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Asymmetric Information in Residential Rental Markets: Implications for the Energy Efficiency Gap

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Abstract

This paper explores whether energy cost information asymmetries exist between landlords and tenants by exploiting variation in which party pays for energy. In a search market context, the effect of energy cost changes on tenant turnover, rents, and efficiency investment should differ between the two payment regimes under asymmetric information but not symmetric information. Using energy cost variation in the form of changes in relative heating fuel prices, I find evidence that tenants are uninformed about energy costs. This results in higher energy expenditures for tenants and implies that information campaigns or efficiency standards may improve market outcomes.

Keywords: Asymmetric Information, Landlord-Tenant Problem, Efficiency Gap
JEL Codes: D82, Q48, R31

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1 Introduction

Asymmetric information has been identified as a potential source of market failure in a wide variety markets such as those for used cars, insurance, labor, and lending.[1] This paper focuses on one setting in which information asymmetries may play a crucial role: investment in energy efficiency in rental housing markets. I present and implement a framework to test for energy cost information asymmetries between landlords and tenants.

In theory, landlords could make energy efficient investments and capitalize them into higher rents. In practice, while landlords may signal that they have an efficient unit, it is difficult for new tenants to assess the veracity of the landlord's claim from a walk-through. Even previous bills have limited value because prospective renters do not know the energy consumption habits of past tenants. The information asymmetry means that renters are not willing to pay for the full savings from more efficient apartment units. As a result, landlords will under-invest in energy efficiency, since they cannot fully recover investments through higher rents. Asymmetric information may also affect tenants' decisions to leave. Tenants who are initially uninformed learn the "true" energy payment for the apartment after they move in. They are more likely to leave an apartment unit with relatively high energy costs than relatively low energy costs.[2]

It is challenging for researchers to empirically identify asymmetric information as the source of market failures because agent attributes that are unobservable to the uninformed party are usually unobservable to researchers as well. As a result, it is hard to separate the effect of uninformed parties on one side of a transaction from unobservable systematic

[1]Lack of information about quality and risk is thought to have selection effects that reduce the volume of transactions in used car markets, insurance, and lending below socially optimal levels (Akerlof 1970, Rothschild and Stiglitz 1976). Asymmetric information is also thought to lead to misallocation of workers to jobs and underinvestment in human capital (e.g. Chang and Wang 1996, Katz and Zilderman 1990 and Waldman 1990).

[2]These predictions have close analogies to asymmetric information models in the labor literature. First, asymmetric information may lead employees to under-invest in general skills because, if new employers cannot observe the investments, workers will not be able to earn higher wages (e.g. Chang and Wang 1996, Katz and Zilderman 1990 and Waldman 1990. Second, low talent workers will be more likely to leave firms after the incumbent employer (but not outside employers) has learned that they are low ability (Greenwald 1986 and Gibbons and Katz 1991).

differences among agents. So, while it is widely believed that asymmetric information has negative effects in a variety of markets, it is difficult to isolate and reliably estimate the magnitude of those effects on market outcomes of interest.

In labor markets, which have close analogies to the landlord-tenant setting, it is impossible to observe "true" levels of ability or to see exogenous variation in individual ability over time, making it difficult to observe whether or not worker talent is fully priced into wages. As a result, studies have relied on variables that are correlated with talent and observable to the researcher, but are unobservable to employers (e.g. Farber and Gibbons 1996, Lange 2007, Schonberg 2007). This technique requires strong assumptions about the evolution of the unobserved talent over time. Other approaches have relied on plausibly exogenous variation in distributions of worker ability across cohorts because individual talent is not readily observable (Kahn 2013). Similarly, in car markets, researchers have relied on variation in the distribution of quality across car makes and models or variation in the distribution of cars sold across types of sellers to find evidence of asymmetric information (e.g. Genesove 1993, Hendel and Lizzeri 1999). These approaches often require strong assumptions about the parameters of those distributions, and it is difficult to quantify the effects of asymmetric information on market outcomes of interest from indirect measures of talent or quality differences.

My approach in the landlord-tenant setting has several unique features for empirically identifying asymmetric information, and quantifying its effects. First, I can directly observe a time-varying component of the unobserved energy cost parameter in the form of shifts in retail heating fuel prices. The energy costs of an apartment unit are a function not just of the efficiency of the appliances and the level of building insulation, but fuel costs and the amount of energy services consumed as well. A shock to any one of these three components leads to a shock in energy costs.

Second, I am able to isolate exogenous variation in energy costs in the form of the difference between heating oil and natural gas prices over time. Fluctuations in these prices have caused large changes to the relative energy costs of units that heat with oil versus units that heat with gas. While most of the U.S. uses natural gas to heat, this study focuses on the northeastern United States where 30-40% of occupied units heat with oil.[3] This allows me to control for unobserved variation in the macroeconomic environment and isolate the effects of relative fuel price changes on relative market outcomes. Using panel data from the American Housing Survey on unit characteristics and monthly rents, I can also control for time-invariant characteristics of apartment units.

In addition, in the landlord-tenant setting, there is variation in which party pays for energy. In roughly half of the apartments that heat with oil or gas in the northeast, the landlord pays for energy instead of the tenant. Under complete information, the incidence of a given level of energy cost should be the same under both payment regimes, similar to a tax.[4] When landlords pay their bills every month they are likely to be well-informed and react to changes in energy costs. This allows me to compare the market outcomes of a potentially well-informed control group to the payment regime when tenants pay for energy. Therefore, I can isolate and quantify the effect of asymmetric information on efficiency investments and other market outcomes.

Previous attempts to quantify the effects of asymmetric information in rental markets use cross-sectional energy consumption surveys to compare the efficiency of buildings and appliances between homeowners and renters that pay for energy themselves. They find that rental units are less likely to have efficient refrigerators, clothes washers and dishwashers (Davis 2012), and are less likely to be well insulated (Gillingham et al. 2012). The identifying assumption in these approaches is that renters and homeowners do not systematically differ in their preferences over energy efficiency. However, renters may be different than homeowners in unobservable ways, so that renters' preferences are divergent enough from homeowners to explain the difference in energy efficiency investments without any market failures.

[3] American Housing Survey National Summary Table 2-5: "Fuels–Occupied Units", years 2005, 2007, and 2009.

[4] It is likely that the level of energy used will depend on the payment regime. I examine this point more closely in both the conceptual framework and empirical sections.

Using a search model context, I make predictions about turnover rates, capitalization and investment in efficiency under both symmetric and asymmetric information. Relative market outcomes should not differ between the two payment regimes if both parties are fully informed, because the incidence of the relative price changes are the same. In contrast, under asymmetric information, there would be no relative shifts in demand from uninformed tenants when the relative prices change, leading to different market outcomes in the two payment regimes.

My results are consistent with the predictions of a housing search model under asymmetric information. First, I find evidence that increases in fuel prices increase turnover more when tenants pay for energy. Landlords in high energy cost units are able to charge higher rents since they have to opportunity to charge the next uninformed tenant more, so even after tenants discover the "true" energy cost, they will be less likely to renew given their match quality.[5] Second, I find that fuel price movements cause shifts in rent in the landlord-pay regime but not the tenant-pay regime. This result is robust to limiting the sample to supply-inelastic urban areas, where any shifts in tenant demand caused by changes in fuel prices would have the highest pass-through rates to rents. Finally, I find evidence that landlords who pay for energy themselves are more likely to make cost saving investments than those who do not.

The price of oil rose relative to natural gas during the first decade of the 21st century and many residences converted from oil to gas. If tenants correctly valued energy costs, the conversion rate from oil to gas during this period would be the same irrespective of which party pays. Back of the envelope calculations suggest that close to 47,000 units in the northeast census region did not convert due to asymmetric information. The foregone savings from these units were as high as \$350 per unit per year or 24% of household energy costs. Overall, energy costs were 2% higher for tenant-pay oil homes than they would

[5] Selection of high energy costs apartments into the pool of available units, is assumed to have a small effect on the distribution of energy costs, since exogenous turnover rates are high in the rental housing market. As a result, landlords do not lower rents enough to prevent turnover since the likelihood of finding a new uninformed tenant is high enough.

have been absent asymmetric information. These estimates are proportionate to the lost savings projections for under-investment in many other major efficiency investments due to asymmetric information, suggesting that lack information over energy costs could have a substantial effect on residential rental energy use. Correcting asymmetric information would reduce energy use roughly 1-3%, an effect equivalent to a short-run electricity price increase of 11-20%.

The presence of asymmetric information between landlords and tenants has implications not only for standard market efficiency, but also for the so-called "energy efficiency gap." This is the observation that many investments in energy efficiency with high returns according to engineering estimates are not realized in actual markets (Allcott and Greenstone 2012). This pattern has been observed by researchers and policy makers since the 1970s (e.g. Blumstein et al. 1980). There are many reasons why we may observe this apparent under-investment in energy efficiency, few of which have been tested empirically. For example, market failures arising from lack of information, lack of attention, or capital constraints may keep people from making investments that are otherwise cost-effective. It is also possible that the true savings from energy efficiency improvements may not match the engineering estimates of savings, making some types of investments less attractive than on paper. Laboratory estimates of savings do not account for improper installation or behavioral factors that affect energy use. This paper is one of the first to provide empirical evidence on one of the pathways for the energy efficiency gap using a causal framework.

It is particularly important to identify market failures that distort energy efficient investment in today's policy climate. Energy efficiency has become a focal point of recent strategies to meet growing energy needs while reducing emissions of greenhouse gases and other pollutants. Governments around the world, attracted by engineering cost savings projections, have invested billions of dollars in energy efficiency. The American Recovery and Reinvestment Act (ARRA) appropriated $97 billion to energy-related funding, $32 billion of which went to energy efficiency and retrofits.[6] In addition, spending on energy efficiency is expected to increase in the future. For example, utilities in the United States spent almost $5 billion of ratepayer money alone in 2010, a number that is expected to double by 2025 (Barbose et. al 2013).

In addition, the EPA's proposed Clean Power Plan, the first national program designed to reduce U.S. greenhouse gas emissions, was projected to meet a significant share of its reductions by 2030 from low-cost energy efficiency improvements (ICF, 2014). The success of these programs in combating climate change depends crucially on the ability to harness energy efficiency savings in a cost effective way. The challenge for researchers and policymakers is to identify circumstances in which market failures may prevent consumers from taking advantage of profitable investment opportunities. Policy makers can then better target policies to address market failures when they are present in order to get higher returns on energy efficiency spending.

The fact that asymmetric information between landlords and tenants can lead to significant under-investment in energy efficiency has important policy implications. For example, programs that provide information to tenants, such as energy audit and disclosure requirements, may to help alleviate information asymmetries. Standards or energy efficiency subsidies can also be used to address the under-investment problem in rental housing. Carbon taxes and cap-and-trade programs will not be as effective in inducing efficient levels of energy efficiency investment in rental markets where uninformed tenants pay for energy, affecting optimal tax policy. For policymakers trying to address both externalities and under-investment under asymmetric information, the optimal energy tax may be below marginal damages coupled with higher subsides than under full information (Allcott et al. 2014).

In the next section, I describe the conceptual framework for the paper. In section 3, I introduce the data used in the analysis. In section 4, I describe the empirical strategy and results for the three market outcomes: unit turnover, rents, and conversion from oil to

[6] McKinsey and Company, 2009. available: http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/the-us-stimulus-program-investing-in-energy-efficiency

gas. In section 5, I explore the implications of energy cost information asymmetries between landlords and tenants for the energy efficiency gap. In section 6, I conclude.

