Frictions in the rental housing market and investments in energy efficiency

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Abstract

Split incentives are a common explanation for the energy efficiency (EE) gap. We show that imperfect matching in the rental housing market may also generate suboptimal investment in EE. In a benchmark without matching imperfections, we show that the first best corresponds to tenants with high energy consumption being matched with landlords who have the lowest costs to invest in EE. With imperfect information about the EE of dwellings, matching may remain efficient but investment in EE is always too low whenever energy expenditures are not fully passed through to the tenant. When tenants' characteristics are also unknown to landlords prior to a match, matching is inefficient. As a consequence, investment efficiency decreases further. It is too low on average. Data from an original survey provides support for these insights.

1- Introduction

There is ample evidence that households and organizations paradoxically fail to invest in energy efficiency measures that would be profitable for them based on net present value calculations (e.g., Gerarden et al., 2015; Gillingham and Palmer, 2014; Jaffe and Stavins, 1994). Gerarden et al. (2015) identify three main reasons for this so-called energy efficiency gap: (i) market imperfections such as incomplete contracts; (ii) behavioral anomalies such as present bias or loss aversion; and (iii) measurement errors.

This paper focuses on market imperfections in the rental housing market. Previous studies have considered adverse selection in the rental market stemming from hidden information about relevant landlord characteristics (which we assimilate in the present paper with the energy performance of their dwelling) and characteristics available only to tenants (such as their baseline consumption) (e.g., Giraudet, 2020).

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First, because it is difficult for tenants to observe the energy performance of buildings, landlords may not be able to pass on the costs of energy efficiency investments such as insulation through higher rents to the beneficiaries of these measures (i.e., the tenants). Split incentives may therefore prevent landlords from investing in energy efficiency measures of rented dwellings. Indeed, numerous empirical studies suggest that the adoption of energy efficiency measures is lower for rented dwellings than for owner-occupied dwellings (e.g., Davis, 2012; Gillingham et al., 2012; Krishnamurthy and Kriström, 2015; Schleich et al., 2019). Availability of a signaling device, such as an energy label, may help overcome this so-called landlord-tenant problem. In fact, the empirical literature recently surveyed by Giraudet (2020) suggests that costs of energy efficiency measures are at least partially capitalized in the rent when energy performance certificates (EPC) are in place.

Second, since rental contracts may include the costs of energy use, tenants with high baseline consumption may choose to rent dwellings with contracts that include these costs. Indeed, the findings by Levinson and Niemann (2004) and Myers (2015) for the US suggest that landlords are unable to screen potential tenants by their baseline consumption.

Most of the existing literature investigates investment inefficiencies *after* a tenant and a landlord have matched and signed a leasing contract. In particular, the literature on split incentives typically considers that a landlord takes her tenant's characteristics as given when she considers investing into EE. Instead, this paper takes a different perspective. We note that the lifetime of EE investments may be much longer than a typical tenant's residence time. In the presence of frictions in the rental housing market, this means that, at the time of investment, landlords may not know the characteristics of the tenants who will actually benefit from this investment in the future. Thus, frictions in the rental housing market may generate inefficient selection of tenants, which in turn may lead to inefficient investments in energy efficiency.

Existing measures such as EPCs (certification of the landlord's side) may solve the asymmetry of information about landlord characteristics. However, we find that these measures fail to restore optimality of selection of tenants whenever landlords pay at least some of the energy expenditures and need to find an adequate tenant – i.e., when the relevant asymmetry of information lies on the tenant's side. In other words, we show that the lack of signaling on the *tenants*' side may also be a source of the energy efficiency gap.

In this paper, we first propose an analytical matching model that provides a realistic representation of the rental housing market. We also show that the split-incentive issue applies to perfectly competitive markets, when landlords' investments in energy efficiency are unobservable. Further, when investments in energy efficiency are made before the relevant information about tenants (their baseline consumption) is revealed, investments are even less efficient. Finally, data from an original survey provide support for these insights.

