Energy efficiency information asymmetries in the rental housing market

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Abstract: Renter-occupied residences are less likely to have energy efficient technologies than are similar owner-occupied residences, resulting in higher energy consumption and increased emissions. Using data from the American Housing Survey, this paper exploits variation in payment-status (who pays the energy bill), to estimate the effect of information asymmetries on the adoption of efficient (Energy Star rated) technologies in the U.S. rental housing market. Results show that, contrary to previous findings, landlords who pay their tenants energy bill are no more likely to install energy efficient technologies, suggesting that information asymmetries play a nominal role in the adoption of efficient technologies in the rental housing market, and are not to blame for the observed gap in saturation of efficient technologies between renter- and owner-occupied residences.

Keywords: information asymmetries; energy efficiency; split incentives; technology adoption; rental housing market; energy efficiency gap

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1 Introduction

Residential energy consumption accounts for 19% of U.S. energy-related carbon emissions (U.S. Energy Information Administration, 2019). To reduce emissions and energy costs, homeowners often choose to install efficient technologies such as Energy Star rated appliances or additional insulation. Since 2005, however, home-rentership has been on the rise, and as of 2016, 37% of heads of households are home-renters rather than homeowners; the highest since 1965 (Pew Research Center, 2017). When residences are rented, landlord-tenant rental contracts give rise to two potential market failures.

The first occurs when landlords pay their tenant's energy bill: tenants face a moral hazard problem and do not have an incentive to conserve energy (Levinson and Niemann, 2004; Gillingham, Kenneth Harding and Rapson, 2012). Such inefficiencies have long been recognized (Blumstein et al., 1980; Fisher and Rothkopf, 1989), and have in large part been resolved by encouraging/requiring residential buildings to be individually metered for energy. Under the Public Utilities Regulatory Policies Act of 1978, newly built apartments are required to be individually metered for electricity, and sub-metering (of all energy types) is encouraged by federal energy efficiency guidelines.[1] As a result tenants pay the energy bill in most residential rental contracts: as of 2011, tenants pay the electricity bill in 89% of renter-occupied units (American Housing Survey).

Requiring tenants to pay the energy bill, however, gives rise to a second potential market failure: landlords who do not pay their tenant's energy bill, may have less incentive to install energy efficient technologies (Davis, 2010; Gillingham, Kenneth Harding and Rapson, 2012). If prospective tenants cannot observe the energy efficiency of candidate housing units (level of insulation, efficiency of appliances, etc.), they will be unwilling to pay a rent premium for any unobserved energy efficiency investments. Landlords will in turn be unwilling to adopt more costly energy efficient technologies. The result is an under-saturation of energy efficient technologies in the rental housing market, causing

[1] "Tenant submetering can be one of the most cost-effective energy conservation measures available. A large portion of the energy use in tenant facilities occurs simply because there is no economic incentive to conserve." 1998 Code of Federal Regulations, Title X, part 435.106.

higher energy consumption and increased emissions.

Concern for energy efficiency information asymmetries in the rental housing market stems from the observed difference in saturation of efficient technologies in renter- and owner-occupied residences: renter-occupied residences are 10% less likely to have energy efficient appliances, and are 16% less likely to be properly insulated relative to similar owner-occupied residences (Davis, 2010; Gillingham, Kenneth Harding and Rapson, 2012). Because most rental contracts require the tenant to pay the energy bill, the difference in saturation is often assumed to be the result of information asymmetries (see Allcott and Greenstone (2012), Gillingham and Palmer (2014), or Gerarden et al. (2017) for review).

The difference in saturation of efficient technologies between renter- and owner-occupied residences, however, is only indicative of information asymmetries if we assume that renters and owners are identical. For example, if renters and owners have different preferences for energy efficiency, then the divergence in preferences may explain the difference in saturation of efficient technologies, absent information asymmetries (Myers, 2017).

The objective of this paper is to identify the causes of the observed difference in saturation of efficient technologies between renter- and owner-occupied units. In particular, I focus on testing the effects of information asymmetries on the adoption of efficient technologies in the rental housing market. I then use these results to identify potential mechanisms that are responsible for the observed difference in saturation of efficient technologies between renter- and owner-occupied residences.

Two existing papers have explored energy efficiency information asymmetries in the rental housing market. Myers (2017) uses a housing search model to predict turnover rates, capitalization, and the adoption of efficient technologies in the northeastern U.S. Their identifying assumption is that under perfect information, a price shock to energy costs should not cause the outcomes of interest (turnover, capitalization, and technology adoption) to vary systematically across energy payment-status. Myers (2017) finds that under a price shock these outcomes do vary systematically by payment-status, and that price shocks affect turnover rates, capitalization, and the adoption of efficient technologies in ways consistent with housing market predictions under asymmetric information. This paper builds on the work of Myers (2017), by using a nationally representative sample (over 40,000 observations) and a reduced-form identification strategy to characterize energy efficiency technology adoption across all regions of the U.S.

Using the nationally representative 2011 American Housing Survey (the same data used in this analysis), Souza (2018) uses variation in energy payment-status to identify the effects of information asymmetries on the adoption of energy efficient appliances. They find that renter-occupied units are less likely to have efficient appliances, but that this difference attenuates when the unit has an energy-included rental contract (a contract in which the landlord pays the energy bill), suggesting the prevalence of information asymmetries. Problematically, Souza (2018) fails to address the simultaneity between a landlords decision to adopt an efficient technology, and their decision to offer an energy-included rental contract. After addressing this simultaneity using an instrumental variables approach, our results contradict those of Myers (2017) and Souza (2018).