2 Conceptual Framework

2.1 Search Frictions and Asymmetric Information

There are important frictions in rental housing markets that make it costly for landlords and tenants to find each other. It takes time for landlords to find tenants interested in renting their units, meaning landlords may experience times when their unit is vacant. Likewise, prospective tenants have to spend time and effort to acquire information about housing options and will be imperfectly informed about the market. A competitive model is therefore a limited framework for the study of rental housing markets because it does not account for these important frictions or predict vacancies. Search models were developed in the labor literature as tractable frameworks for markets with these kinds of frictions (see Rogerson et al. 2005 for a summary of search-theoretic models in the labor market) and have been used to model the matching process of landlords and tenants (e.g. Read 1993, Read 1997, Arnott and Igarashi 2000).

Little work has been done to model the effects of asymmetric information in rental housing markets, but its effects have been well explored in labor markets with similar search frictions. Neither employers nor tenants can exhaustively screen as there are some facets of the match that are difficult to perfectly forecast. This means aspects of jobs and apartments are "experience goods," i.e., their quality can only be determined once the match is formed (Nelson, 1970). Therefore, employers (current tenants) have more information about a current employee (apartment unit) than prospective employers (prospective tenants).

This type of asymmetric information creates two effects of interest that have been identified in the labor literature: 1) inefficient matching and 2) under-investment in human capital. Inefficient matching affects employee turnover rates and wages. Under asymmetric information, new employers cannot write contracts based on worker ability, so low talent workers will be more likely to leave firms after the incumbent employer (but not outside employers) has learned that they are low ability (Greenwald 1986 and Gibbons and Katz 1991). Likewise, high talent workers might leave firms at inefficiently low rates. As a result, low-ability workers are overpaid relative to their productivity and high-ability workers are underpaid. Even after incumbent employers learn workers true ability, high talent workers will still be underpaid relative to the symmetric information case since their outside option will not be as high. Asymmetric information may also lead workers to under-invest in general skills (e.g. Chang and Wang 1996, Katz and Zilderman 1990, and Waldman 1990). If new employers cannot observe the investments, workers will not be compensated for them. Even with incumbent employers, workers will earn less from their investments, because their outside option will not be as high.

In what follows, I describe three analogous predictions in for the rental housing setting under asymmetric information related to turnover rates, rents and energy cost saving investments. Tenants are analogous to employers and apartment units to employees. As with worker ability, the energy costs of an apartment are difficult for tenants to observe until the match is formed. This asymmetric information about energy costs leads to: 1) inefficient matching and 2) under-investment in cost-saving capital. Inefficient matching between landlords and tenants affects turnover rates and rents. First, higher energy cost units will turn over faster and lower energy cost units will turn over slower than would be efficient. Second, tenants will overpay for units with high fuel costs and underpay for units with low fuel costs compared to the symmetric information case, i.e. the incidence of energy payments will be higher for tenants. Even after tenants learn the true fuel costs of an apartment unit, they will still overpay for higher energy cost units relative to the symmetric information case because landlords can charge the next uninformed tenant more. In addition, asymmetric information will lead to under-investment in cost-saving capital. If new tenants cannot observe investments, landlords will not be compensated for them.

2.2 Empirical Setting

While most of the U.S. heats with natural gas, 30-40% of New England housing heats with oil largely due to its historical availability. For example, piped natural gas was not delivered to the region until the mid-1950's, making older homes are more likely to be oil heated (Castaneda, 1993). In addition, in the mid-1970's federal natural gas price control policies lead to several years of shortages in the northeast, which restricted access to gas heating for new construction (Davis, 2011). Since the wellhead price controls were lifted in 1978, natural gas heating has been getting more common in new construction in the region, with the exception of a brief increase in homes built with oil in the mid-1980's following the crude oil price collapse of 1986.

Whether landlords or tenants pay for heat is largely determined by whether tenants' consumption is individually metered. There are economies of scale in master metering, particularly for larger multi-unit buildings. Therefore, builders may choose to install central heating given considerations such as the heating and metering technology available and the fuel prices at the point of construction.

Since landlords have to make significant investments to switch their payment regime and/or fuel type, variation exists in both heating fuel type and payment regime due to historical reasons, which are uncorrelated with current fuel price differences. In what follows, I leverage this variation to derive several predictions for housing market outcomes under asymmetric information, which I will then take to the data.[7]

2.3 Variation in Payment Regime

Let R be the total housing cost inclusive of the energy payment, μ. If r is the listed rent, then the total housing price will be $R = r_{tpay} + \mu$ for tenant-pay units and $R = r_{lpay}$ for landlord-pay units. Assume a tenant is indifferent between two otherwise identical units

[7] In Appendix A1 I provide a more formal derivation these predictions using a simple 4 period search model.

independent of payment regime and fuel type as long as the total housing cost, R, is the same. In the tenant-pay regime, whether or not a tenant is informed about energy costs affects her decision to rent at a given rate, r_{tpay} since it affects her perception of R. On the other hand, in the landlord-pay regime, whether or not a tenant is informed about energy costs does not affect her decision to rent at r_{lpay} since it has no effect on her perception of R.

2.3.1 Landlord Pays For Energy

Landlords choose a rent level to maximize profit, trading off the probability the unit will be vacant and the payoff they get from occupancy, $r_{lpay} - \mu$. Since tenants' information status does not affect their decision to rent at a given rate, r_{lpay}, it also has no effect on landlords' choice of what rental rate to offer a prospective tenant for a given probability distribution of occupancy as a function of rent. The rent that landlords choose, r^*_{lpay}, will be increasing in μ. All else equal, landlords with higher energy costs will choose higher rents since the relative benefit of having a tenant as opposed to being vacant is lower than for landlords with lower energy costs.

When it is time for tenants to decide whether or not to renew a lease, they will again be fully informed about R. Landlords choose the rent to offer an incumbent tenant trading off the probability the tenant will stay and the revenue they will receive against what they would earn if the tenant decides to go.

Landlords will make investments in energy cost saving capital if the net present value (npv) of expected savings exceeds the cost of the investment. Since rental amounts and occupancy levels in the landlord-pay regime are not affected by tenants' information status, neither are energy investment decisions.

2.3.2 Tenant Pays For Energy: Full Information

Assume for now that the energy cost will be the same for the unit independent of which party pays.[8] Since a tenant is indifferent between two otherwise identical units independent of payment regime and fuel type, they will be equally likely to rent a unit in the tenant-pay regime as the landlord-pay regime if $R_{lpay} = R_{tpay}$. As a result, landlords will choose rent, r^*_{tpay}, where $r^*_{tpay} + \mu = r^*_{lpay}$. In other words, the incidence of the energy payment will be the same independent of which party pays, similar to a tax. Figure 1 displays the relationship between energy costs and rent charged for a unit under the two different payment regimes.

The solid black line represents the positive relationship between the landlord's choice of rent in the landlord-pay regime, r^*_{lpay}, and energy costs. When tenants are fully informed, $R^*_{lpay} = r^*_{lpay} = R^*_{tpay} = r^*_{tpay} + \mu$. While R is the same independent of which party pays, the monthly rent differs between the two payment regimes by the level of μ. The solid gray line represents the negative relationship between rent and energy costs in the tenant-pay regime. Higher costs lower the probability that tenants will rent, so landlords with high energy cost units choose lower rents than landlords with low energy cost units.

Since the incidence of the energy payment is the same irrespective of which party pays, the effect of changes in energy costs on turnover rates and investment in efficiency would be the same for both payment regimes as well. In this sense, the landlord-pay regime can serve as a full information counterfactual for outcomes in the tenant-pay regime.

2.3.3 Tenant Pays For Energy: Asymmetric Information

The incidence of energy costs will no longer be the same under both payment regimes if there are information asymmetries. For simplicity, assume that when tenants lack information, they will match with a unit based on the expected energy payment, $\bar{\mu} = E[\mu]$, rather

[8] In reality, tenants have little incentive to conserve when they face zero marginal cost of consumption and may to use more energy when landlords pay for it. Though, existing literature suggests the difference in usage is relatively small in magnitude, 0.5-.75% of energy expenditure (Levinson and Niemann (2004)). I discuss the impact of moral hazard in the landlord-pay regime on the market predictions in what follows (section 2.6).

than the true energy payment.[9] The dashed gray line in Figure 1 represents the relationship between monthly rent, r_{tpay}^{asy}, and energy costs for the tenant-pay regime under asymmetric information. Since tenants will be equally likely to rent all otherwise identical units independent of energy costs, the line has zero slope.[10] If tenants are totally uninformed, they will feel the full incidence of the energy payment, where the combined rent and energy payment is, $R_{tpay}^{asy} = r_{tpay}^{asy} + \mu$. Tenants will pay more for high energy cost units and less for low energy cost units relative to the landlord-pay regime. Even after tenants learn the true fuel costs of an apartment unit, they will still overpay for higher energy cost units relative to the landlord-pay regime, because landlords can charge the next uninformed tenant more.[11]

2.4 Relative Fuel Price Movements

The benefit of having two major heating fuels is that I can control for trends in equilibrium market outcomes common to units with both fuels, thus isolating the effect of fuel price movements on the outcomes of interest. Under symmetric information, the incidence of fuel price movements will be the same under both payment regimes, i.e. $\frac{\partial R_{lpay}^{*}}{\partial p} = \frac{\partial R_{tpay}^{*}}{\partial p}$. However, under asymmetric information, the incidence of the energy payment is higher for both prospective and incumbent tenants in the tenant-pay regime than the landlord-pay regime, i.e. $\frac{\partial R_{lpay}^{*}}{\partial p} < \frac{\partial R_{tpay}^{asy}}{\partial p}$.

Tenants decide whether or not to renew based on their match quality with the apart-

[9] Another way to model asymmetric information about fuel costs, which would yield similar predictions in my empirical context, would be to assume that tenants do know whether they heat with oil or gas, but they are not aware of how the prices move relative to each other over time.

[10] Fuel price increases raising rents in the landlord-pay regime and having no effect on rents in the tenant-pay regime is consistent with asymmetric information. However, this result could also be consistent with symmetric information with certain combinations of supply and demand elasticities. If housing supply were perfectly elastic or demand were perfectly inelastic, rents would adjust with energy costs in the landlord-pay regime but not the tenant-pay regime. In both of these particular cases the incidence of the energy cost would fall entirely on the tenant. In the landlord-pay regime, landlords would adjust rent to fully pass-through energy costs. In the tenant-pay regime, rents would not adjust to changes in energy costs, resulting in no compensation for tenants. In the empirical section I limit the sample to supply inelastic areas to determine whether the effects of energy cost on rent are driven by the relative supply and demand elasticity rather than asymmetric information

[11] For a more formal derivation of equilibrium rent r and housing costs R for both incumbent and prospective tenants, see Appendix A1.

ment unit and their combined rent and energy costs, R. Therefore, all else equal, tenants are less likely to renew after an increase in R and more likely to renew after a decrease in R. Under symmetric information, fuel price increases would not have a differential effect on the probability of turnover in the two different payment regimes. However, under asymmetric information, we would expect to see a differential effect.

Testable prediction 1: Under asymmetric information, higher energy prices will cause higher turnover rates in the tenant-pay regime than the landlord-pay regime.

Under asymmetric information, the incidence of energy costs will be higher on tenants in the tenant-pay regime than the landlord-pay regime. A direct test of this prediction would be to evaluate the effect of energy costs, μ, on the combined rent and energy payment, R using relative fuel price movements as an instrument for energy costs. Unfortunately, the AHS does not have energy consumption information. However, even though the incidence of fuel price movements cannot be compared directly between the two payment regimes, it is possible to test whether the effects of fuel price movements on rents are consistent with asymmetric information.