The remainder of the paper is organized as follows. Section 2 proposes a simple model of matching in the rental housing market and derives some formal propositions. Section 3 describes and discusses the empirical results. Section 4 concludes.

2- A simple model of matching in the rental housing market

2.1- Base model

Our theoretical model is inspired from the model proposed by Mailath, Postlewaite, and Samuelson (2017). The rental housing market is characterized by a unit mass of landlords and a unit mass of tenants. Landlords pay a share θ of their tenants' energy expenditures, while tenants pay the remaining $1-\theta$. In practice, it is often the case that $\theta = 0$ (tenants pay their energy expenditures) or $\theta = 1$. In the latter case, energy expenditures are paid by the landlord who may charge a fixed fee to the tenant that is independent of actual consumption (e.g., a utility-included rental contract). This happens for instance when there is no individual metering. We allow for intermediate θ to account for situations where the landlord covers only certain usages (e.g. the landlord does not pay for electricity but may provide central heating).

Landlords are indexed by $\in [0,1]$. Prior to being matched with a tenant, they may invest in energy efficiency which lowers tenants' energy consumption by a share $r \in [0,1]$. An EE level of r is assumed to come at cost

$$c(r,l) = \frac{r^{2+k}}{(2+k)l^k} \tag{1}$$

The higher l, the cheaper it is for landlords to invest in EE. We constrain landlords of type $l = 0$ to choose $r = 0$ (costs of provision of EE are infinite). k is an exogenous, strictly positive parameter. As k increases away from 0, landlords become more heterogeneous with respect to their cost of investment in EE.

Tenants are indexed by $t \in [0,1]$, which represents their baseline consumption. We normalize energy prices to 1. A tenant t matched with a landlord who invested r in EE pays energy expenditures of $(1-\theta)(1-r)t$. The tenant's matched landlord pays the remaining $\theta(1-r)t$. Hence, the investment an EE level r generates a joint benefit of rt.

Matching takes place in a competitive market. In the general model, we allow for personalized pricing: each landlord l may offer a specific price $p(r,t)$ to each tenant t, that will depend on her (the landlord's) own investment r. This price corresponds to the rent. The utility of a landlord l matched with tenant t is:

$$\Pi_l(r,l,t) = p(r,t) - \theta(1-r)t - \frac{r^{2+k}}{(2+k)l^k} \tag{2}$$

Tenant's utility is:

$$\Pi_t(r,t) = \overline{u} - p(r,t) - (1-\theta)(1-r)t \tag{3}$$

where $\overline{u}$ is the tenant's utility from having a dwelling. We assume this utility to be the same for all tenants and large enough so all tenants seek a dwelling.

2.2- Benchmark: perfect information

In our benchmark model, we assume that both landlord- and tenant-specific characteristics (energy-efficiency of the dwelling and baseline consumption of the tenant, respectively) are public knowledge. For each matched pair of a tenant t and a landlord l, the total surplus maximization problem is :

$$\max_{r} \ \overline{u} - t(1-r) - \frac{r^{2+k}}{(2+k)l^{k}} \tag{4}$$

The supermodularity of the value created by a match (rt) implies that efficient matching is positive assortative: the tenants with highest energy consumption are matched with the landlords for whom investing in EE is cheapest: $t = l$. With $t = l$ we get for the optimal EE level:

$$r^{*} = l \tag{5}$$

For such an investment to arise in practice, a market equilibrium needs to exist. An equilibrium exists if and only if there exists a price function $p(r,t)$ such that: (1) each tenant is matched with the landlord whose investment r maximizes the payoffs of Equation [4], (2) each landlord l is matched with the tenant t who maximizes her payoffs and makes a payoff-maximizing investment r, and (3) all agents make non-negative payoffs.