This paper contributes to the literature on residential energy efficiency technology adoption in two important ways. The first is the development of a theoretical framework that is used to conceptualize an owner's decision to adopt an efficient technology and identify the mechanisms that may drive the gap in saturation of efficient technologies between owner- and renter-occupied residences. The second is a refinement of the current analysis on energy efficiency technology adoption in the rental housing market: I address the simultaneity in the owners technology adoption decision, allow for heterogenous effects of housheold/unit characteristics across tenure-status, and use nationally representative sample. After extending the analysis of Myers (2017) and Souza (2018), we find that landlords who pay their tenants energy bill are no more likely to install efficient technologies, suggesting that information asymmetries play a nominal role in the adoption of efficient technologies in the rental housing market, and are not to blame for the observed gap in saturation of efficient technologies between renter- and owner-occupied residences.

In the next section, a simple framework is developed to analyze the adoption of efficient technologies in renter- and owner-occupied residences (section 2). In section 3 we survey descriptive statistics of householder and housing unit characteristics, before analyzing how information asymmetries affect the adoption of efficient technologies (section 4). Finally, with results in hand, the simple framework is revisited to discuss which mechanisms may be at play in driving the gap in saturation of energy efficient technologies in renter- and owner-occupied residences (section 5).

2 Theoretical framework

A simple framework is needed to analyze the adoption of efficient technologies in renter- and owner-occupied residences. The framework describes the owner's purchase decision between two energy consuming goods that differ in energy efficiency, and the occupant's energy consumption decision.[2] The owner and occupant may be the same person, in which case the unit is owner-occupied, or they may be different, in which case the unit is renter-occupied (landlords are simply owners of renter-occupied units). This framework is applicable to many purchase decisions involving energy consuming durable goods (e.g. heater, air-conditioner, lighting, etc.), but can also be applied to water consuming durable goods (e.g. toilets, showers, sprinkler systems, etc.).

For tractability the framework is described in terms of an owner's decision to purchase a heating system and the occupant's choice of heat output, since space heating a cooling are the most consumptive end-uses in U.S. residences (U.S. Energy Information Administration, 2019). It can, however, be easily extended to other energy use and purchase decisions. In the first period, the owner chooses which heat system to install (energy efficient or inefficient), and makes the purchase. In the second period, the occu-

[2]The framework used to model the purchase decision builds on the work of Allcott et al. (2011) and Allcott and Greenstone (2012).

pant consumes heat output, which results in energy costs. Energy costs are paid by the owner for owner-occupied units, and renter-occupied units with energy-included rental contracts. Rental contracts are considered energy-included when the occupant reports that they do not pay an additional bill (separate from rent) for their energy use.

We normalize energy prices from different sources using the price/BTU of energy input denoted by P_{BTU}. We let heat output be equal to $\text{Heat}_\tau = BTU * E_\tau$, where BTU is energy input and E_τ is the energy efficiency factor. The energy efficiency factor (E_τ) varies with the type of heat system $\tau \in \{\text{efficient, inefficient}\}$, and $E_{\text{inefficient}}$ is less than $E_{\text{efficient}}$. Lastly, to account for the role of payment-status on energy use and technology adoption we let $I(\text{occupant-pays})$ be an indicator that equals one if the occupant pays the energy bill, and zero otherwise. Then, occupants choose energy consumption (BTU) and consumption of a composite good (X) to solve their utility maximization problem:

$$\begin{aligned} &\max_{BTU,X} U(\text{Heat} = BTU \times E_\tau, X), \\ \text{subject to:}& \\ &P_{BTU} \times BTU \times I(\text{occupant-pays}) + X \leq \text{Income}, \end{aligned} \tag{1}$$

Utility is increasing in X, and exhibits diminishing marginal returns (i.e. $U'_X > 0$, and $U''_X < 0$). Utility is also increasing in heat, but only at low levels of heat consumption; we assume there exists Heat_{opt} beyond which occupants are made worse off by increasing their heat consumption (i.e. at low levels of heat $U'_{\text{Heat}}(\text{Heat}_{\text{low}}) > 0$, at high levels of heat $U'_{\text{Heat}}(\text{Heat}_{\text{high}}) < 0$, $U''_{\text{Heat}} < 0$, and $U'_{\text{Heat}}(\text{Heat}_{\text{opt}}) = 0$).

Then assuming an interior solution (and rewriting the budget constraint recognizing that $BTU = \frac{\text{Heat}}{E\tau}$), first order conditions of the occupant's utility maximization problem are given by:

$$U'_{Heat} - \lambda \frac{P_{BTU}}{E_\tau} \times I(\text{occupant-pays}) = 0 \quad (2)$$

$$U'_X - \lambda = 0 \quad (3)$$

$$\text{Income} - P_{BTU} \times BTU \times I(\text{occupant-pays}) - X = 0 \quad (4)$$

When tenants do not pay for heat ($I(\text{occupant-pays}) = 0$), their heat consumption is not limited by their budget constraint, so they consume at their bliss point denoted by Heat_{opt} ($U'_{Heat} = 0$, and any more consumption would lead to disutility). Tenants who do not pay for heat consume Heat_{opt} regardless of energy efficiency ($\text{Heat}^*_{0,\text{efficient}} = \text{Heat}^*_{0,\text{inefficient}} = \text{Heat}_{opt}$).