Testable Prediction 2: Under asymmetric information, fuel price increases will increase rent in the landlord-pay regime, but have little to no effect on rent in the tenant-pay regime.

In addition, landlords will be less likely to make energy cost saving investments when uninformed tenants pay for energy than when they pay for energy themselves. When uninformed tenants pay for energy, landlords receive a lower premium for energy efficient units than when tenants are fully informed or landlords pay for energy themselves. The investment considered in this paper is the decision to convert from oil to gas. Let, W_{it}, be the NPV in period t of having unit i in the rental market, with the heating fuel indicated by superscripts. Landlords convert from oil to gas if the premium from having a gas unit on the market, as opposed to an oil unit, exceeds the upfront capital costs of investment, K_{it}:

$$W_{it}^{gas} - W_{it}^{oil} > K_{it}$$

Again, since the incidence of the energy costs is the same irrespective of which party pays, there should be no difference in switching from oil to gas rates between the two payment regimes under full information. When tenants lack information and pay for energy, it creates a distortion in the market where the premium from have a less expensive gas unit is reduced and landlords are less likely to invest in switching from oil to gas. Let $\Gamma \in (0,1)$ represent the distortion in a landlord's investment caused by asymmetric information so that:

$$\Gamma \left[W_{lpay_{it}}^{gas} - W_{lpay_{it}}^{oil}\right] = W_{tpay_{it}}^{gas} - W_{tpay_{it}}^{oil}$$

$\Gamma < 1$, indicates that asymmetric information creates a distortion that leads landlords to under-value energy cost savings in the tenant-pay regime.

Testable prediction 3: Under asymmetric information, higher price differences between oil and gas will cause higher conversion rates from oil to gas in the landlord-pay regime than in the tenant-pay regime.

2.5 Switching Payment Regime

Another effect of asymmetric information is that landlords with more efficient units will have the incentive to switch to the landlord-pay regime, where they can benefit more from having lower energy costs. On the other hand, landlords with less efficient units will have the incentive to switch to the tenant-pay regime, where the full incidence is born by the tenant. I do not directly test this prediction in my empirical analysis because there is a non-trivial amount of measurement error in the AHS in the classification of payment regime. There is also measurement error in fuel type, but with fuel type it is obvious that the unit is not changing 3 or 4 times over the sample, and those units can be removed when analyzing the fuel conversion decision. It is not as obvious with payment regime how to separate actual conversions from measurement error and directly test predictions.

While I do not explicitly analyze the payment regime decision, in the empirical section I carefully consider that landlords might switch payment regimes and discuss how I control for its effects on market outcomes.

2.6 Moral Hazard When Landlords Pay for Energy

So far I have assumed that there is no moral hazard and tenants use the same amount of energy whether they pay for it or not. However, in reality, tenants have little incentive to conserve when they face zero marginal cost of consumption and may use more energy when landlords pay for it.[12] Levinson and Niemann (2004) use residential energy consumption surveys to compare self-reported thermostat adjustment patterns between individuals that pay for energy themselves, and those that have energy included in the rent. They find that respondents are more likely to turn the thermostat down when they leave and at night when they pay for energy than when they do not. They estimate the effect of this behavioral change to be relatively small, 0.5-0.75% of total energy expenditure.

While the overuse caused by moral hazard is likely to be small, it could affect the market outcomes of interest, even if tenants are fully informed about energy costs. Let $\mu = p * q$, where p is the price of fuel and q is the quantity of energy consumed. If tenants use more energy in the landlord-pay regime, $q^{lpay} > q^{tpay}$, then $\frac{\partial R^{*lpay}}{\partial p} > \frac{\partial R^{*tpay}}{\partial p}$. When tenants are choosing to renew a lease in two otherwise identical high energy cost apartments and there has been a relative fuel price increase during their tenure, they may be more likely to leave the unit in the landlord-pay regime than the tenant-pay regime, because the housing cost, R^*, went up by more in the landlord-pay regime. Therefore, if fuel prices cause higher turnover in the tenant-pay regime than the landlord-pay regime, it is strong evidence of asymmetric information.

[12] So far I have assumed that tenants are homogenous in their energy use. With heterogeneity in use, high energy users would be more likely to rent landlord-pay units. This selection on the part of tenants may also lead to higher energy consumption in the landlord-pay regime than the tenant-pay regime

While it may be that $\frac{\partial R^{*lpay}}{\partial p} > \frac{\partial R^{*tpay}}{\partial p}$, this does not affect the predictions that I am able to test for the effects of fuel price movements on rent. I predict that fuel price increases will increase rent in the landlord-pay regime whether or not tenants are informed. In the tenant-pay regime, fuel price increases will decrease rent if tenants are informed but have little to no effect on rent if tenants are uninformed. However, without supply and demand elasticities or energy use information, the magnitude of the effect in the two payment regimes is not directly comparable, even in the absence of moral hazard. If fuel price movements have little to no effect on rent, particularly in supply inelastic areas, this is strong evidence of asymmetric information.

Under asymmetric information, price difference increases will make conversion from oil to gas more attractive in the landlord-pay regime than the tenant-pay regime. This effect could be exaggerated if tenants use more energy when landlords pay. I address the relative impacts of these two effects on conversion rates in the broader implications of asymmetric information for the energy efficiency gap (section 5).

3 Data

3.1 Rental Housing Data

I use data from the national American Housing Survey (AHS) from 1985 to 2009, which surveys over 50,000 households every two years and is designed to be representative of the housing stock in the United States. Beginning in 1985, the same housing units were surveyed every odd numbered year with additions to reflect new construction. I focus on the Northeast Census region, where 30–40% of homes heat with oil over the time period.[13]

The AHS reports data on many attributes of the housing unit. My main variables of interest are monthly rent, whether utilities are included in the rent, and primary heating fuel.

[13]The Northeast Census region, region 1, is comprised of the following states: Maine, New Hampshire, Vermont, New York, Massachusetts, Connecticut, Rhode Island, Pennsylvania, and New Jersey.

I also use data on other attributes, including number of rooms, bathrooms, half bathrooms and bedrooms, year built, a degree day variable, household income, degree of urbanization, and number of units in the building. In addition, I use several indicator variables for the presence of clothes dryers, dishwashers, central air, room air, and poor living conditions.[14] There is little identifying geographic information other than the four census regions, a range of heating and cooling degree days, and a five-level scale of urbanization.

I use only rental housing units that pay rent on a monthly basis. This excludes 3% (1507 observations) from the sample, which are recorded as paying annually, weekly, or quarterly. In addition, I drop observations that have any rental adjustment limitations. These limitations include rent adjustments due to the relationship with the owner, rent control/stabilization, households that receive vouchers to help pay the rent, and occupants of public housing. I drop about 12% of the remaining sample (5592 observations) due to these limitations on rental adjustments, mostly due to rent control.

A housing unit's primary heating fuel can change between surveys, if landlords invest in new capital equipment and infrastructure. In addition, there can be some errors in reporting the fuel type during the enumeration of the survey. In some cases there is missing information on which party pays for the heating fuel. If the unit was categorized as vacant, the payment information was not available. I take several steps to eliminate units with primary heating fuels other than oil or gas, reduce the noise from errors in the sample, and fill in information for vacant units (see Appendix A2).

My final sample has 6163 housing units. I assign each housing unit the most common heating fuel and most common payment regime observed for that unit in order to provide summary statistics at the household level in Table 1. In units where gas is the primary heating fuel, tenants pay the utilities in 69% of cases and in units where oil is the primary

[14] A unit is classified as having severely inadequate living conditions if there is no running water, a tub or shower, or flush toilet, or if there are frequent break downs of heating equipment, or if electricity is not used or there is exposed wiring. A unit can also be classified as having moderately inadequate living conditions if it lacks complete kitchen facilities, toilets break down frequently, or an unvented heater is the mean heating equipment.

heating fuel, tenants pay the utilities in 29% of cases.

Table 1 displays the results of t-tests comparing the means of the covariates between the two different payment regimes. Units where landlords pay for energy differ in predictable ways from those where tenants pay for energy. For both heating fuels, in units where landlords pay for energy, there are more units in the building, units are smaller (i.e. fewer rooms, bedrooms, bathrooms, etc.), they are less likely to have big appliances such as dishwashers and clothes dryers, they are more likely to have poor conditions, and people with lower incomes live there. The units are also slightly older on average when tenants pay for energy.

Figure 2 displays the distribution of the number of rooms, bathrooms, and units in the building as well as decade built, degree day scale, and urbanization scale. Importantly, there is good overlap of these covariates between the four heating fuel and payment regime combinations, meaning there are good counterfactual comparisons across unit types.

While the mean covariate differences are significant among different types of units, I will be able to flexibly control for differential trends in payment regime and for differential trends in unit characteristics with covariate indicator-by-year fixed effects. Any remaining unobserved variation between oil and gas units or between the two payment regimes would have to be correlated with changes in the difference in price between oil and gas in order to bias my estimates.

3.2 Heating Fuel Price Data

I create regional fuel price variables for the Northeast Census Region as a consumption-weighted average of state-level annual residential prices reported by the EIA. For natural gas prices, I use average residential natural gas prices weighted by natural gas deliveries to residential consumers. For heating oil prices, I use U.S. number 2 distillate residential prices weighted by distillate fuel oil sales for residential consumers.[15] There is little variation in retail prices among the states as fluctuations in heating fuel prices are largely determined

[15] EIA state level natural gas prices are sourced from forms EIA-857 and EIA-910. No. 2 Distillate prices by sales type are sourced from forms EIA-782A&B and consumption levels come from form EIA-821.

by world or national markets with adjustments for transportation costs. I inflate all prices to real 2014 dollars using the consumer price index. Both natural gas and heating oil prices were converted into the same units, dollars per MMBTU, in order to make them comparable.

Figure 3 displays the price variation in natural gas and residential heating oil prices from 1985 to 2009. In the late 1980's, the per-BTU prices of oil and gas were comparable, followed by a period in the 1990's when oil was less expensive than gas. In the mid-2000s, oil became much more expensive as world demand increased and in 2009, natural gas started getting less expensive with the development of hydraulic fracturing techniques. Importantly, the variation in the difference in fuel prices does not follow a simple linear trend, allowing me to identify the effects of fuel price variation on housing marker outcomes.

4 Empirical Strategy and Results

4.1 Unit Turnover

4.1.1 Empirical Strategy

If tenants are not informed about energy costs, more of the incidence of a fuel price increase is borne by both prospective and incumbent tenants in the landlord-pay regime than the tenant-pay regime. As a result, the effect of relative price increases on turnover will be higher in the tenant-pay regime than the landlord-pay regime.