[Proposition 1] *When there is no asymmetry of information, there exists an equilibrium where matching and investments are efficient. The clearing price (up to a constant) and equilibrium investment are:*

$$\begin{aligned} p^{*}(t,r) &= \theta(1-r)t + rt - \frac{t^{2}}{2} \\ r^{*} &= l \end{aligned} \tag{6}$$

[proof] Our proof is detailed in the appendix and follows Mailath, Postlewaite, and Samuelson (2017).

[end of proof]

Proposition 1 states that there exists a price function such that the rental housing market is in equilibrium and matching and investments in EE both correspond to the surplus maximizing ones. We observe that the equilibrium price depends on both r and t: in general, personalized pricing is a necessary condition to efficiency. Further, from the first term of Equation [6], we observe that the clearing price corresponds to a complete pass-through of landlord's contribution to energy expenditures into the rent (first term): when landlords pay tenants' energy expenditures, they should be able to pass these expenditures through the rent, so they may appropriate the benefit from their EE investment. The two last terms correspond to a partial pass-through of the costs of investment in EE.

2.3- Landlord characteristics are unknown to tenants

We now depart from the benchmark model and consider the case when r is unknown to tenants. This may for example happen if there is no EPC to allow for landlords to signal their quality (here, the energy performance of their dwelling). In this case, prices cannot depend on r. A landlord's problem is to choose r and $p(t)$ to maximize:

$$\max_{r,t} p(t) - \theta t(1-r) - \frac{r^{2+k}}{(2+k)l^k} \tag{7}$$

, where the key difference with (2) is that the price may depend on t but not on r.

[Proposition 2] *When EE investments are unobservable by the tenant, matching is efficient ($t = l$) but investments are suboptimally low. The clearing price and equilibrium investment are:*

$$\begin{aligned} p_1(t) = &\quad t\theta\left(1 - \frac{t}{2}\theta^{\frac{1}{1+k}}\right) \\ r_1(l,k) = &\quad l\theta^{\frac{1}{1+k}} \leq r^* \end{aligned} \tag{8}$$

[proof] See appendix.

[end of proof]

Even though matching is efficient, investments are too low whenever landlords do not pay the entire energy expenditures: the equilibrium investment $r_1(l,k)$ is optimal (Equation [6]) if and only if $\theta = 1$. This corresponds to the case where landlords pay the entire energy expenditures, thereby fully internalizing the benefits of their investments. As θ decreases (tenants pay a larger share of the energy expenditures), investments become increasingly inefficient. If $\theta = 0$, no investment is made. This situation corresponds to the standard split-incentive problem.

We finally note that $r_1(l,k)$ increases in k: the more differentiated the landlords, the less competition amongst them. As a consequence, they are able to extract more of the surplus that their investment generated, which results in more investments in EE.

2.3- Tenants characteristics unknown to landlords

We now consider the mirror case in which energy efficiency is public information (i.e., there are effective EPCs), but tenants' baseline consumption is not observable by landlords. In that case, the price posted by landlords may depend on their dwellings' EE level r but not on tenants' baseline consumption t.

From Equation 3, we obtain that tenants choose the optimal contract such that $p'(r) = (1-\theta)\ \hat{t}(r)$, where $\hat{t}(r)$ denotes the baseline consumption of a tenant who selects a landlord with EE level r. Landlords choose $r(l)$ so as to maximize Equation (2). Because matching remains efficient, we can write that $\hat{t}\big(r(l)\big) = l$. We derive the following Proposition:

[Proposition 3] *When EE investments are observable, but tenant characteristics are tenants' private information, matching is efficient ($t = l$) but investments are suboptimally low. The equilibrium investment is implicitly defined by:*

$$r_2^{k+1}(l,k) = l^{k+1} - \theta l^k \left(1 - r_2^{k+1}(l,k)\right)\left(\frac{\partial\, r_2(l,k)}{\partial l}\right)^{-1} \quad (9)$$

[proof] See appendix

[end of proof]