When tenants do pay for heat ($I(\text{occupant-pays}) = 1$), they equate the marginal utility per dollar of heat consumption with that of the composite good:

$$\frac{U'_{\text{Heat}} E_\tau}{P_{BTU}} = U'_X. \quad (5)$$

Equation 5 implies that when tenants pay for heat ($I(\text{occupant-pays}) = 1$), they consume less than they would under a utility-included contract ($\text{Heat}^*_{0,\tau} > \text{Heat}^*_{1,\tau}$). Furthermore, because $E_{\text{efficient}} > E_{\text{inefficient}}$, tenants who do pay for heat consume more of it when they have the efficient heater ($\text{Heat}^*_{1,\text{efficient}} > \text{Heat}^*_{1,\text{inefficient}}$).[3] These results follow economic intuition: occupant's who face the highest marginal cost of heat output (those that pay for heat and have an inefficient heater) will consume the least heat, whereas occupant's who face the lowest marginal cost of heat output (those that do not pay for heat) will consume the most.

The occupants choice of heat output can be written as a function of the price of heat ($\frac{P_{BTU}}{E_\tau} \times I(\text{occupant-pays})$), the price of the composite good (normalized to one), and household income. This analysis is primarily focused on how payment-status and energy

[3]Follows from the fact that $U''_{\text{Heat}} < 0$ and $U'_{\text{Heat}}(\text{Heat}_{1,\text{efficient}}, X) < U'_{\text{Heat}}(\text{Heat}_{1,\text{inefficient}}, X)$.

efficiency affect the heat consumption and technology adoption decisions, so we denote the occupant's optimal choice of heat output (energy input) as a function of payment-status and energy efficiency alone: $BTU^*_{I(\text{occupant-pays}),\tau}$. We do, however, acknowledge the affects of income and prices on the heat output decision (and subsequent technology adoption decision) in our empirical analysis by including household income and regional dummies to control for income and prices respectively.

Using the occupant's heat output decision, we can characterize the owner's purchase decision. The owner purchases the efficient heat system if the expected net present value of doing so is positive. The incremental upfront cost of the efficient heat system is C, and the risk-adjusted discount rate is $r > 0$. The parameter γ embodies the role of asymmetric information and is used to weight the value of expected energy cost savings. All other costs (and benefits) that are associated with the purchase of the efficient heat system, and are internalized by the owner, are captured in ξ. Then, the owner should purchase the efficient heat system if the discounted sum of energy cost savings and additional costs/benefits (ξ), is greater than the incremental upfront cost:

$$\frac{1}{1+r}\left(\gamma P_{BTU}(BTU^*_{\text{inefficient}} - BTU^*_{\text{efficient}}) + \xi\right) > C. \tag{6}$$

When an owner installs the efficient heat system they capitalize on energy cost savings either directly, if they are the ones paying the energy bill, or indirectly, through rent premiums. Due to information asymmetries, rent premiums imperfectly capture energy cost savings, so γ is allowed to vary by payment-status: $\gamma_{I(\text{owner-pays})}$ where $I(\text{owner-pays}) = 1$ if the owner pays the energy bill, and zero otherwise. In practice we might imagine $\gamma_1 = 1$, because there are no information asymmetries when the owner pays the energy bill, and $\gamma_0 \in [0, 1]$.

Installing an efficient heat system generates several additional costs/benefits (included in ξ) that affect only the occupant: noise, aesthetic, features, etc. These additional costs/benefits that do not affect the owner directly, are imperfectly captured through rent premiums, so ξ is allowed to vary by occupancy-status: ξ_s where $s \in$ {owner: owner-occupied, renter: renter-occupied}. The risk-adjusted discount rate is also allowed to vary by occupancy-status: owners may have different credit constraints if they are investing in renter- versus owner-occupied units. Then the revised owner purchase decision is given by:

$$\frac{1}{1+r_s}\left(\gamma_{I(\text{owner-pays})} P_{BTU}(BTU^*_{I(\text{occupant-pays}),\text{inefficient}} - BTU^*_{I(\text{occupant-pays}),\text{efficient}}) + \xi_s\right) > C, \tag{7}$$

where optimal energy input, $BTU^*_{I(\text{occupant-pays}),\tau}$, is the solution to the occupants utility maximization problem.

By comparing the owner's willingness to pay for the efficient technology across different payment- and occupancy-status (equation 7), we are able to shed light on the mechanisms that drive the differences in saturation of efficient technologies. Consider an owner's willingness to pay for the efficient heat system when the unit is owner-occupied, compared to their willingness to pay when the unit is renter-occupied and the tenant pays the energy bill. Previous findings have shown that owner-occupied residences are more likely to have efficient technologies than are similar renter-occupied residences (Davis, 2010; Gillingham, Kenneth Harding and Rapson, 2012). Therefore an owner's willingness to pay must be higher when the unit is owner-occupied. That is,

$$\begin{aligned} WTP(\text{owner-pays, owner-occupied}) &= \frac{\gamma_1 P_{BTU}(BTU^*_{1,\text{inefficient}} - BTU^*_{1,\text{efficient}}) + \xi_{\text{owner}}}{1 + r_{\text{owner}}} \\ &> \frac{\gamma_0 P_{BTU}(BTU^*_{1,\text{inefficient}} - BTU^*_{1,\text{efficient}}) + \xi_{\text{renter}}}{1 + r_{\text{renter}}} \\ &= WTP(\text{occupant-pays, renter-occupied}). \end{aligned} \tag{8}$$

This inequality holds if $\gamma_1 > \gamma_0$, and $r_{\text{owner}} = r_{\text{renter}}$, $\xi_{\text{owner}} = \xi_{\text{renter}}$. That is if, due to information asymmetries, renters value energy savings from the efficient heat system less than owners, and the additional costs/benefits, and discount rate are equal across owners and renters. This is the explanation generally accepted in the literature. The inequality in equation 8 also holds, however, if $\gamma_1 = \gamma_0$ (no information asymmetries), and either $r_{\text{owner}} < r_{\text{renter}}$, or $\xi_{\text{owner}} > \xi_{\text{renter}}$. That is, there are no information asymmetries, but the risk adjusted discount rate (r_s) is lower for owners when they are purchasing efficient appliances for owner-occupied units, and/or the additional benefits that are internalized by the owner (ξ_s) are larger when the unit is owner-occupied. Contrary to the previous literature, analysis in section 4 suggests the latter.