For the purposes of this analysis, a unit is designated as "turned-over" if it is either vacant or has a new tenant and was occupied at the time of the previous survey (2 years ago). Observations were removed if they were the first observation of the panel, missing from the previous survey, or were vacant (not occupied) in the previous survey, as they would not be eligible to turn-over. The estimation of the effect of fuel price changes on the probability of turnover is as follows.

$$T_{it} = \beta_0 + \beta_2 \mathrm{P}_{it} + \beta_2 \mathrm{P}_{it} \times \mathrm{I}^{\mathrm{tpay}}_{it} + \beta_3 \mathrm{I}^{\mathrm{oil}}_{it} + \beta_4 \mathrm{I}^{\mathrm{oil}}_{it} \times \mathrm{I}^{\mathrm{tpay}}_{it} + \mathbf{X}_{it}\beta + \gamma_t \times \mathrm{I}^{\mathrm{tpay}}_{it} + \gamma_t \times \mathbf{vin}_{it} + \omega_i + \epsilon_{it} \tag{1}$$

The dependent variable, T_{it}, is a binary indicator for turnover of unit i in survey year t. The fuel price, P_{it}, is the annual weighted average for the northeast and varies whether unit i is oil or gas. Whether a unit heats with oil is indicated by, $\mathrm{I}^{\mathrm{oil}}_{it}$, and $\mathrm{I}^{\mathrm{tpay}}_{it}$ indicates the tenant pays for the heating fuel. Year fixed effects, γ_t, are interacted with the tenant-pay indicator as well as building vintage fixed effects $\mathbf{vin}$. The matrix $\mathbf{X}_{it}$ contains covariates, ω_i are unit fixed effects, and ϵ_{it} is the error term. The covariates in the matrix $\mathbf{X}_{it}$ include indicators for household income bins, the presence of clothes dryers, dishwashers, central air, room air, and poor living conditions. For specifications without unit fixed effects, I control for other time-invariant physical characteristics about the unit and its location with indicator variables for number of rooms, bathrooms, half bathrooms and bedrooms, a degree day variable, degree of urbanization, and number of units in the building.

The thought experiment is to determine all else equal, how fuel costs affect unit turnover. It is normally difficult to separate the effect of fuel price movements on housing market outcomes from other macroeconomic trends. The advantage of having two fuel types, is that it is possible to control for these trends with year fixed effects, and therefore isolate the effect of fuel price movements on turnover. Since there is no cross-sectional variation in price, year fixed effects are collinear with one fuel price, so that the identifying variation is the difference between the price of oil and the price of gas. The identifying assumption of this approach is that oil units do not systematically differ from gas units in an unobservable or inadequately controlled for way that is correlated with the difference in price between oil and gas.

The coefficient of interest is β_2, which is an estimate of the differential effect of fuel price increases on turnover in the tenant-pay regime as opposed to the landlord-pay regime. With flexible trends for units where tenants pay for energy, I control for any yearly variation in turnover rates in the tenant-pay regime that might be common to both fuels. I also include flexible trends for the unit vintage to account for differential impacts of vintage on turnover as a housing unit ages.

4.1.2 Endogenous Switching of Heating Fuel or Payment Regime

One potential concern is that when landlords make investments to switch their fuel type or payment regime in response to the variation in the price difference between fuel types, it will cause a compositional change among the four fuel type and payment regime combinations. The advantage of panel data is that I can control for the time-invariant quality of a unit. Therefore, even if units with higher unobserved quality change fuel type or payment regime in response to price changes, it will not bias my estimates. However, it may be that landlords upgrade other aspects of the unit that are unobserved in the data when they convert the heating fuel. For example, they may redo the kitchen and buy a new gas stove. Then, the units post-conversion will have an unobservably higher quality than before the conversion and may be less likely to turn-over, which could bias my estimates of the turnover response to the fuel price variation.

Few if any landlords will convert from gas to oil over the time period since oil is the dirtier, less convenient, and more expensive fuel.[16] If upgrades are happening, β_3, would be negative and would control for this systematic increase in quality (decrease in turnover probability) when converting from oil to gas. With a unit fixed effects regression, β_3 is identified from the units that convert. Another time landlords might make upgrades would be in converting from the landlord-pay regime to the tenant-pay regime. Switching from tenant-pay to landlord-pay should be almost costless, so it is unlikely that major upgrades are associated with those conversions. If units were getting unobservably nicer when they switched to tenant pay, the flexible trend for tenant-pay units would control for the systematic increase

[16]In the sample, 15% of units that heat with oil are recorded as gas in later surveys. For units that heat with gas, less than 4% are recorded as oil in later surveys. Some of the recorded changes will be due to measurement error, making it rare for gas units to convert to oil.

in quality.

4.1.3 Results

Figure 6 is a graphical depiction of the thought experiment. It shows the difference in mean turnover rates between oil and gas units in the tenant pay regime as compared to the landlord pay regime for the sample period. If higher relative fuel prices cause oil units to turn-over faster relative to gas when tenants pay for energy than when landlords pay for energy, we would expect to see the difference-in-differences in probability of turnover across the fuel types (oil−gas) and payment regimes (tenant pay−landlord pay) to follow the price variation. The solid line is price of fuel oil minus the price of gas in $/MMBTU. The difference-in-differences in probability of turnover (the dashed line) appears to be correlated with the price variation, which is consistent with the presence of asymmetric information.

Table 2 shows the results from the estimation. The first column shows the result for the estimation without unit fixed effects whereas the second column includes unit fixed effects. The point estimates of the fuel price coefficient are close to zero and statistically insignificant indicating that an increase in fuel price does not increase the probability of turnover when landlords pay for energy. The estimate of the coefficient on the interaction term of fuel price with the tenant-pay regime is positive and significant. These findings are consistent with asymmetric information. Relative fuel prices increase relative turnover rates more in the tenant-pay regime than the landlord-pay regime.

Columns 3 displays results for a robustness test of the identifying parallel trends assumption between the four payment regime and heating fuel combinations. Year fixed effects interacted with indicators for several of the covariates in the model are included as controls (number of bedrooms, number of bathrooms, number of rooms, units in the building, decade built, degree day variable, degree of urbanization). The concern is that there is something else following a trend that differentially affects turnover rates of certain payment regime/heating fuel combinations. These year-by-covariate interactions allow me to control flexibly for trends in observable differences between the housing types. Many unobservable differences are likely correlated with these observable differences. The point estimates of the fixed effects regressions change little with the inclusion of flexible trends in the covariates. This suggests that differences in the capitalization rates are driven by the fuel price variation and not by unobservable trends correlated with certain utility regime and heating oil combinations.

The point estimates on the interaction term of fuel price and payment regime is consistent across specifications, ranging from 2 to 3 percentage points. There is an average turnover rate of 33% across the biannual surveys (about 16% a year). Therefore, a $1/MMBTU increase in fuel price increases the probability of turnover by 6-9%.

4.2 The Effect of Fuel Price Movements on Rents

An implication of information asymmetry is that the incidence of fuel cost movements will be higher for tenants in the tenant-pay regime than the landlord-pay regime. If prospective tenants have no information about energy costs, they will be inelastic to fuel price movements. As a result, rents will not be as negatively correlated with fuel price movements, even for incumbent tenants in the tenant-pay regime under asymmetric information as opposed to full information. When landlords pay for energy, tenants are always fully informed of their combined rent and energy cost payment. If fuel costs go up, rents will increase, reflecting higher landlord costs. Therefore, rents will be positively correlated with fuel price movements in the landlord-pay regime, whether tenants are informed about energy costs or not.

Figure 6 shows the variation over time in the difference in mean rent between oil and gas units and the difference in price between oil and gas. The panel on the left shows the differences in mean rent and fuel prices when landlords pay for energy. As oil gets expensive relative to natural gas, the difference in rent for apartments where energy costs are included should get bigger, reflecting the higher difference in the marginal costs of heating. The rent difference does appear to follow the price pattern when landlords pay for energy.

The right panel of Figure 6 shows the difference between the mean rent between gas units and oil units when tenants pay for energy and the difference in fuel prices. Recall that if the price changes were being capitalized into the rents, oil homes would receive a discount relative to natural gas units when the price of oil is above the price of natural gas. This is because oil units are less attractive than gas units for tenants that have to make the utility payments. The mean rent difference in the graph shows the premium that gas units are getting relative to oil units, which does not appear particularly correlated with the price variation.

In order to estimate the effect of fuel price movements on rents I estimate equation (1) with monthly rent as the dependent variable.[17] Table 3 shows the results of this estimation. The two column are the results of the model with and without unit fixed effects. The point estimate of the fuel price coefficient is positive and statistically significant indicating that fuel price increases cause increases in rent when landlords pay for energy. The estimated effect of fuel price movements on rent in the tenant-pay regime is the addition of the fuel price coefficient and the coefficient on the interaction between fuel price and payment regime ($\beta_2 + \beta_3$). The point estimate of this effect is close to zero and statistically indistinguishable from zero. According to the EIA, the average home that uses oil as a primary heating fuel uses between 77 and 105 MMBTU/year.[18] If a \$1/MMBTU price increase were spread over a 12 month period, full pass-through would be \$6–\$9 per month. Therefore, the incidence of energy price movements on the tenant appears to be relatively high.

Elasticity of the housing supply can also affect the degree to which shifts in demand get capitalized into rents. The effect of fuel price movements on rent could also be consistent with a very elastic housing supply, where shifts in supply (from landlords who pay energy)

[17]For this analysis I drop any units coded as vacant. The highest rental amounts in the survey are top-coded for privacy concerns, so I also drop the top 1% and bottom 1% of rent values for each survey year, limiting my analysis to the middle 98% of the distribution of rents.

[18]Source: Energy Information Administration Winter Fuels Outlook from the Short Term Energy Outlook. Years 2000 to 2013.

would affect rent levels, but shifts in demand (from tenants who pay energy) would not.

However, housing supply in the northeastern United States is relatively inelastic. Housing prices have escalated faster than construction costs over time, suggesting that development space is limited. Urban areas such as Boston and New York, the largest metropolitan areas in my sample, are particularly inelastic (Glaeser et al. 2008). When housing supply is inelastic, we would expect to see the greatest effects of shifts in demand on monthly rents when tenants pay for energy in supply-inelastic markets. So, as a robustness check, in column 3, I limit my sample to areas classified as "urban" where the elasticity of housing supply is likely to be relatively inelastic. Even when the sample is limited to urban areas, with inelastic supply conditions, fuel price movements have little effect on rents in the tenant-pay regime.

Column 4 shows the results for the robustness test of the parallel trends assumptions. In column 4, the model was estimated with covariate indicator by year fixed effects for the following covariates: number of bedrooms, number of bathrooms, number of rooms, units in the building, decade built, degree day variable, degree of urbanization. With the inclusion of these flexible trends, the point estimate changes little, suggesting that the differences in monthly rent are driven by the price differences and not unobservable trends in the housing unit characteristics.

4.3 Converting Heating Fuel from Oil to Natural Gas

Under asymmetric information, we would expect higher price differences between oil and gas will cause higher conversion rates from oil to gas in the landlord-pay regime than in the tenant-pay regime. Converting from oil heat to natural gas heat requires high upfront costs, so that it is unlikely that a unit would change heating fuels more than once over the sample. There is potential for measurement error of converting, particularly if I observe heating fuel changing more than once in the sample. I trim the sample in order to isolate only those observations that are likely to be true heating fuel conversions. The sample is limited to those observed 4+ times, which is about 38% of the units in the sample (1047 units, 7234 observations).[19] The sample only includes oil homes that have either switched fuel types once or never. Once a unit switches to gas, subsequent observations are removed for that unit. I observe 364 conversions (34% of units) from heating oil to natural gas from 1989 to 2009.

I use the following linear probability model in order to test whether landlords who pay for energy are more likely to make the conversion investment than those who do not pay for energy as the price of oil increases relative to natural gas:

$$convert_{it} = \beta_0 + \beta_1 \mathrm{I}^{\mathrm{lpay}}_{it-1} + \beta_2 \mathrm{I}^{\mathrm{lpay}}_{it-1} \times (\mathrm{p}^{\mathrm{oil}}_t - \mathrm{p}^{\mathrm{gas}}_t) + \mathbf{X}_{it}\beta + \gamma_t \times \mathbf{vin}_{it} + \epsilon_{it} \tag{2}$$

Here $convert_{it}$ is an indicator for whether unit i converted to gas in year t. $\mathrm{I}^{\mathrm{lpay}}_{it-1}$ is an indicator for whether the landlord pays for energy. I use lagged values for the payment regime status since it may be influenced by the current period's price. The price of oil and gas are $\mathrm{p}^{\mathrm{oil}}$ and $\mathrm{p}^{\mathrm{oil}}$ respectively.