Unfortunately, no closed-form solution of Equation (9) is available. However we may note that optimality requires $\frac{\partial\, r_2(l,k)}{\partial l} > 0$, which by (9) results in investment $r_2(l,k)$ being lower than the optimal level l. Contrary to the previous case in which landlord characteristics were known but tenant characteristics were not, investment is optimal when $\theta = 0$: when tenants pay their entire energy expenditures ($\theta = 0$), EPCs alone induce optimal matching and investments in EE. When landlords pay some or all of the energy expenditures ($\theta > 0$), efficiency requires that tenants' baseline consumption be revealed to landlords prior to matching. Otherwise, high-demand tenants may self-select into high-efficiency dwellings, prompting landlords to invest less into EE.

This finding echoes Levinson and Niemann (2004) and Myers (2015), who find that high-demand tenants self-select into utility-included contracts (θ large). This channel for adverse selection is shut down in our case where all contracts have the same energy-expenditure policy θ. However, when the common policy settles on $\theta > 0$, Proposition 3 shows that some adverse selection may persist based on dwellings' EE. This drives landlords to strategically decrease their investment in EE relative to the optimal level.

2.5- Both landlords' and tenants' characteristics are private information

Previous literature typically assumes that landlords know tenants' characteristics before renting out their dwellings. We now relax this assumption. When the characteristics of both tenants and landlords are unobservable, the price cannot depend on these characteristics. As a consequence, all tenants and landlords are matched randomly. Landlord l expects to be matched with a tenant t with baseline energy consumption $\mathbb{E}[t]$. A landlord's problem is to choose r to maximize:

$$\max_r -\theta\mathbb{E}[t](1-r) + p - \frac{r^{2+k}}{(2+k)l^k} \quad (9)$$

where the price p does not depend on agents' characteristics r and t.

[Proposition 4] *In the presence of strong matching frictions, the equilibrium investment is:*

$$r_3(l,k) = r_1(l,k)\left(\frac{\mathbb{E}[t]}{l}\right)^{\frac{1}{1+k}} \tag{10}$$

Landords with low investment costs ($l > \mathbb{E}[t]$) invest less and landlords with high costs ($l < \mathbb{E}[t]$) invest more than when only landlords' characteristics are unknown (Proposition [2]). On average, landlords invest less.

[proof] See appendix

[end of proof]

Proposition [4] states that when there are matching frictions in the rental housing market in the sense that both tenant and landlord characteristics are disclosed only after the match is sealed, investment is lower than in the case when only landlord characteristics are unobservable. In other words, the uncertainty about future tenant characteristics generates suboptimal investments. Low cost landlords fail to invest enough in EE while inefficient landlords invest too much. Overall, investment in the rental housing sector is too low. We note that this effect does not presume landlords to be risk averse. Allowing for landlords to be risk averse would strengthen our results, because the expected returns from investments would be uncertain.

2.6- Tenants on a long-term lease: investment when tenants' characteristics are known

The analysis so far assumed that investments in EE occurred before matching and before tenants' characteristics are revealed. This assumption is particularly realistic when tenants are on short-term leases, so any investment in EE would mostly benefit future tenants whose characteristics are unknown. We now turn to a scenario where tenants are on long-term leases. In this case, tenants and landlords are assumed to be first matched randomly as in Section 2.4. Over time, a landlord gets to know her tenant's characteristics and then may invest in EE, assuming that tenant's characteristics will not change over time. In this case, a landlord's optimization problem becomes:

$$\max_{r} \quad p - \theta t(1-r) - \frac{r^{2+k}}{(2+k)l^k} \tag{13}$$

where t is random but known to landlord l at time of investment. Proposition [4] derives the optimal investment.

