least in  
7 these data.

8         We find a weak relationship between adoption and some architectural characteristics of the  
9 house (see table 6). While larger houses are more likely to include zoned systems (perhaps due to  
10 greater energy efficiency savings potential), the number of rooms and the architectural style do  
11 not affect adoption as expected. A house that is a standard deviation larger has a greater  
12 probability of adopting of 1.0% to 4.4%. However, because larger houses are likely to consume  
13 more energy, these findings highlight tradeoffs related to economic development and  
14 sustainability.

15         Some results may be unexpected to some, especially those using a narrower physical-  
16 technical-economic model of adoption (Lutzenhiser 2014). Having multiple stories mattered to  
17 developers, but not to homeowners. The age of the house and house systems, such as the roof  
18 mattered, but this relationship was not straightforward. These findings highlight the importance  
19 of the lifecycles of HVAC systems as well as timing of home renovations. Socioeconomic  
20 characteristics at the neighborhood level matter, such as education levels. But perhaps most  
21 interestingly, the importance of the effects of neighbors is consistently one of the strongest  
22 drivers of zoned HVAC adoption on homeowners, while having no effect on developers. This  
23 points to social processes like sorting and search costs as significant factors in homeowner

1 adoption of this greener technology. More generally, different adoption determinants between  
2 decision-makers suggests targeting policies by owner type (e.g., building codes for developers,  
3 “early retirement” programs for homeowners’ existing systems, lowering search costs for owner-  
4 occupants).

5 Corresponding policies to promote adoption might leverage education, incentives, rule  
6 changes, or even behavioral tendencies. The results here offer mixed implications for policy. The  
7 results suggest that education (proxied by neighborhood education) may be a lever to improving  
8 energy efficiency. Home suitability, as measured by house size and whether a house is multi-  
9 story, suggests that certain homes might be better candidates for zoned HVAC adoption, but that  
10 developers (i.e., those who sell new construction) may be more responsive than homeowners  
11 (i.e., those who resell homes) to design issues. Finally, that higher taxes deter energy efficiency  
12 adoption across all three models suggests prominent disincentives to home investment in areas  
13 with higher tax rates.

14 Nevertheless, these direct paths may not be as effective as indirectly seeding adoption via  
15 pilot programs or targeted adoption subsidies. For home renovations, neighbors may provide  
16 more opportunity for learning (information sharing, copycatting) and more incentives to adopt  
17 (keeping up with the Joneses) than conventional policy tools. The neighborhood adoption rate  
18 was one of the few house-specific characteristics – other than house size – that was positive in all  
19 four models (renovations and new installation; heating and A/C) and statistically significant in  
20 two (heating for renovations and A/C for new installations) of the four models. If a policy could  
21 induce adoption of zoned heating systems in five additional homes out of the 40 sales in the  
22 previous five years in a particular block group, the probability of the next sale having adopted a  
23 zoned heating system between sales would rise from a baseline of almost 2% to around 30%.

1 This is a dramatic increase in the likelihood of future adoption.

2       Beyond the particular technology and region studied here, the results point to lessons for  
3 other contexts and for the broader literature on energy efficiency behavior. Recent studies in  
4 Africa (Haselip et al. 2015, Eder et al. 2015) share a similar theme with the present study: social  
5 context complements narrow economic and financial factors. Better understanding the social  
6 context of adoption decisions is as important as it is challenging, whether those decisions occur  
7 in Belgium (Mlecnik 2010), Wisconsin (Schelly 2014), or Sunderland (Walker et al. 2014). Our  
8 results offer quantitative evidence of neighbors' previous adoption influencing households'  
9 decisions, addressing an important question in this literature. Our findings also advance our  
10 understanding of other important and unresolved questions, such as how the identity of the  
11 decision maker matters (Wilson et al. 2015, Ellsworth-Krebs et al. 2015), how retrofitting  
12 decisions differ from de novo installations (Mlecnik 2010), and how well simple economic  
13 "payback" models explain behavior (Schelly 2014, Wilson et al. 2015).