The coefficient of interest is β_2, which can be interpreted as the increase in the probability that a landlord will convert from oil to gas when landlords pays for energy as opposed to when tenants pay for energy if the price of oil increases by \$1/MMBTU relative to the price of natural gas.

Figure 6 displays a graphical representation of the basic experiment. It plots the price difference between oil and natural gas ($\mathrm{p}^{\mathrm{oil}} - \mathrm{p}^{\mathrm{gas}}$) in \$/MMBTU (left y-axis) and the difference in the proportion of converting from oil to natural gas between units where landlords pay for energy and units where tenants pay for energy (right y-axis). The relative proportion of conversions when the landlord pays for energy relative to when the tenant pays for energy appears to follow the pattern of the price difference variation, particularly in the

[19] In Appendix A3 I show results using samples limited to 3+ units and 5+ units with similar point estimates.

later years as the price of oil gets higher than that of natural gas.

Table 4 shows the estimation results from the conversion regression described above. The dependent variable equals zero when the home heats with oil and equals one if the home converts fuel type to gas. The first two columns display the results for the estimation equation with and without covariates. The coefficient on the interaction term $\mathrm{I}^{\mathrm{lpay}}_{t-1}\times(\mathrm{p}^{\mathrm{oil}}\text{-}\mathrm{p}^{\mathrm{gas}})$ is positive and significant. This indicates that landlords are more likely to make an investment to convert to gas as it gets relatively less expensive compared to oil if they pay for energy themselves rather than the tenant. For a \$1/MMBTU increase in the price of oil relative to natural gas, landlords that pay for energy are 1 percentage point more likely to convert to gas than landlords that do not pay for energy. With a baseline conversion rate of 8% biannually, a \$1/MMBTU increase in the price of oil relative to natural gas increases the probability that a unit where the landlord pays for energy will convert to gas by 12.5% relative to a unit where tenants pay for energy.

The third column in Table 4 displays results for the robustness test of the identifying parallel trends assumption between units where landlords pay for energy and units where tenants pay for energy. The coefficient on the interaction term $\mathrm{I}^{\mathrm{lpay}}_{t-1}\times(\mathrm{p}^{\mathrm{oil}}\text{-}\mathrm{p}^{\mathrm{gas}})$ changes little with the inclusion of covariate indicator by year fixed effects, suggesting that the differences in conversion rates are driven by the price variation and not by unobservable trends correlated with landlords paying for energy or specific unit attributes.[20]

5 Implications for the Energy Efficiency Gap

I find that the effect of fuel price movements on turnover rates, rents, and investment in converting from oil to gas differ between the two payment regimes in ways that are consistent with the presence of asymmetric information between landlords and tenants. The distortion of greatest interest for the energy efficiency gap is under-investment in cost savings when

[20] As with the turnover and monthly rent models, indicators for the following covariates are interacted with year fixed effects: number of bedrooms, number of bathrooms, number of rooms, units in the building, decade built, degree day variable, degree of urbanization)

tenants pay for energy. During the sample period, the price of oil was higher per MMBTU than the price of natural gas from 2005-2009 and many units in the northeast converted from oil to natural gas. My results imply a one percentage point difference in bi-annual conversions between the landlord-pay regime and the tenant-pay regime per $1/MMBTU price difference between oil and natural gas. In what follows, I will use these estimates to approximate the effect of asymmetric information on fuel conversions and energy expenditures for the 2005-2009 period.

In order to perform this analysis I begin with the simplifying assumption that the same proportion of units would convert from oil to gas in both payment regimes under full information. Assuming that the conversion rate would be the same for both payment regimes requires that the amount of energy used by tenants would be similar. On the one hand, tenants have the incentive to use more energy when it is included in the rent. On the other hand, with asymmetric information about energy costs, landlords that pay for energy will be more likely to make energy efficient investments, which will reduce energy consumption.[21]

Let, q, be the number of houses that would convert from oil to gas absent any information distortion. Under asymmetric information, landlords in the tenant-pay regime do not receive as much of a premium for less expensive heating fuel and as a result fewer houses, $q' < q$, convert. In order to approximate the number of housing units that would have converted over the past two years and did not due to asymmetric information, $q - q'$, I

[21]While it is beyond the scope of this paper to estimate the effect of moral hazard on energy use, as mentioned above previous estimates suggest relatively small effects, 0.5-0.75% of total energy expenditure (Levinson and Niemann, 2004). In addition, Gillingham et al. (2012) find that owner occupied dwellings are 20% more likely to have well-insulated attics/ceilings and 12-14% more likely to have well-insulated walls than tenant-pay rental units. While homeowners are different than renters, their estimates indicate that the lack of insulation in rental units where tenants pay for energy leads to greater additional energy consumption than overuse when landlords pay for energy. If under-investment in efficiency from asymmetric information dominates the effect of moral hazard on energy use as these results suggest, there may be more cost effective opportunities to convert from oil to gas in the tenant-pay regime than the landlord-pay regime. If this were the case, the assumption that conversion rates would be similar in both payment regimes under symmetric information would lead to an under-estimate of the effect of the information distortion. To the extent moral hazard dominates the effect of under-investment the assumption would lead to over-estimation of the effect of the information distortion.

use the result that a \$1/MMBTU price difference between oil and natural gas results in one percentage point fewer conversions bi-annually in the tenant-pay regime under asymmetric information. In 2005, when the price of oil rose above the price of natural gas, $q - q'$ is estimated as the number of tenant-pay oil units in the northeast multiplied by .01 times the price difference. In subsequent years, $q - q'$ is the sum of the number of units that did not convert over the current two year period as well as previous two year periods as a result of asymmetric information. Table 5 columns 3–4 display the number of tenant-pay oil units in the northeast and the results of these under-conversion estimations.[22] Over the six year period, I estimate that close to 47,000 units, or around 9% of tenant-pay oil units did not convert from oil to gas that otherwise would have absent asymmetric information.

In order to estimate the difference in energy expenditure if the primary heating fuel is gas rather than oil, I use the Heating Fuel Comparison Calculator developed by the EIA, which takes into account fuel heat content and standard furnace efficiency ratings. For two years of expenditure, these estimates range from \$300-\$700 and are reported in column 5 of Table 5. The savings from converting from oil range between 12% and 24% of heating fuel expenditure for oil units, as reported in column 6 of Table 5.[23] In column 6, I calculate the lost savings from the units that did not convert from oil to gas due to asymmetric information as a proportion of total expenditure on energy in tenant-pay oil homes. I find that by the end of the six year period, asymmetric information increased energy costs by about 2% of the entire annual energy cost for tenant-pay oil units.

Converting from oil to gas is just one of the many capital investment decisions that landlords are faced with on a regular basis. The heating fuel used and its price are one of the most easily observed energy cost features of an apartment unit, which suggests that under-

[22]The number of tenant-pay oil units are calculated by subtracting the number of rental units with fuel oil costs included in the rent from the number of rental units that use fuel oil as reported in AHS National Summary Table: "Selected Housing Costs–Renter Occupied Units", 2005, 2007 and 2009.

[23]Calculations were made using the RECS 2009 average annual site consumption for a rental unit in the Northeast using fuel oil of 53.2 MMBTU. The prices were plugged into the Heating Fuel Comparison Calculator (available: www.eia.gov/neic/experts/heatcalc.xls) to get cost comparison for the two fuels taking into account fuel heat content and the standard efficiency ratings of 78% for oil furnaces and 82% for gas furnaces.

investment in efficiency due to asymmetric information could be much more pervasive. For instance, it is much more difficult for tenants to observe how well insulated an apartment is, or the efficiency of major appliances such as air conditioners and refrigerators.

I find that close to 9% of tenant-pay oil houses do not convert to natural gas due to asymmetric information. The lost savings are 12-24% of heating fuel expenditure for houses that did not convert due to the information problem, which represents about 2% of the entire heating fuel cost for tenant-pay oil units. Previous work suggests that these under-investment and lost savings estimates are roughly proportionate to the effect of asymmetric information across many different energy efficiency investments. Gillingham et al. (2012) and Davis (2012) find a similar level of under-investment when comparing investments of owner occupied dwellings to renters that pay for energy. Gillingham et al. (2012) find that owner occupied dwellings are 20% more likely to have well-insulated attics/ceilings and 12-14% more likely to have well-insulated walls than tenant-pay rental units. In addition Davis (2010) estimates that renters are 1-10% less likely to have energy efficient light bulbs and appliances such as refrigerators, dishwashers, room air conditioners, and clothes washers than homeowners. Engineering estimates suggest that annual savings from cost effective air sealing and insulating (15%) and upgrading to Energy Star appliances such as furnaces (13%), air conditioners (10-14%), dishwashers (29%), refrigerators (15%) and clothes washers (20%) have a similar range of cost savings to those from converting from oil to gas in the first decade of the 2000's.[24]

While these numbers offer a rough approximation of the magnitude of the information problem, an added energy consumption of 1-3% due to under-investment in efficiency would have a considerable effect on residential rental energy use. As a comparison, using Reiss and White's (2008) short-run electricity price elasticity estimates of -0.18 to -0.1, utilities would need a 10-17% short-run price increase to achieve a 1-3% reduction in energy consumption.

[24]For annual savings from air sealing and insulating, see EPA's "Methodology for Estimated Energy Savings from Cost-Effective Air Sealing and Insulating," (https://www.energystar.gov/index.cfm?c=home_sealing.hm_improvement_methodology). For savings from Energy Star appliances, see Sanchez et al. (2008) Table 5.

6 Conclusion

This paper provides and implements a framework to test for asymmetric information between landlords and tenants. When tenants lack information, landlords under-invest in energy efficiency because they cannot capitalize those investments into higher rents. In this analysis I draw on theoretical insights from search markets to make predictions about turnover rates, capitalization of energy costs into rents, and investment in cost-saving capital under symmetric and asymmetric information.

I exploit the fact that heating oil and natural gas prices have fluctuated over time, changing the relative energy costs of units that heat with oil versus units that heat with gas. I focus on the northeastern United States, where for historical reasons, many apartment units still heat with oil. This allows me to estimate the effect of a change in energy costs, while controlling for unobserved changes in the macroeconomic environment. In addition, I take advantage of the fact that in some apartments the landlord pays for energy and in some apartments the tenant pays for energy. When landlords pay for energy, the combined rent and energy payment is known to tenants upfront. As a result, market outcomes when landlords pay for energy can serve as a well-informed baseline to compare with market outcomes when tenants pay for energy.

I find turnover, capitalization of energy costs into rents, and investments in converting from oil to gas differ between the landlord and tenant-pay regimes in ways consistent with asymmetric information. I find that as the price of oil rose relative to that of natural gas from 2005-2009, close to 47,000 units in the northeast census region did not convert due to asymmetric information. The foregone savings from these units were as high as $350 per unit per year or 24% of household heating fuel costs. Overall, heating fuel costs were 2% higher for tenant-pay oil homes than they would have been absent asymmetric information.

These estimates are proportionate to the under-investment and lost saving projections of many other major efficiency investments due to asymmetric information, suggesting that lack information over energy costs could have a substantial effect on residential rental energy use. Correcting asymmetric information would reduce energy use roughly 1-3%, an effect equivalent to a short-run electricity price increase of 11-20%.