3 Data

Data for analysis comes from the 2011 American Housing Survey. The American Housing Survey is a biannual longitudinal survey of the U.S. housing stock. For each survey year data is collected on housing unit and household characteristics (Tables 1 – 3). The 2011 American Housing Survey included a topical module on energy efficiency, which asked respondents which appliances were installed in the unit and which of their appliances were Energy Star rated (Tables 4 and 5). Respondents were also asked which type of energy (electricity, natural gas, fuel oil, etc.) each of their appliances used, and energy payment-status (who pays the energy bill) for each type of energy (Table 6).

Descriptive statistics are compared across occupancy-status (owner- or renter-occupied) and payment-status (who pays the energy bill). The owner pays the energy bill in all owner-occupied units. In general, payment-status is specific to the particular type of energy use. For example, the landlord may pay for heat because the unit is heated with a gas fired central boiler, while the tenant may pay for air-conditioning which runs on sub-metered electricity. Descriptive statistics presented in most of the tables below are not compared across each payment-status for each energy-type. Instead, in many of the tables below energy payment-status refers to which party pays for electricity.

On average, owners are older, more educated, and have higher income than do renters. Owners are disproportionately more likely to be white, and less likely to be

Black, Asian, Indigenous, or Other races (Table 1). Owner-occupied units tend to have more total occupants, and the mean number of adult occupants in owner-occupied units is approximately two; the mean number of adult occupants in renter-occupied units is approximately 1.5.

Renters, on average, have similar education levels, and race compositions, regardless of energy payment-status. Renters with landlords that pay their energy bill, however, tend to be older, and have lower income; they also have fewer total occupants, and fewer adult occupants.

Table 1: Householder/household descriptive statistics

	(1)	(2)	(3)	p-value of difference		
	Owner	Renter: Landlord Pays	Renter: Tenant Pays	(1)-(2)	(1)-(3)	(2)-(3)
Household income	75,583	26,578	38,432	0.000	0.000	0.000
Householder age	54.322	49.462	41.666	0.000	0.000	0.000
Less than highschool	0.108	0.246	0.173	0.000	0.000	0.000
Completed highschool	0.256	0.277	0.265	0.048	0.032	0.296
Some college	0.166	0.203	0.207	0.000	0.000	0.683
Completed college	0.335	0.209	0.283	0.000	0.000	0.000
Graduate degree	0.135	0.066	0.072	0.000	0.000	0.285
White	0.858	0.688	0.703	0.000	0.000	0.193
Black	0.088	0.219	0.211	0.000	0.000	0.415
Asian	0.036	0.050	0.050	0.002	0.000	0.939
Indigenous	0.006	0.018	0.014	0.000	0.000	0.210
Other race	0.013	0.025	0.022	0.001	0.000	0.531
# of occupants	2.572	1.906	2.475	0.000	0.000	0.000
# of adult occupants	1.990	1.495	1.742	0.000	0.000	0.000

Landlords may pay for the use of some fuels, but not for others. In this table, the 'Landlord Pays' and 'Tenant Pays' indicators are specific to which party pays for electricity.

Owner-occupied housing units tend to be newer, and larger than renter-occupied units (Table 2). Among renter-occupied units, the monthly rent is similar across payment-status, although units in which the landlord pays the electric bill tend to be of lower quality in that they are older, smaller, and more likely to be part of larger multi-unit buildings.

Renter-occupied units are more likely to be centrally located in a city, or in an urban area (Table 3). The Mountain and Pacific combined census division have the highest

Table 2: Housing unit descriptive statistics

	(1) Owner	(2) Renter: Landlord Pays	(3) Renter: Tenant Pays	p-value of difference (1)-(2)	(1)-(3)	(2)-(3)
Rent	-	879.12	885.835	-	-	0.761
Building age	42.270	50.668	46.144	0.000	0.000	0.000
# bedrooms	2.983	1.580	2.124	0.000	0.000	0.000
# baths	1.731	1.120	1.301	0.000	0.000	0.000
# half baths	0.376	0.097	0.158	0.000	0.000	0.000
# dens	0.123	0.015	0.031	0.000	0.000	0.000
# total rooms	6.071	3.716	4.551	0.000	0.000	0.000
Has a garage	0.728	0.188	0.402	0.000	0.000	0.000
Has a porch	0.888	0.489	0.733	0.000	0.000	0.000
Has a fireplace	0.406	0.045	0.153	0.000	0.000	0.000
Has garbage disposal	0.512	0.373	0.494	0.000	0.000	0.000
Has trash compactor	0.038	0.014	0.022	0.000	0.000	0.007
Use electricity	0.999	1.000	1.000	0.000	1.161	0.039
Use natural gas	0.717	0.656	0.637	0.000	0.000	0.098
Use fuel oil	0.084	0.133	0.071	0.000	0.000	0.000
Use other oil	0.092	0.021	0.031	0.000	0.000	0.012
Single unit building	0.902	0.177	0.394	0.000	0.000	0.000
# stories	2.000	4.334	2.394	0.000	0.000	0.000
Apt 2-5 units	0.036	0.207	0.213	0.000	0.000	0.599
Apt 6-10 units	0.017	0.112	0.139	0.000	0.000	0.001
Apt 11-25 units	0.019	0.140	0.144	0.000	0.000	0.609
Apt 26-50 units	0.008	0.079	0.049	0.000	0.000	0.000
Apt 51-100 units	0.007	0.103	0.031	0.000	0.000	0.000
Apt 101-200 units	0.005	0.113	0.018	0.000	0.000	0.000
Apt 201+ units	0.005	0.068	0.013	0.000	0.000	0.000