14       Overall, this research highlights how energy efficiency adoption rates are influenced by  
15 numerous factors beyond a narrow set of financial attributes (Wilson et al. 2015) and simple  
16 cost-benefit analysis. We find that house and neighborhood characteristics play an important role  
17 in energy efficiency investment. Neighbor behavior also matters, even if the investments in  
18 HVAC upgrades are not particularly visible to neighbors. Prior research on technological  
19 diffusion has focused primarily on the diffusion associated with highly visible conspicuous  
20 investments and consumption, such as solar panels and Prius cars, which consumers adopt to  
21 signal their conservation-related values (Bollinger and Gillingham 2011, Sexton and Sexton  
22 2014). Zoned HVAC systems, similar to window caulking or attic insulation inconspicuously  
23 confer energy efficiency. Yet neighbor effects persist in this context as well, suggesting that

1 mechanisms other than “keeping up with the Joneses,” “competitive altruism,” “conspicuous  
2 conservation,” or “green signaling” may be at work. These findings reinforce the call for  
3 research on the mechanisms that shape interpersonal influence in social networks, as well more  
4 research into the social context in which decision-makers choose to invest in energy efficiency.  
5

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1 Table 1: Variable Descriptions

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Variable	Description
Zoned Heating	Dummy for zoned heating system
Zoned A/C	Dummy for zoned A/C system
$\Delta$ Zoned Heating	Dummy for zoned heating system (installed between sales)
$\Delta$ Zoned A/C	Dummy for zoned A/C system (installed between sales)
Neighborhood adoption: heating	Share of houses sold with zoned heating within the previous 5-year window in the block group
Neighborhood adoption: A/C	Share of houses sold with zoned A/C within the previous 5-year window in the block group
1 - 5 years	Dummy for house age at the time of sale
6 - 10 years	Dummy for house age at the time of sale
11 - 25 years	Dummy for house age at the time of sale
25 - 50 years	Dummy for house age at the time of sale
51 - 100 years	Dummy for house age at the time of sale
100+ years	Dummy for house age at the time of sale
Multistory	Dummy for house with multiple stories
Rooms	Number of rooms
Square footage (log)	log(square footage)
Lot size (log)	log(lot size in square feet)
Tax rate	Effective property tax rate
Interest rate	Averaged 30-year fixed mortgage interest rate, from HSH Associates National Monthly Mortgage Statistics
Distance to CBD (log)	log(distance to Central Business District)
Median household income (log)	Block-group median household income, interpolated 1992-2004
Median house value (log)	Block-group median house value, interpolated 1992-2004
Population density (log)	Block-group population density (people per square mile), interpolated 1992-2004
Percent vacant	Percent of housing units vacant in the block group, interpolated 1992-2004
Percent renters	Percent of housing units occupied by renters in the block group, interpolated 1992-2004
Percent college graduate	Percent of college graduates in the block group, interpolated 1992-2004
Sale in YEAR	Dummy for property's sale in YEAR
Spring	Dummy for property's sale in spring (March – May)
Summer	Dummy for property's sale in summer (June – August)
Fall	Dummy for property's sale in fall (September – November)
Winter	Dummy for property's sale in winter (December – February)
$\Delta$ square footage (log)	Difference in <i>square footage (log)</i> between sales
$\Delta$ lotsize (log)	Difference in <i>lot size (log)</i> between sales
$\Delta$ interest rate	Difference in <i>interest rate</i> between sales
Time elapsed	Time elapsed between sales (years)
Rehab	Dummy for houses rehabilitated after initial sale