The energy efficiency gap has been recognized in the theoretical and policy literature for over 30 years. While there are multiple hypotheses as to why we might see this gap, few have been tested empirically. This paper provides some of the first empirical evidence on one of the pathways for the energy efficiency gap using a causal framework. It is particularly important to identify market failures that distort energy efficient investment in today's policy environment where governments are spending billions of dollars a year on energy efficiency.

The existence of asymmetric information between landlords and tenants has important policy implications. Programs that provide information to tenants such as energy audit and disclosure requirements, may be used to help alleviate information asymmetries. In addition, energy efficiency standards or energy efficiency subsidies for rental housing might be a cost effective way to address the under-investment problem. Asymmetric information also has implications for policymakers trying to address both energy externalities and under-investment in efficiency, since it suggests that price signals from carbon policies such as cap-and-trade programs may not induce efficient levels of investment energy efficiency in rental markets where tenants pay for energy. The optimal energy tax may be below marginal damages coupled with higher subsides than under full information.

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Tables

Table 1: Covariate Comparison Between Payment Regimes

	Tenant Pays Energy	Landlord Pays Energy	P-value of Diff
bedrooms	2.316	1.566	0.00***
rooms	4.945	3.725	0.00***
half baths	0.184	0.070	0.00***
bathrooms	1.140	1.020	0.00***
units in building	6.240	37.168	0.00***
degree day scale	2.301	2.431	0.00***
clothes dryer	0.469	0.151	0.00***
dishwasher	0.288	0.191	0.00***
decade built	1944	1945	0.03**
room air	0.463	0.516	0.00***
central air	0.165	0.100	0.00***
moderate conditions	0.065	0.065	0.95
bad conditions	0.030	0.080	0.00***
real income ($)	53,081	45,022	0.00***
Observations	3311	2852	

Notes: Data are from the American Housing Survey for the Northeast Census Region, years 1985-2009. An observation is an apartment unit. The payment regime and heating fuel status were assigned as the most commonly observed status for that unit. All dollar amounts are inflated to 2014 dollars.

Table 2: Estimation of the Effect of Fuel Prices on the Probability of Turning Over

dependent variable: turnover	(1)	(2)	(3)
fuel price	-0.00862	-0.00361	-0.00495
	(0.00567)	(0.00631)	(0.00667)
fuel price $\times$ I^{tpay}	0.0215**	0.0246**	0.0307***
	(0.00924)	(0.0103)	(0.0109)
I^{oil}	-0.0589***	-0.0467*	-0.0378
	(0.0155)	(0.0277)	(0.0282)
$I^{tpay} \times I^{oil}$	0.0117	0.0376	0.0474
	(0.0220)	(0.0302)	(0.0313)
Covariates	Yes	Yes	No
Payment Regime $\times$ Year FE	Yes	Yes	Yes
Decade Built $\times$ Year FE	Yes	Yes	Yes
Unit FE	No	Yes	Yes
Covariate $\times$ Year FE	No	No	Yes
N	13273	13273	13273

Notes: The unit of observation is apartment unit$\times$year. Fuel price is the retail price of home heating oil or natural gas ($/MMBTU) for the Northeast Census region. The dependent variable is a binary variable indicating unit turnover. All prices are inflated to 2014 dollars. All specifications include payment regime by year indicator and decade built indicator by year indicator flexible trends. Standard errors are in parentheses and clustered at unit level. ***, ** and * denote statistical significance at the 1, 5 and 10 percent levels.

Table 3: Estimation of the Effect of Fuel Prices on Rent

dependent variable: rent	(1)	(2)	(3)	(4)
fuel price	4.279	6.667**	6.919**	8.131***
	(3.464)	(2.929)	(3.167)	(3.107)
fuel price × I^{tpay}	-2.788	-6.773	-7.142	-6.486
	(5.627)	(4.428)	(5.519)	(4.599)
I^{oil}	71.67***	-18.31	-22.77*	-11.36
	(9.973)	(12.00)	(12.50)	(12.00)
$I^{tpay} \times I^{oil}$	-17.43	-12.69	-17.26	-14.44
	(15.23)	(12.69)	(13.88)	(12.85)
Covariates	Yes	Yes	Yes	No
Payment Regime×Year FE	Yes	Yes	Yes	Yes
Decade Built×Year FE	Yes	Yes	Yes	Yes
Unit FE	No	Yes	Yes	Yes
Urban Only	No	No	Yes	No
Covariate×Year FE	No	No	No	Yes
N	22708	22708	19950	22708

Notes: The unit of observation is apartment unit × year. Fuel price is the retail price of home heating oil or natural gas ($/MMBTU) for the Northeast Census region. The dependent variable is monthly rent. All prices are inflated to 2014 dollars. All specifications include payment regime by year indicator and decade built indicator by year indicator flexible trends. Standard errors are in parentheses and clustered at unit level. ***, ** and * denote statistical significance at the 1, 5 and 10 percent levels.

Table 4: Estimation of the Effect of Relative Fuel Prices on the Relative Probability of Converting From Oil to Gas

dependent variable: convert to gas	(1)	(2)	(3)
$I^{lpay}_{t-1} \times (p^{oil}\text{-}p^{gas})$	0.0118***	0.0104***	0.0111**
	(0.00389)	(0.00386)	(0.00522)
I^{lpay}_{t-1}	0.00468	-0.0225**	-0.0148
	(0.00840)	(0.0107)	(0.0107)
Covariates	No	Yes	No
Decade BuiltxYear FE	Yes	Yes	Yes
CovariatexYear FE	No	No	Yes
N	5177	5177	5177

Notes: The sample is limited to those observed 4+ times, which is about 38% of the units in the sample (1047 units, 5177 observations). The sample only includes oil homes that have either switched fuel types once or never. Once a unit switches to gas, subsequent observations are removed for that unit. The unit of observation is apartment unit×year. p^{oil} is the retail price of home heating oil ($/MMBTU), p^{gas} the retail price of natural gas ($/MMBTU) for the Northeast Census region. All prices are inflated to 2014 dollars. All specifications include decade built indicator by year indicator flexible trends. Standard errors are in parentheses and clustered at unit level. ***, ** and * denote statistical significance at the 1, 5 and 10 percent levels.

Table 5: Estimates of the Effects of Asymmetric Information on Conversion from Oil to Gas and Energy Expenditure

Year	$P^{oil} - P^{gas}$	Tenant-Pay Oil Units	$q - q'$	Bi-annual Savings	Savings as % of Oil Expenditure	Lost Savings as % of Tenant-Pay Oil Expenditures
2005	$1.43	546,000	7,800	$300	12%	0.2%
2007	$4.28	518,000	29,979	$706	24%	1.4%
2009	$3.24	523,000	46,917	$596	21%	2%

Notes: All prices and savings are inflated to 2014 dollars.

Figures

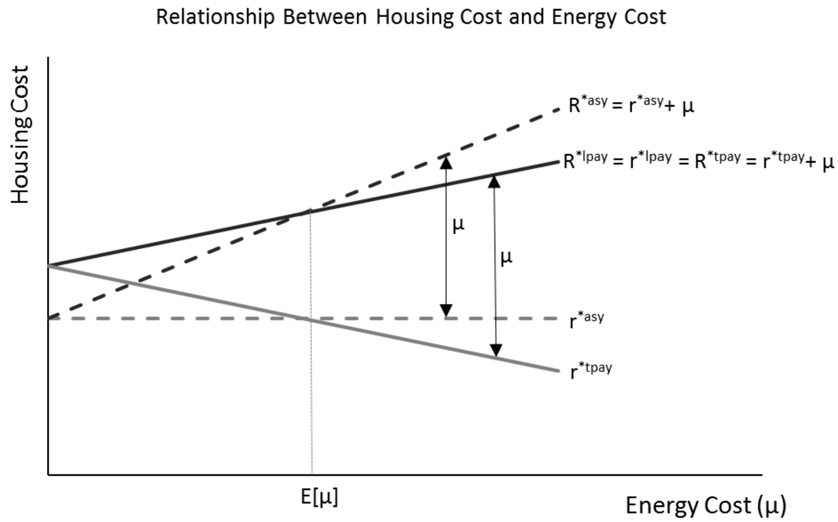


Figure 1: Notes: This is a conceptual diagram of the relationship between housing cost and energy cost. R indicates the combined housing costs of rent, r and energy cost, μ. Star superscripts indicate equilibria where $R^{*lpay} = r^{*lpay}$ in the landlord-pay regime, $R^{*tpay} = r^{*tpay} + \mu$ in the tenant-pay regime under full information and $R^{*asy} = r^{*asy} + \mu$ in the tenant-pay regime under asymmetric information.

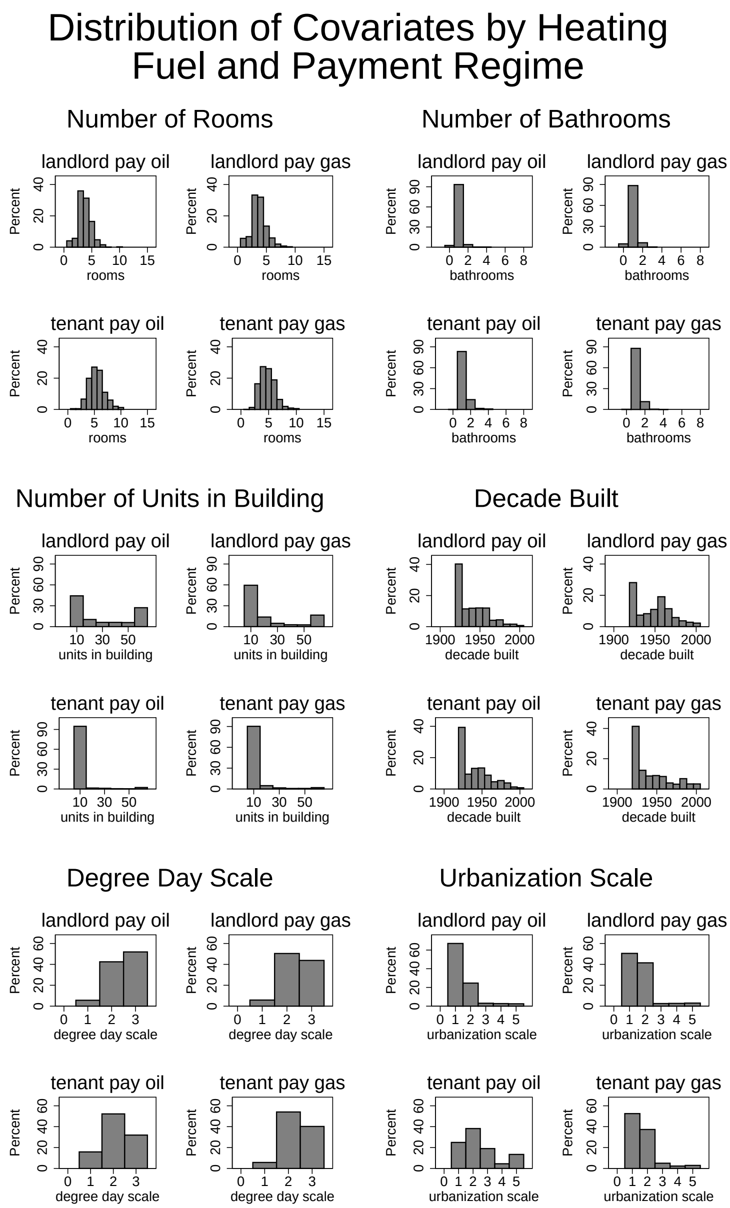


Figure 2: Notes: Data are from the American Housing Survey for the Northeast Census Region, years 1985-2009. An observation is an apartment unit. The payment regime and heating fuel status were assigned as the most commonly observed status for that unit

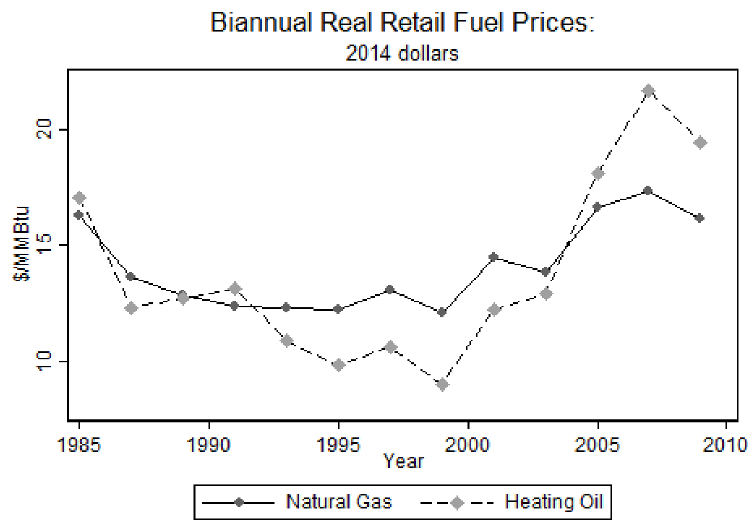


Figure 3: Notes: The prices are the consumption weighted average retail prices ($/MMBTU) for the states in the Northeast Census region. All prices are inflated to 2014 dollars.