Landlords may pay for the use of some fuels, but not for others. In this table, the 'Landlord Pays' and 'Tenant Pays' indicators are specific to which party pays for electricity.

proportion of renter-occupied units (33.9%), followed by the Middle Atlantic division (32.1%). Regions with a 'Mild' climate have the highest proportion of renter-occupied units (32.1%), while regions with the 'Coldest' climate have the lowest proportion of renter-occupied units (23.2%). Among renter-occupied units, those located in colder climates are more likely to have an electricity-included rental contract, and units with electricity-included rental contracts are more likely to be located in a central city.

Table 4 shows the adoption of common appliances (air conditioning, central heat, refrigerator, dishwasher, clothes washer, and clothes dryer) across occupancy-status. Renter-occupied units are less likely to have most of these appliances, though renter-

Table 3: Unit geographic descriptive statistics

	(1)	(2)	(3)	p-value of difference		
	Owner	Renter: Landlord Pays	Renter: Tenant Pays	(1)-(2)	(1)-(3)	(2)-(3)
Central city of MSA	0.224	0.540	0.426	0.000	0.000	0.000
Inside MSA, but not central - urban	0.357	0.271	0.347	0.000	0.037	0.000
Inside MSA, but not central - rural	0.147	0.030	0.063	0.000	0.000	0.000
Outside MSA, urban	0.075	0.110	0.087	0.000	0.000	0.004
Outside MSA, rural	0.196	0.048	0.074	0.000	0.000	0.000
New England	0.049	0.076	0.043	0.000	0.006	0.000
Middle Atlantic	0.123	0.216	0.142	0.000	0.000	0.000
East North Central	0.161	0.119	0.138	0.000	0.000	0.009
West North Central	0.072	0.077	0.059	0.420	0.000	0.004
West South Central	0.115	0.087	0.114	0.000	0.892	0.000
East South Central and South Atlantic	0.281	0.189	0.234	0.000	0.000	0.000
Mountain and Pacific	0.199	0.237	0.269	0.000	0.000	0.002
Coldest	0.108	0.119	0.080	0.155	0.000	0.000
Cold	0.261	0.300	0.238	0.000	0.000	0.000
Cool	0.221	0.281	0.230	0.000	0.034	0.000
Mild	0.184	0.166	0.233	0.025	0.000	0.000
Mixed	0.140	0.072	0.126	0.000	0.000	0.000
Hot	0.085	0.062	0.092	0.000	0.013	0.000

Landlords may pay for the use of some fuels, but not for others. In this table, the 'Landlord Pays' and 'Tenant Pays' indicators are specific to which party pays for electricity. Climate zones, defined by the U.S. Census Bureau, are a function of the number of heating and cooling degree days (see American Housing Survey codebook for details).

occupied units are slightly more likely to have central heat, and a refrigerator.

To compare the adoption of efficient Energy Star rated appliances across occupancy- and payment-status, the sample is restricted to units that have any version of the appliance (Energy Star rated or otherwise) (Table 5).[4] Within this sub-sample, renter-occupied units are 16% less likely to have an Energy Star rated air conditioning system, and 13% less likely to have an Energy Star rated heat system than owner-occupied units. Renter-occupied units are also 20% less likely to have an Energy Star rated refrigerator, and 20% less likely to have an Energy Star rated dishwasher.

[4] Energy Star is an information program implemented by the U.S. Environmental Protection Agency that sets energy efficiency standards and awards qualifying durable goods an Energy Star label. Energy Star rated appliances have been approved to meet stringent energy efficiency standards.

Table 4: Adoption of appliances (Energy Star rated or otherwise)

	(1) Owner	(2) Renter	p-value (1)-(2)
Central AC	0.687	0.532	0.000
Central Heat	0.940	0.947	0.001
Clothes Washer	0.870	0.551	0.000
Clothes Dryer	0.853	0.518	0.000
Refrigerator	0.962	0.996	0.000
Dishwasher	0.706	0.498	0.000

Central Heat excludes units whose primary source of heat is a wood-burning stove, fireplace, portable space heater, cooking stove, or a room heater burning kerosene, gas, or oil.

Table 5: Adoption of *Energy Star* rated appliances

	(1)	(2)	(3)	p-value of difference		
	Owner	Renter: Landlord Pays	Renter: Tenant Pays	(1)-(2)	(1)-(3)	(2)-(3)
Energy Star Central AC	0.261	0.108	0.110	0.000	0.000	0.837
Energy Star Central Heat	0.209	0.071	0.077	0.000	0.000	0.274
Energy Star Clothes Washer	0.421	0.315	0.278	0.000	0.000	0.102
Energy Star Clothes Dryer	0.180	0.156	0.162	0.189	0.000	0.780
Energy Star Refrigerator	0.435	0.232	0.235	0.000	0.000	0.781
Energy Star Dishwasher	0.412	0.215	0.203	0.000	0.000	0.563

The 'Landlord Pays' and 'Tenant Pays' indicators are specific to the fuel used by each appliance, and which party pays for the use of that fuel.