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1 Table 2: Descriptive Statistics  
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Variables	Full sample	New-construction		Renovations	New-installation (A/C)		New-installation (heat)	
	Mean (standard deviation)							
Zoned Heating	0.022 (0.15)	0.088 (0.28)	0.007 (0.09)	-	-	-	-	-
Zoned A/C	0.032 (0.18)	0.128 (0.33)	0.001 (0.04)	-	-	-	-	-
Δ Zoned Heating	-	-	0.010 (0.10)	0.011 (0.10)	0.013 (0.12)			
Δ Zoned A/C	-	-	0.016 (0.13)	0.016 (0.13)	0.018 (0.13)			
1 - 5 years	0.09 (0.29)	-	0.07 (0.26)	0.04 (0.20)	0.06 (0.24)			
6 - 10 years	0.09 (0.28)	-	0.11 (0.32)	0.04 (0.19)	0.08 (0.28)			
11 - 25 years	0.19 (0.39)	-	0.20 (0.40)	0.07 (0.25)	0.15 (0.35)			
26 - 50 years	0.39 (0.49)	-	0.40 (0.49)	0.32 (0.47)	0.41 (0.49)			
51 - 100 years	0.15 (0.36)	-	0.17 (0.38)	0.39 (0.49)	0.24 (0.43)			
100+ years	0.01 (0.12)	-	0.01 (0.11)	0.06 (0.23)	0.02 (0.13)			
Age unknown	0.04 (0.20)	-	0.03 (0.17)	0.08 (0.28)	0.03 (0.18)			
Multistory	0.61 (0.49)	0.92 (0.27)	0.60 (0.49)	0.46 (0.50)	0.49 (0.50)			
Rooms	7.51 (1.73)	8.86 (1.69)	7.34 (1.60)	6.66 (1.64)	7.04 (1.69)			
Square footage (log)	7.22 (0.38)	7.42 (0.32)	7.18 (0.35)	6.97 (0.42)	7.10 (0.38)			
Lot size (log)	9.07 (0.37)	9.19 (0.29)	9.05 (0.34)	8.94 (0.40)	9.00 (0.38)			
Tax rate	1.70 (0.33)	1.75 (0.33)	1.71 (0.35)	1.80 (0.36)	1.71 (0.35)			
Interest rate	7.40 (0.87)	7.46 (0.80)	7.74 (0.66)	7.77 (0.71)	7.61 (0.72)			
Distance to CBD (log)	-0.88 (0.44)	-0.65 (0.37)	-0.85 (0.48)	-0.86 (0.57)	-0.92 (0.49)			
Neighborhood adoption: heating	0.020 (0.05)	0.041 (0.07)	0.018 (0.04)	0.012 (0.03)	0.017 (0.04)			
Neighborhood adoption: A/C	0.028 (0.06)	0.06 (0.09)	0.02 (0.05)	0.02 (0.04)	0.02 (0.05)			
Median household income (log)	11.10 (0.35)	11.25 (0.31)	11.07 (0.33)	10.89 (0.37)	11.07 (0.35)			
Median house value (log)	12.17 (0.46)	12.32 (0.41)	12.19 (0.45)	12.02 (0.54)	12.14 (0.50)			
Population density (log)	8.18 (0.83)	7.40 (0.96)	8.13 (0.86)	8.37 (0.91)	8.28 (0.84)			
Vacant housing unit rate	2.74 (2.89)	4.10 (3.95)	2.65 (2.53)	3.39 (2.91)	2.80 (2.90)			
Percent renters	14.77 (15.34)	9.81 (11.82)	13.98 (14.54)	21.80 (16.71)	14.57 (14.23)			
Percent college graduate	37.25 (20.28)	42.89 (18.37)	36.37 (19.40)	29.83 (22.67)	35.66 (20.79)			
Sales in 1992	0.04 (0.19)	0.02 (0.14)	-	0.00 (0.05)	-			
Sales in 1993	0.04 (0.19)	0.02 (0.15)	0.01 (0.08)	0.01 (0.09)	0.01 (0.09)			
Sales in 1994	0.05 (0.21)	0.05 (0.21)	0.00 (0.05)	0.00 (0.06)	0.00 (0.06)			
Sales in 1995	0.07 (0.26)	0.06 (0.24)	0.01 (0.09)	0.01 (0.11)	0.01 (0.09)			
Sales in 1996	0.08 (0.27)	0.09 (0.28)	0.03 (0.16)	0.04 (0.20)	0.02 (0.13)			
Sales in 1997	0.08 (0.28)	0.11 (0.31)	0.04 (0.21)	0.06 (0.23)	0.04 (0.19)			
Sales in 1998	0.10 (0.30)	0.13 (0.33)	0.07 (0.26)	0.08 (0.26)	0.07 (0.26)			
Sales in 1999	0.10 (0.30)	0.14 (0.35)	0.10 (0.29)	0.10 (0.31)	0.07 (0.26)			