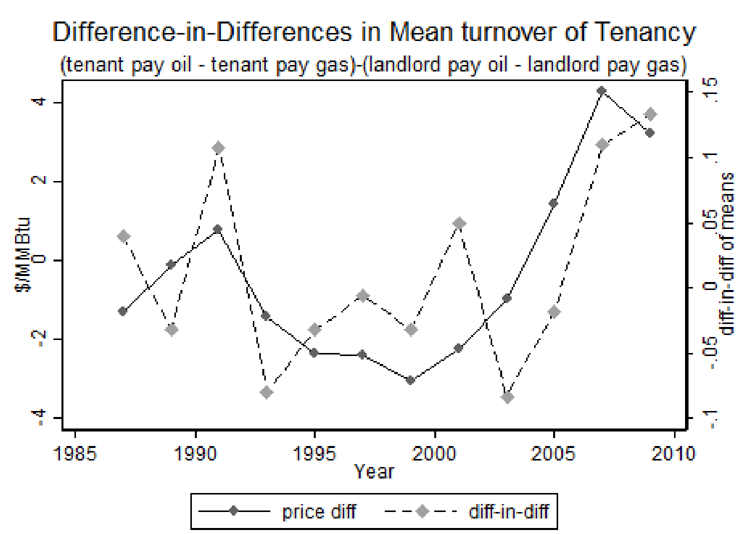


Figure 4: This figure shows the difference-in-differences in mean probability of turnover for oil units minus gas units when tenants pay energy costs as opposed to when landlords pay energy costs ((tenant pays oil-tenant pays gas)-(landlord pays oil-landlord pays gas)). The price difference is the average retail price of home heating oil ($/MMBTU) minus the average retail price of natural gas ($/MMBTU) for the Northeast Census region. All prices are inflated to 2014 dollars.

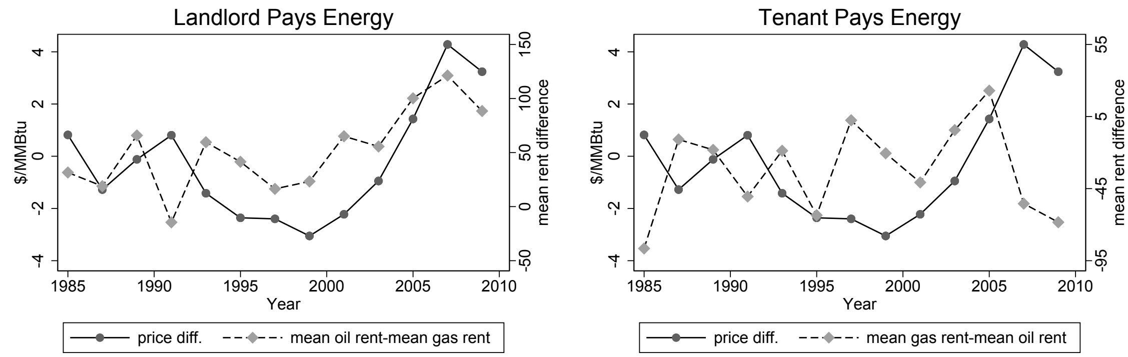


Figure 5: The panel on the left shows the difference in mean rent of oil units minus gas units when landlords pay for the energy costs. The panel on the right shows the difference in mean rent of gas units minus oil units when tenants pay for the energy costs. The price difference shown in both graphs is the average retail price of home heating oil ($/MMBTU) minus the average retail price of natural gas ($/MMBTU) for the Northeast Census region. All prices are inflated to 2014 dollars.

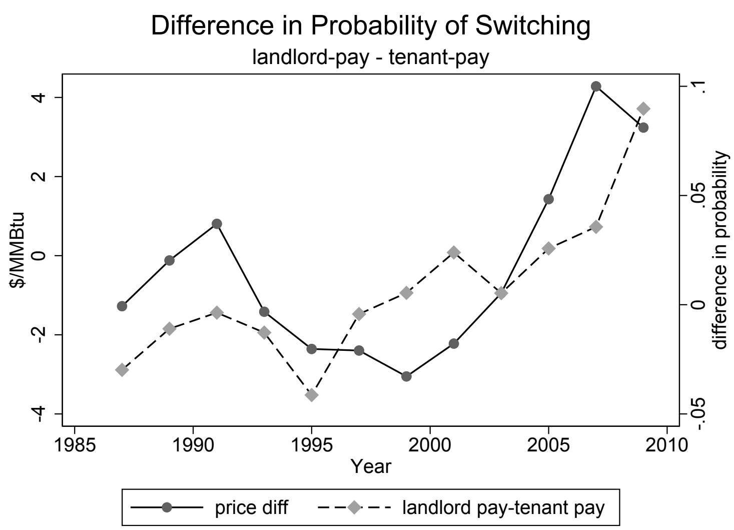


Figure 6: This Figure plots the difference in mean probability of converting from oil to natural gas when landlords pay for energy vs. when tenants pay for energy. The price difference is the average retail price of home heating oil ($/MMBTU) minus the average retail price of natural gas ($/MMBTU) for the Northeast Census region. All prices are inflated to 2011 dollars.

Appendix

For Online Publication

A1 4 Period Search Model

In what follows, I use a simple four period search model to derive the effects of asymmetric information on the incidence of relative fuel price shocks in the tenant-pay regime as compared to the landlord-pay regime. Under full information, the incidence would be the same under both payment regimes. However, under asymmetric information, the incidence is higher for tenants in the tenant-pay regime as opposed to the landlord-pay regime. The incidence difference means relative energy cost shocks lead to: (1) different housing costs for both incumbent and prospective tenants, (2) different turnover rates, and (3) different investment decisions to switch fuel type or payment regime.

A1.1 Model Set Up

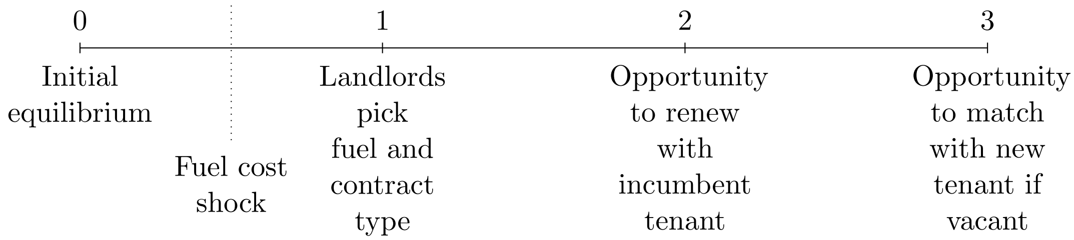
I make several assumptions in order to simplify the exposition and tractability of the model. I assume that the number of potential landlords and renters is the same, that housing units are of homogenous quality and that payment regime and fuel type are uncorrelated with other unit characteristics. However, these assumptions are not required for the predicted market outcomes and I relax them for the empirical analysis.

For simplicity, assume a housing stock with of homogeneous quality where units cost the same to construct and maintain but vary idiosyncratically in their characteristics. Some units may have two large bedrooms and others three small ones, or one might have a built-in entertainment system, and another a luxury kitchen. Tenants have a distribution of idiosyncratic preferences across these characteristics that determine their match quality with a unit. A known fraction of housing units heat with oil and the remainder heat with natural gas. All units are similarly energy efficient so that the energy cost is strictly a function of fuel price. In addition, in some known fraction of units the landlord is responsible for the energy cost and in the remainder the tenants are responsible. Suppose fuel type and payment regime are initially independently and identically distributed over characteristic space.

Landlords can invest to switch their payment regime and/or fuel type. The costs of converting payment regime and fuel type each independently vary across units with known distributions. This can be thought of as characteristics about a unit's structure that idiosyncratically create higher or lower switching costs, and the cost of changing payment regime is not be correlated with the cost of changing fuel type.

The timeline below outlines the basic structure of the model. Period 0 is the initial equilibrium, most of the units have a tenant, though some will be vacant. The cost of oil and gas is the same, therefore energy costs do not vary across units. Between period 0 and period 1 there is an exogenous shock to fuel cost, so that oil becomes more expensive than natural gas. In period 1, landlords can decide whether they would like to make payments to change either the fuel type or the energy payment regime in response to the change in relative fuel prices.

In period 2, landlords with occupied units offer their incumbent tenants take it or leave it rents. Incumbent tenants will choose to renew or not at the rent level offered based on their match quality. In period 3 any unit that was vacant in periods 0-1 or became vacant in period 2 will have an opportunity to match with a tenant. Since there is an equal number of housing units and tenants, each prospective landlord and renter will have one opportunity to match. Here, again, landlords will offer take it or leave it rents and prospective tenants will choose to form a contract based on their match quality and level of rent offered. If no contract is formed, tenants will get the utility from their outside option and landlords will earn zero profit.



As in the main body of the paper, let R be the total housing cost inclusive of energy payment, μ. If r is the listed rent, then the total housing price will be $R = r^{tpay} + \mu$ for tenant-pay units and $R = r^{lpay}$ for landlord-pay units. Also, as before, assume a tenant is indifferent between two otherwise identical units independent of payment regime and fuel type as long as the total housing cost, R is the same.

Assume that the utility from renting is a function of the housing cost, R, and an idiosyncratic match quality parameter, ϕ, which represents deviation from a tenant's ideal unit. The match quality parameter ϕ is drawn from a known distribution, which tenants discover when they visit the unit, but remains unknown to the landlord. A tenant will form a contract if the utility from renting, $u(R, \phi)$ is higher than the utility of the outside option, u^0. The tenant determines a reservation rent, or the maximum amount they would be willing to pay for a unit accounting for match quality so that the utility from being housed at the reservation rent is equal to the utility from the outside option, i.e. $u(R, \phi) = u^0$.