Among renter-occupied units, however, units with landlords that pay the energy bill are no more likely to have Energy Star versions of each appliance than are units in which the tenant pays the energy bill. Of course further analysis is needed to reliably comment on the effect of payment-status on the adoption of Energy Star appliances, but this descriptive statistic suggests that payment-status may have a nominal effect on the adoption of efficient appliances.

Lastly, Table 6 shows fuel use by each appliance, and payment-status by each fuel type and each appliance. Table 6 is restricted to the subset of renter-occupied housing units that have adopted the given appliance in any form (Energy Star rated or otherwise). Each cell represents the percent of appliances that use the given energy type. For example, among renter-occupied units with central heat, 46.0% of units' central heat system is fueled by electricity.

The 'Landlord Pays' column (Table 6) reports the percentage of renter-occupied units with the given appliance, that have a landlord who pays the appliances fuel bill (bill corresponding to the fuel used by the appliance). For example, landlords pay the heat bill in 20.4% of the renter-occupied units with central heat. The 'Landlord Pays' row reports the percentage of renter-occupied units connected to the given fuel type, that have a landlord who pays the bill. For example, landlords pay the electric bill in 11.3% of renter-occupied units that have electricity.

Table 6: Fuel use and payment-status

	Electricty	Natural Gas	Fuel Oil	Other fuels[a]	Landlord Pays
Central Heat	0.460	0.465	0.069	0.006	0.204
Central AC	0.981	0.019	-	-	0.089
Clothes Dryer	0.842	0.157	-	-	0.062
Clothes Washer	1.000	-	-	-	0.061
Refrigerator	1.000	-	-	-	0.112
Dishwasher	1.000	-	-	-	0.067
Landlord Pays	0.113	0.265	0.752	0.494	

[a] Other fuels include wood, coal, kerosene, or any other fuel.

Of all end uses, landlords are most likely to pay for central heat, followed by refrigeration. Among all energy types, landlords are most likely to pay for fuel oil, though fuel oil is only used in 7.9% of renter-occupied units in our sample. It is far more common to observe a unit in which the landlord pays for natural gas: 17% of renter-occupied units use and have a landlord that pays for natural gas.

4 Estimation and results

The objective of this analysis is to estimate the effect of information asymmetries on the adoption of energy efficient technologies including: central heaters, central air conditioners, clothes dryers, clothes washers, refrigerators and dishwashers. To accomplish this we first estimate the effect of payment-status on owners' energy efficiency technology adoption decision. Then, given the estimated effect of payment-status on energy efficiency adoption, we revisit the owner's willingness to pay function (equation 7) to identify the effect of information asymmetries on the adoption of energy efficient technologies.

4.1 The effect of payment-status on the adoption of energy efficient technologies

To estimate the effect of payment-status on energy efficient technology adoption, we use a latent variable linear probablity model. Souza (2018) uses a similar identification strategy, with two notable distinctions. First, Souza (2018) assumes that all covariates affect the efficiency adoption decision in renter- and owner-occupied units equally. That is, the marginal effect of an additional bedroom, for example, on the likelihood of a unit having an efficient heater is equal for renter- and owner-occupied residences. While this assumption does not seem inherently insidious, it is not supported by the data and results in biased parameter estimates. Second, Souza (2018) does not address the simultaneity of the landlords decision to pay the energy bill, and their decision to install an efficient technology. The following analysis addresses each of these concerns, and generates results that contradict the findings of Souza (2018).

Adoption of an efficient appliance $e \in$ {central heat, central air conditioning, clothes dryer, clothes washer, refrigerator, dishwasher} in housing unit i can be characterized by the following latent variable model:

$$\text{WTP}^*_{i,e} = \alpha_e \text{I(owner-pays)}_{i,e} + X_i\beta_e + \epsilon_{i,e}, \tag{9}$$

where $\text{WTP}^*_{i,e}$ is housing unit i's willingness to pay for the efficient appliance e, and $\text{I(owner-pays)}_{i,e}$ equals one if the landlord pays for the energy that appliance e consumes and zero otherwise. Then, housing unit i will adopt the efficient appliance e if the owner's willingness to pay for the efficient version is greater than the incremental upfront cost. That is:

$$\text{Efficient}_{i,e} = \begin{cases} 0, & \text{if } \text{WTP}^*_{i,e} < C \\ 1, & \text{if } \text{WTP}^*_{i,e} \geq C. \end{cases}$$

Then, the effect of payment-status on the adoption of the efficient appliance e, can be estimated by replacing $\text{WTP}^*_{i,e}$ with $\text{Efficient}_{i,e}$ in equation 9.

It may be, however, that payment-status is endogenous in equation 9: landlords may be more likely to pay their tenants energy bill (offer an energy-included rental contract) if the unit is energy efficient (has efficient appliances). This problem can be characterized as a simultaneous equations linear probability model (Angrist, 2001):

$$\text{Efficient}_{i,e} = \alpha_e \text{I(owner-pays)}_{i,e} + X_i\beta_e + \epsilon_{i,e} \tag{10}$$

$$\text{I(owner-pays)}_{i,e} = \rho_e \text{Efficient}_{i,e} + \delta_e Z_i + X_i\phi_e + \omega_{i,e}. \tag{11}$$