Sales in 2000	0.10 (0.30)	0.13 (0.33)	0.12 (0.33)	0.13 (0.34)	0.10 (0.29)
Sales in 2001	0.09 (0.29)	0.10 (0.30)	0.14 (0.35)	0.14 (0.35)	0.13 (0.33)
Sales in 2002	0.10 (0.30)	0.07 (0.26)	0.17 (0.38)	0.16 (0.37)	0.18 (0.38)
Sales in 2003	0.10 (0.30)	0.06 (0.24)	0.20 (0.40)	0.18 (0.38)	0.24 (0.42)
Sales in 2004	0.05 (0.21)	0.03 (0.17)	0.10 (0.30)	0.09 (0.28)	0.14 (0.35)
Spring	0.21 (0.41)	0.21 (0.41)	0.29 (0.45)	0.28 (0.45)	0.31 (0.46)
Summer	0.26 (0.44)	0.23 (0.42)	0.33 (0.47)	0.32 (0.47)	0.29 (0.46)
Fall	0.18 (0.39)	0.18 (0.38)	0.22 (0.41)	0.21 (0.41)	0.23 (0.42)
Winter	0.13 (0.34)	0.17 (0.38)	0.16 (0.37)	0.19 (0.39)	0.17 (0.37)
Δ square footage (log)	-	-	0.05 (0.19)	0.07 (0.30)	0.06 (0.21)
Δ lotsize (log)	-	-	-0.01 (0.21)	-0.02 (0.21)	-0.02 (0.23)
Δ interest rate	-	-	-0.79 (0.97)	-0.73 (0.94)	-0.82 (0.93)
Time elapsed	-	-	3.73 (2.31)	4.01 (2.73)	3.22 (2.39)
Rehab	-	-	0.01 (0.12)	0.03 (0.20)	0.01 (0.14)

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<sup>a</sup> Renovations and new-installations samples are combined as **repeat** sample for simplification. The descriptive statistics of these two samples are generally similar. Variables measured at time of first sale.

1 Table 3: Logit Results for New-Construction Sample

Number of obs. =	6770		6770	
Log likelihood =	-1373.031		-1276.951	
McFadden's pseudo-R <sup>2</sup> =	0.480		0.434	
	<b>A/C</b>		<b>Heating</b>	
<b>Variables</b>	<b>Coef.</b>	<b>Std. Err.</b>	<b>Coef.</b>	<b>Std. Err.</b>
Multistory	0.612	(0.324) *	0.924	(0.402) **
Rooms	0.051	(0.049)	0.007	(0.048)
Square footage (log)	4.042	(0.307) ***	3.502	(0.298) ***
Lot size (log)	0.524	(0.192) ***	0.081	(0.186)
Tax rate	-1.609	(0.484) ***	-1.430	(0.457) ***
Interest rate	0.124	(0.174)	0.391	(0.183) **
Neighborhood adoption	1.960	(4.524)	-0.489	(5.044)
Distance to CBD (log)	-0.649	(0.388) *	-0.212	(0.371)
Median household income (log)	-0.321	(0.520)	-0.807	(0.506)
Median house value (log)	0.449	(0.387)	0.629	(0.374) *
Population density (log)	0.035	(0.109)	0.198	(0.114) *
Percent vacant	-0.004	(0.018)	0.020	(0.018)
Percent renters	0.002	(0.009)	0.003	(0.009)
Percent college graduate	1.501	(0.770) *	1.901	(0.760) **
Sales in 1998	0.187	(0.237)	0.359	(0.249)
Sales in 1999	0.079	(0.204)	-0.059	(0.212)
Sales in 2000	0.146	(0.209)	-0.126	(0.217)
Sales in 2001	0.149	(0.245)	0.183	(0.252)
Sales in 2002	0.767	(0.307) **	0.637	(0.319) **
Sales in 2003	0.390	(0.411)	0.480	(0.423)
Sales in 2004	0.821	(0.435) *	0.794	(0.452) *
Summer	0.353	(0.133) ***	0.263	(0.140) *
Fall	0.156	(0.153)	0.228	(0.159)
Winter	-0.013	(0.155)	0.219	(0.160)
Constant	-41.043	(6.083) ***	-33.269	(5.822) ***

\*p < .10. \*\*p < .05. \*\*\*p < .01.