As in the main body of the paper, in the tenant-pay regime, whether or not a tenant is informed about energy costs affects her decision to rent at a given rate, r^{tpay} since it affects her perception of R. On the other hand, in the landlord-pay regime, whether or not a tenant is informed about energy costs does not affect her decision to rent at r^{lpay} since it has no effect on her perception of R. Therefore, tenants' information status will affect the landlord's maximization problem in the tenant-pay regime, but not the landlord-pay regime.

A1.2 Equilibrium Rents and Total Housing Costs

In what follows, I will derive the equilibrium rents r and total housing costs R offered in periods 2 and 3 for each of 3 landlord problems: 1) Landlord pay for energy, 2) Tenant pays for energy: full information, and 3) Tenant pays for energy: Asymmetric information. Then, I describe how relative fuel price shifts affect market outcomes including turnover, rent levels, and landlords' decisions to switch fuel type or payment regime for each of the 3 landlord problems.

A1.2.1 Landlord pays for energy

In period 3, landlords choose a rent level to maximize profit, trading off the probability of vacancy and the payoff they get from occupancy, $r_3^{lpay} - \mu$. Let $\theta_3(r)$ be the probability that the tenant will form a contract in period 3 for a given level of posted rent. The probability of renting is a function of the distribution of the match quality parameter, which is known to the landlord. The landlord's maximization problem is as follows.[25]

$$\max_{r_3^{lpay}} \ \theta_3(r_3^{lpay}) \cdot (r_3^{lpay} - \mu)$$

$$r_3^{*lpay} = -\frac{\theta_3(r_3^{lpay})}{\theta_3'(r_3^{lpay})} + \mu$$

In period 2, the landlord is trading off profit from raising the rent on the current tenant and their expected payoff, E_3 if the current tenant leaves and they have the opportunity to match with a new tenant in period 3, where $E_3 = \theta_3(r_3^{*lpay}) \cdot (r_3^{*lpay} - \mu)$. Tenants will choose whether stay based on their match quality and the level of rent offered. They will stay if the utility of staying outweighs the expected utility from the opportunity to match with a new unit in period 3. In period 2, the landlord's maximization is as follows, where θ_2 is the probability of an incumbent tenant remaining.

[25] $\theta_3'(r^{lpay})$ is the first derivative with respect to r, where $\theta_3'(r_3^{lpay}) < 0$

$$\max_{r_2^{lpay}} \; \theta_2(r_2^{lpay}) \cdot (r_2^{lpay} - \mu) + (1 - \theta_2(r_2^{lpay})) \cdot E_3$$

$$r_2^{*lpay} = E_3 - \frac{\theta_2(r_2^{lpay})}{\theta_2'(r_2^{lpay})} + \mu$$

A1.2.2 Tenant pays for energy: Full information

When tenants pay for energy, μ enters the landlord's maximization by reducing the probability of renting for given level of listed rent, r_3^{tpay}. The landlord's maximization is as follows for periods 2 and 3.

Period 3

$$\max_{r_3^{tpay}} \; \theta_3(r_3^{tpay} + \mu) \cdot (r_3^{tpay})$$

$$r_3^{*tpay} = -\frac{\theta_3(r_3^{tpay} + \mu)}{\theta_3'(r_3^{tpay} + \mu)}$$

Period 2

$$\max_{r_2^{tpay}} \; \theta_2(r_2^{tpay} + \mu) \cdot (r_2^{tpay}) + (1 - \theta_2(r_2^{tpay} + \mu)) \cdot E_3$$

$$r_2^{*tpay} = E_3 - \frac{\theta_2(r_2^{tpay} + \mu)}{\theta_2'(r_2^{tpay} + \mu)}$$

Under full information, $R^{*lpay} = r^{*lpay} = R^{*tpay} = r^{*tpay} + \mu$ in both periods 2 and 3. Since a tenant is indifferent between two otherwise identical units independent of payment regime and fuel type, they will be equally likely to rent a unit in the tenant-pay regime as the landlord pay regime if $R^{*lpay} = R^{*tpay}$. As a result, landlords will choose rent where $r^{*lpay} = r^{*tpay} + \mu$. In other words, the incidence of the energy payment will be the same independent of which party pays for energy, similar to a tax. The incidence of the energy payments on landlords versus tenants depends on θ, which is determined by the elasticity of supply and demand.[26]

A1.2.3 Tenant pays for energy: Asymmetric information

The incidence of energy costs will no longer be the same under both payment regimes if there are information asymmetries. As in the main body of the paper, for simplicity, assume that when tenants lack information, they will match with a unit based on the expected energy payment, $\bar{\mu} = E[\mu]$, rather than the true energy payment. Incumbent tenants will be fully informed having had experience making energy payments and will choose to renew or not based on μ. The landlord's maximization is as follows for periods 2 and 3.

Period 3

$$\max_{r_3^{asy}} \; \theta_3(r_3^{asy} + \bar{\mu}) \cdot (r_3^{asy})$$

$$r_3^{*asy} = -\frac{\theta_3(r_3^{asy} + \bar{\mu})}{\theta_3'(r_3^{asy} + \bar{\mu})}$$

Period 2

$$\max_{r_2^{asy}} \; \theta_2(r_2^{asy} + \mu) \cdot (r_2^{asy}) + (1 - \theta_2(r_2^{asy} + \mu)) \cdot E_3^{asy}$$

$$r_2^{*asy} = E_3^{asy} - \frac{\theta_2(r_2^{asy} + \mu)}{\theta_2'(r_2^{asy} + \mu)}$$

If tenants are totally uninformed, they will feel the full incidence of the energy payment,

[26] For example, assume preferences and unit characteristics are distributed uniformly over characteristic space so that $\phi \sim U(0, \bar{\phi})$. If b is the cost of the outside option, tenants will rent if $b > r + \phi$, so that the probability of renting is $Pr(\phi < b - r) = \theta(r) = \frac{b-r}{\bar{\phi}}$. In this special case, the incidence would be born in equal parts by landlords and tenants where $r^{*lpay} = \frac{b+\mu}{2}$ and $r^{*tpay} = \frac{b-\mu}{2}$.

where the combined rent and energy payment is, $R^{*asy} = r^{*asy} + \mu$. Since the incidence of a change in relative energy price will fall entirely on tenants, the change in relative total house payment for a new tenant R_3, will be higher in the tenant-pay regime under asymmetric information than in either the landlord-pay regime, or the tenant-pay regime with symmetric information, i.e. $\frac{\partial R_3^{asy}}{\partial p} > \frac{\partial R_3^{lpay}}{\partial p} = \frac{\partial R_3^{tpay}}{\partial p}$.

Likewise, if prospective tenants are fully uninformed, none of incidence of a relative energy price change will fall on the landlord in period 3 ($\frac{\partial E_3^{asym}}{\partial p} = 0$). As a result, landlords will not lower their relative rent in response to a relative price increase in period 2 to the same extent they would if prospective tenants were fully informed. Therefore, the incidence of price changes are higher even for incumbent tenants in the tenant-pay regime under asymmetric information than for either the landlord-pay regime, or the tenant-pay regime with symmetric information, $\frac{\partial R_2^{asy}}{\partial p} > \frac{\partial R_2^{lpay}}{\partial p} = \frac{\partial R_2^{tpay}}{\partial p}$.

These differences in the incidence of energy costs will cause differences in turnover decisions, rent levels, energy cost saving investments, and payment regime decisions for the two payment regimes under asymmetric information. First, since tenants decide whether to stay or not depending on their match quality and R, all else equal, relative fuel price increases will increase relative turnover in the tenant pay regime more than in the landlord-pay regime. Second, relative fuel price increases will increase relative rent in the landlord-pay regime, but have little to no effect on relative rent in the tenant-pay regime. Third, in since landlords do not feel the full incidence of relative fuel price movements in the tenant pay regime, they will be less likely to make investments to lower energy costs in Period 1.

Another effect of asymmetric information is that landlords with more efficient units may switch to the landlord-pay regime, where they can benefit more from having lower energy costs. On the other hand, landlords with less efficient units will prefer to switch to the tenant-pay regime, where the full incidence is born by the tenant. As I describe in the main body of the paper I am not able to directly test for payment regime switching, though I do control for its effects in the empirical analysis.

A2 Data Cleaning

I take several steps to reduce the noise from errors in the sample and fill in information for vacant units. First, for the time invariant features of the apartment, including number of rooms, bedrooms, bathrooms, year built, number of units in the building, degree day zone and urbanization indicator, I replaced all entries with the most commonly observed value for the unit. Second, I recoded lone observations of a heating fuel type. If, for example, the heating fuel for a particular unit is listed as gas one year but is oil in the previous and following surveys, it is recoded as oil. Switching primary fuel type is time consuming and often requires a large upfront investment. It is therefore unlikely that a unit will convert heating fuels multiple times in a short period. Last, for vacant units, I replaced the missing values for payment regime with the value from the previous survey where the information was recorded.

I then further limited the sample in several ways order to focus the analysis on units with oil and natural gas as primary heating fuels. First, I dropped housing units if the majority of observations listed a primary heating fuel other than oil or gas. Second, in order to eliminate units that use multiple fuels for heat, I dropped units if they switch primary heating fuels more than once or if oil is listed as a primary heating fuel and natural gas as a secondary heating fuel or vice versa. In some cases there is missing information on which party pays for the heating fuel. I also dropped housing units if the payment type was missing or did not match the heating fuel (either oil or gas) for a majority of that unit's observations. This results in dropping 36% of the remaining sample (15,304 observations), mostly due to the fact that the primary heating fuel was electricity rather than heating oil or natural gas.

A3 Robustness Checks of Sample Restrictions for Conversion from Oil to Gas Estimations

Table A1 displays the results from estimations with variations on how I trim the sample for conversion from oil to natural gas. I still require that a unit only converts heating fuel once, as it would be highly unlikely that a building owner would make the investment to convert heating fuels more than once in a 20 year period and would be much more likely to be measurement or survey error. For the estimate in the first two column, I restrict the sample to units I observe only three or more times rather than four or more times. In column 2, I restrict the sample to units I observe five or more times. The point estimates on the coefficient of interest $\mathrm{I}^{\mathrm{lpay}}\times(\mathrm{p}^{\mathrm{oil}}\text{-}\mathrm{p}^{\mathrm{gas}})$ are very similar to the initial estimates in Table 4. Therefore, my results are not highly sensitive to the exact criteria that I choose to define the sample.

Appendix Tables

Table A1: Estimation of the Effect of Relative Fuel Prices on the Relative Probability of Converting From Oil to Gas

dependent variable: convert to gas	(1)	(2)
$I_{t-1}^{\text{lpay}} \times (p^{\text{oil}}\text{-}p^{\text{gas}})$	0.00721*	0.00915**
	(0.00388)	(0.00401)
I_{t-1}^{lpay}	-0.0240**	-0.0240**
	(0.0108)	(0.0110)
Covariates	Yes	Yes
Decade Built×Year FE	Yes	Yes
N	5885	4656

Notes: In column 1 the sample is limited to units observed 3+ times, which is about 52% of the units in the sample (1431 units, 5885 observations). In column 1 the sample is limited to units observed 5+ times, which is about 31% of the units in the sample (849 units, 4656 observations). The sample only includes oil homes that have either switched fuel types once or never. Once a unit switches to gas, subsequent observations are removed for that unit. The unit of observation is apartment unit×year. p^{oil} is the retail price of home heating oil ($/MMBTU), p^{gas} the retail price of natural gas ($/MMBTU) for the Northeast Census region. All prices are inflated to 2014 dollars. All specifications include decade built indicator by year indicator flexible trends. Standard errors are clustered at unit level. ***, ** and * denote statistical significance at the 1, 5 and 10 percent levels.