To consistently estimate equation 10 we need a variable (instrument) Z, that affects payment-status ($\delta_e \neq 0$) and satisfies the exclusion restriction. Trash payment-status, which is an indicator that equals 1 if the landlord pays for trash service, and zero otherwise, satisfies both of these conditions. Trash payment-status is a relevant and valid instrument because it is correlated with energy payment-status through underlying preferences for including additional fees in the payment of rent, but otherwise uncorrelated with the landlords efficiency purchase decision. Then equation 10 can be estimated consistently using two-stage least squares (Imbens and Angrist, 1994; Angrist, 2001). First stage results are available in the appendix (Table A1). In all specifications the effective F-statistic indicates that we can reject the null of weak instruments at the 5% confidence level (Olea and Pflueger, 2013).[5]

Estimates of the average treatment effect of payment-status on the adoption of each appliance e are given by the second stage results (Table 7). All unit, household, and

[5] Effective F-statistics for each model: Heat: 124,000; AC: 128,000; Fridge: 201,000; Dishwasher: 102,000; Dryer: 125,000; Washer: 126,000.

geography characteristics are included as controls (except rent, which would be endogenous and is thus excluded). All controls are included as dummy variables. Continuous variables such as # of rooms are converted to dummy variables: one variable for each level. Some variables (# of units in the building, building age, householder age, and household income) were binned to create dummy variables.[6] Each regression is restricted to the subset of renter-occupied units that have appliance e in any form (Energy Star rated or otherwise).

Table 7: Probability the unit has an Energy Star appliance (equation 10)

	Heat	AC	Fridge	Dishwasher	Dryer	Washer
I(owner-pays)$_{i,e}$	-0.013	0.048	-0.066	-0.14	-0.067	0.050
	(0.07)	(0.12)	(0.11)	(0.17)	(0.13)	(0.16)
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Unit characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Geographic characteristics	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.053	0.072	0.078	0.083	0.049	0.082
# of observations	40,498	22,445	42,177	21,520	21,429	22,654

Notes: Standard errors in parenthesis. For each column Payment-status=1 if the fuel used by the corresponding appliance is included in the price of rent. All regressions are restricted to the sub-sample of renters who have the appliance. For example, only 40,498 units have central heat, so column 1 is restricted to the 40,498 renter-occupied units with central heat.

Units with energy-included rental contracts are no more likely to have efficient appliances than are similar units without energy-included rental contracts (Table 7). That is, the effect of payment-status on the adoption of efficient technologies is nominal. Examination of household, unit, and geographic characteristics shows that newer homes, and those with a lower number of adult occupants are more likely to have efficient appliances. We also find that homes in rural areas, and homes in cool, mild, and mixed climates are all more likely to have efficient appliances.

In addition to our primary results (Table 7), we also present two supplementary regression models to estimate the effects of payment-status on energy efficient technology

[6] The number of the units in the building is binned as shown in Table 2. Building age is cutoff at units built before 1920, and binned in 10 year increments from 1920-1970, 5 year increments from 1971-1990, and 1 year increments from 1991-2011. Householder age is binned in 10 year increments with cutoffs at less than 20 years old, and over 70 years old. Household income is binned in $10,000 increments with cutoffs at less than $0 and more than $200,000.

adoption (Table 8). In both models, our independent variable of interest is the number of appliances whose fuel is included in the price of rent. The intuition is that the higher the count of appliances with fuel included in the price of rent, the less likely information asymmetries are to interfere with the energy efficient technology adoption decision, and the more likely landlords should be to install efficient appliances.

Model (1) in Table 8 is a count data model, with the count of all energy efficient appliances within a unit as the dependent variable. To estimate the causal effect of the number of appliances with fuel included in the price of rent we use an instrumental variables Tobit regression (Newey, 1987), with trash payment-status as our instrument.[7] Results show that the count of appliances with fuel included in the price of rent has no effect on the number of energy efficient appliances installed in the unit.

Model (2) in Table 8 is a fractional regression model, with the share of total appliances that are energy efficient as the dependent variable. To estimate the causal effect of the number of appliances with fuel included in the price of rent we use a control function approach (Papke and Wooldridge, 2008), with trash payment-status as our exclusion restriction (instrument). Results show that the count of appliances with fuel included in the price of rent has no effect on the share of total appliances that are energy efficient.

Table 8: The effect of payment-status on the count/share of Energy Star appliances

	(1)		(2)	
Number of appliances w/ fuel included	-0.14	(0.16)	-0.031	(0.05)
First stage residuals			0.050	(0.05)
Household characteristics	Yes		Yes	
Unit characteristics	Yes		Yes	
Geographic characteristics	Yes		Yes	
# of observations	42,248		42,248	

Notes: Standard errors are in parenthesis. In both models, the sample is restricted to renter-occupied units with at list one of the listed appliances (energy efficient or otherwise).

Results from this supplementary analysis confirm the findings of our primary regression analysis, and indicate that payment-status has little effect on the adoption of

[7] First stage results for both Model (1) and (2) in Table 8 are available in the appendix (Table A2).

efficient appliances.

4.2 The effect of information asymmetries on the adoption of energy efficient technologies

To identify the effect of information asymmetries on the adoption of energy efficient technologies, we revisit our theoretical framework. Recall the owner's willingness to pay for the efficient heat system:

$$\frac{1}{1+r_s}\left(\gamma_{\text{I(owner-pays)}} P_{BTU}(BTU^*_{I(\text{occupant-pays}),\text{inefficient}} - BTU^*_{I(\text{occupant-pays}),\text{efficient}}) + \xi_s\right) > C, \tag{12}$$

where $s \in$ {renter-occupied (renter), owner-occupied (owner)}; I(owner-pays) $= 1$ if the owner pays for heat, zero otherwise; and I(occupant-pays) $= 1$ if the occupant pays for heat, zero otherwise.