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1 Table 4: Logit Results for Renovations Sample

	A/C		Heating	
Variables	Coef.	Std. Err.	Coef.	Std. Err.
Number of obs. =	18163		18163	
Log likelihood =	-987.268		-632.206	
McFadden's pseudo-R <sup>2</sup> =	0.462		0.468	
6 - 10 years	-1.212	(0.277) ***	-1.352	(0.389) ***
11 - 25 years	-1.367	(0.245) ***	-1.499	(0.332) ***
26 - 50 years	-1.937	(0.240) ***	-1.890	(0.305) ***
51 - 100 years	-1.443	(0.254) ***	-1.446	(0.317) ***
100+ years	-1.003	(0.452) **	-1.859	(0.792) **
Age unknown	-0.637	(0.407)	-0.270	(0.470)
Multistory	-0.180	(0.184)	-0.236	(0.237)
Rooms	0.028	(0.058)	0.082	(0.078)
Square footage (log)	3.277	(0.336) ***	1.744	(0.436) ***
Lot size (log)	-0.042	(0.230)	0.220	(0.289)
Tax rate	-1.289	(0.399) ***	-1.564	(0.501) ***
Interest rate	0.457	(0.268) *	0.147	(0.341)
Neighborhood adoption	7.853	(5.051)	25.252	(7.251) ***
Distance to CBD (log)	-0.590	(0.333) *	-0.198	(0.412)
Median household income (log)	0.449	(0.553)	-1.808	(0.635) ***
Median house value (log)	-0.028	(0.399)	0.904	(0.485) *
Population density (log)	0.078	(0.128)	0.099	(0.167)
Percent vacant	0.050	(0.025) **	0.048	(0.032)
Percent renters	0.016	(0.008) *	-0.002	(0.010)
Percent college graduate	1.381	(0.872)	2.377	(1.062) **
Sale in 1998	2.025	(1.078) *	-0.581	(0.830)
Sale in 1999	1.844	(1.058) *	0.258	(0.691)
Sale in 2000	1.771	(1.060) *	0.006	(0.704)
Sale in 2001	2.007	(1.058) *	0.233	(0.698)
Sale in 2002	1.946	(1.083) *	0.165	(0.760)
Sale in 2003	2.241	(1.131) **	0.357	(0.871)
Sale in 2004	2.294	(1.141) **	0.686	(0.888)
Summer	-0.186	(0.170)	-0.023	(0.223)
Fall	-0.148	(0.200)	-0.106	(0.266)
Winter	-0.275	(0.219)	-0.268	(0.287)
Δ square footage (log)	3.535	(0.333) ***	2.909	(0.405) ***
Δ lotsize (log)	-0.222	(0.354)	-0.267	(0.443)

Δ interest rate	0.253	(0.231)	0.080	(0.296)
Time elapsed	0.094	(0.051) *	0.018	(0.066)
Rehab	0.416	(0.348)	0.488	(0.427)
Constant	-37.780	(6.629) ***	-11.536	(7.848)

\*p < .10. \*\*p < .05. \*\*\*p < .01.

Note: Both models include dummy variables for the year of the (second) sale.