Results from our analysis of the effect of payment-status on adoption of energy efficient technologies show that renter-occupied units are equally likely to have an efficient heat system regardless of payment-status. Therefore, the owner's willingness to pay for the heat system must also be equal regardless of payment-status:

$$\begin{aligned} WTP(\text{owner\_pays, renter\_occupied}) &= \frac{\gamma_1 P_{BTU}(BTU^*_{0,\text{inefficient}} - BTU^*_{0,\text{efficient}}) + \xi_{\text{renter}}}{1 + r_{\text{renter}}} \\ &\approx \frac{\gamma_0 P_{BTU}(BTU^*_{1,\text{inefficient}} - BTU^*_{1,\text{efficient}}) + \xi_{\text{renter}}}{1 + r_{\text{renter}}} \\ &= WTP(\text{occupant\_pays, renter\_occupied}). \end{aligned} \tag{13}$$

Levinson and Niemann (2004) and Gillingham, Kenneth Harding and Rapson (2012) both show that renters consume approximately the same amount of heating/cooling regardless of payment-status (i.e. we observe no variation in thermostat settings across payment-status). Therefore the occupant's choice of energy consumption is constant across payment status ($BTU^*_{I(\text{occupant-pays}),\tau} = BTU^*_\tau$), and equation 13 implies $\gamma_1 \approx \gamma_0$:

there are no information asymmetries with respect to heating and cooling. If renters usage behaviors is also constant across payment-status for other energy consuming goods (dishwashing, refrigeration, clothes washing, and clothes drying), then our results are also indicative of the absence of information asymmetries in those settings as well. In summary, information asymmetries play only a nominal role in driving the observed difference in saturation of efficient technologies between renter- and owner-occupied residences. Therefore, the question remains: if information asymmetries are not driving the observed energy efficiency gap, then what is?

5 Discussion

Given that information asymmetries do not explain the observed gap in saturation of efficient technologies between renter- and owner-occupied residences, our theoretical framework suggests two alternative mechanisms to explain the difference in saturation. Recall that the observed difference in saturation of efficient appliances between owner- and renter-occupied units suggests that owners' willingness to pay is higher when the unit is owner-occupied compared to when it is renter-occupied. Restating equation 7:

$$\begin{aligned} WTP(\text{owner-pays, owner-occupied}) &= \frac{\gamma_1 P_{BTU}(BTU^*_{1,\text{inefficient}} - BTU^*_{1,\text{efficient}}) + \xi_{\text{owner}}}{1 + r_{\text{owner}}} \\ &> \frac{\gamma_0 P_{BTU}(BTU^*_{1,\text{inefficient}} - BTU^*_{1,\text{efficient}}) + \xi_{\text{renter}}}{1 + r_{\text{renter}}} \\ &= WTP(\text{occupant-pays, renter-occupied}). \end{aligned} \tag{14}$$

Because empirical results suggest that information asymmetries are nominal ($\gamma_0 \approx \gamma_1$), the inequality in equation 14 implies that $r_{\text{owner}} < r_{\text{renter}}$, or $\xi_{\text{owner}} > \xi_{\text{renter}}$. That is, the risk adjusted discount rate (r_s) is lower for owners when they are purchasing efficient appliances for owner-occupied units, and/or the additional benefits that are internalized by the owner are larger (or costs lower) when the unit is owner-occupied.

There are several potential explanations for these findings. The risk adjusted discount rate will be lower for homeowners than landlords if homeowners can borrow at a lower rate, face fewer liquidity constraints, have a longer time horizon, etc. Additionally, unobserved benefits will be higher (or costs lower) for homeowners than landlords if homeowners place a higher value on features associated with efficiency (noise, aesthetic, etc.), receive more energy efficiency subsidies, face lower installation costs, etc.

In any case, if the goal is to close the gap in saturation of energy efficient appliances between owner- and renter-occupied residences, our model suggests that policy makers should consider policies targeted at: (1) lowering discount rates for landlords, and (2) decreasing/increasing the relative costs/benefits of efficient technology adoption in rental housing units. Discussion of the nature a scope (and justification) of such policies is a topic of future research.

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Appendix Materials

Table A1: First stage results: probability that payment-status I(owner-pays)$_{i,e}$ = 1 (equation 11)

	(Heat)	(AC)	(Fridge)	(Dishwasher)	(Dryer)	(Washer)
I(owner-pays)$_{i,trash}$ (Z_i)	0.083***	0.075***	0.070***	0.073***	0.066***	0.082***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Unit characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Geographic characteristics	Yes	Yes	Yes	Yes	Yes	Yes
# of observations	40,498	22,445	42,177	21,520	21,429	22,654

Notes: Standard errors in parenthesis. For each column Payment-status I(owner-pays)$_{i,e}$=1 if the fuel used by the corresponding appliance is included in the price of rent. All regressions are restricted to the sub-sample of renters who have the appliance. For example, only 40,498 units have central heat, so column 1 is restricted to the 40,498 renter-occupied units with central heat.

Table A2: First stage results: (1) IV Tobit, (2) Fractional regression model

	(1)		(2)	
I(owner-pays)$_{i,trash}$ (Z_i)	0.46***	(0.02)	0.44***	(0.02)
Household characteristics	Yes		Yes	
Unit characteristics	Yes		Yes	
Geographic characteristics	Yes		Yes	
# of observations	42,248		42,248	

Notes: Standard errors are in parenthesis. In both models, the sample is restricted to renter-occupied units with at list one of the listed appliances (energy efficient or otherwise).