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1 Table 5: Logit Results for New-Installations Sample

Number of obs. =	2682		1337	
Log likelihood =	-132.453		-56.234	
McFadden's pseudo-R <sup>2</sup> =	0.615		0.544	
	A/C		Heating	
Variables	Coef.	Std. Err.	Coef.	Std. Err.
Multistory	0.497	(0.509)	0.061	(0.823)
Rooms	-0.210	(0.151)	0.141	(0.224)
Square footage (log)	2.593	(0.972) ***	2.636	(1.446) *
Lot size (log)	1.509	(0.630) **	1.116	(0.793)
Tax rate	0.544	(0.809)	-2.344	(1.303) *
Interest rate	-0.528	(0.694)	-1.714	(0.964) *
Neighborhood adoption	37.287	(16.799) **	10.871	(25.485)
Distance to CBD (log)	-0.202	(0.628)	-1.019	(0.993)
Median household income (log)	-1.252	(1.196)	-0.827	(2.235)
Median house value (log)	0.676	(1.003)	-1.407	(1.514)
Population density (log)	1.666	(0.546) ***	-0.427	(0.573)
Percent vacant	0.029	(0.074)	0.060	(0.083)
Percent renters	-0.037	(0.021) *	-0.001	(0.035)
Percent college graduate	2.854	(1.864)	2.706	(3.087)
Sale in 1998/1999 <sup>a</sup>	-0.639	(1.248)	-4.536	(1.482) ***
Sale in 2000	-0.042	(1.225)	-2.424	(1.387) *
Sale in 2001	-0.405	(1.291)	-3.965	(1.389) ***
Sale in 2002	-1.307	(1.450)	-	-
Sale in 2003	-0.535	(1.673)	-	-
Sale in 2004	-1.576	(1.713)	-	-
Sale in 2002/2003/2004 <sup>a</sup>	-	-	-6.197	(2.068) ***
Summer	-0.409	(0.473)	0.450	(0.704)
Fall	-0.411	(0.578)	-1.084	(1.013)
Winter	-0.472	(0.538)	-0.337	(0.964)
Δ square footage (log)	3.995	(0.654) ***	5.343	(1.295) ***
Δ lotsize (log)	1.371	(1.320)	1.158	(1.734)
Δ interest rate	-0.311	(0.594)	-1.040	(0.874)
Time elapsed	-0.058	(0.144)	0.106	(0.254)
Rehab	1.060	(0.540) *	-0.785	(1.736)
Constant	-41.903	(15.920) ***	12.079	(23.323)

2 \*p < .10. \*\*p < .05. \*\*\*p < .01.

3 <sup>a</sup> Due to small sample for some years, the *Sale in YEAR* dummies combine some categories here.

1 Table 6: Joint Hypothesis Tests for Unrestricted Models<sup>a</sup>

Group of variables	Renovations				New-Constructions			
	A/C		Heat		A/C		Heat	
	$\chi^2$	p	$\chi^2$	p	$\chi^2$	p	$\chi^2$	p
architectural styles	37.21	0.06	14.56	0.95	24.85	0.41	18.50	0.78
structural styles	8.17	0.70	7.82	0.73	6.34	0.85	9.14	0.61
exterior types	6.13	0.41	6.84	0.33	101.76	<0.001	81.40	<0.001
roofing types	7.28	0.06	12.63	0.01	13.86	0.03	8.2	0.04
age categories	58.04	<0.001	45.14	<0.001	n/a	n/a	n/a	n/a

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3 <sup>a</sup> Model specifications follow those in Tables 3 and 4, except for inclusion of vectors of dummy  
4 variables for the groups: architectural styles (American 4-Square, Bi-Level, Brownstone,  
5 Bungalow, Cape Cod, Colonial, Contemporary, Cottage, English, Farmhouse, French  
6 Provincial, Georgian, Greystone, Long, Mediterranean/Spanish, Prairie, Quad Level, Queen  
7 Anne, Ranch, Rowhouse, Step Ranch, Traditional, Tri-Level, Tudor, Victorian, Other),  
8 structural types (1 story, 1.5 story, 2 stories, 3 stories, 4 stories, coach house, hillside, Raised  
9 ranch, split level, split level w/sub, other), exterior materials (Aluminum/Vinyl/Steel, brick,  
10 cedar, frame, stucco, stone, clad trim), and roof materials (Asphalt/Glass(Rolled),  
11 Asphalt/Glass(Shingles), Wood Shakes/Shingles).