[Proposition 5] *In the presence of matching frictions, but when tenant characteristics are known at time of investment, the equilibrium investment is:*

$$r_4(l,k,t) = l^{\frac{k}{1+k}}\theta^{\frac{1}{1+k}}t^{\frac{1}{1+k}} \tag{14}$$

[proof] Results from the maximization of expression (13)

[end of proof]

Contrary to the previous case of Proposition 4, landlords invest more when their tenants have a high baseline consumption. The expected investment is:

$$\mathbb{E}_l[r_4(l,k)] \quad = \frac{1+k}{1+2k}\frac{1+k}{2+k}\theta^{\frac{1}{1+k}}$$

Because $f(x) = x^{\frac{1}{1+k}}$ is concave, $\mathbb{E}_l[r_4(l,k)] > \mathbb{E}_l[r_3(l,k)]$ if and only if $k < 0$, i.e., if the costs of EE investments are not too convex.

3- Indicative empirical evidence

This section first derives a set of conjectures from the theoretical model presented in Section 2. Then, we test these conjectures employing original data from a recent survey in Germany.

3.1- Conjectures derived from the conceptual model

Section 2 showed that imperfect information about landlords' investments generated a split incentive problem, even in the context of perfect competition amongst landlords. Further, when, in addition, tenants' characteristics are unknown to landlords prior to investing, investment is suboptimal. From this, we may derive three testable conjectures:

1) When landlords can signal their EE investments through an EPC, they invest more in EE.

2) Tenant turnover affects the investment in EE.

3) When matching is imperfect (e.g. demand and supply are unbalanced), investment is lower.

The first conjecture derives from the comparison of Proposition 1 on the one hand and propositions 2 and 4 on the other hand. When investments can be signaled, efficiency may be restored.

The second conjecture derives from the fact that a landlord gets to know her tenant's characteristics over time. As the tenant stays longer, the landlord becomes more accurate information about her tenant's energy usage. More importantly, when a tenant tends to stay longer, the landlord may expect that the tenant's characteristics will not change much in the coming years.[2] The comparison of Proposition 2 and 4 shows that a better knowledge of the characteristics of tenants in the future allows for more investment.

The third conjecture may seem counter-intuitive as one may think that landlords would be more inclined to invest and signal the quality of their rental property in the case where finding a tenant is difficult. Our model shows that, on the contrary, matching frictions imply that landlords do not know which type of tenants they will be matched with in the future. Overall, they invest less in EE, as the return on investment is insufficient.

3.2- The data

Our empirical analysis relies on an online survey which was carried out in July and August 2018 as part of a larger research project. The household panel was provided by NORSTAT, an international market research company. NORSTAT recruited participants via quota sampling to gather data representative of gender, age (between 18 and 65 years), income, and regional population distribution. For the purpose of the present analysis, we used a subsample of this survey, consisting of416 German landlords (they own at least one dwelling which they rent out to a tenant). Landlords who were renting out multiple dwellings were asked to answer the survey for the dwelling where thermal insulation could be improved the most. The main part of the survey comprised of a discrete choice experiment on hypothetical technology adoption, which is not used in the present analysis. The survey included items on building characteristics, energy costs, past energy efficiency investments, tenant characteristics, and household socio-economic characteristics.

3.3- Results

Our variable of interest is "Landlord_has_invested", which takes value 1 if the landlord ever invested in energy efficiency in the rented dwelling, 0 otherwise. We regress "Landlord_has_invested" against various covariates.

"Utilities_included" takes value 1 if the landlord pays either the electricity or heating expenditures or both, 0 otherwise. A positive value corresponds to a large θ in the model of Section 2. "Tenant_tenure" is the tenure of the tenant in the current dwelling in years. It may represent the quality of information of a landlord about her current tenant. "Market_frictions" takes value 1 if landlords declared that it would be difficult for them to find a new tenant, should the current lease be terminated, and 0 otherwise. "EPC" takes value 1 if the dwelling has an EPC, which allows for a landlord to signal its EE level. "Low_baseline" takes discrete values ranging from 1 to 5,1 if the landlord declared she thought her tenant is energy-inefficient to 5 if she thinks he conserves energy.

[2] We made the simplifying assumption that the baseline consumption of a given tenant is persistent over time. However, we acknowledge that events such as changes in professional or family situation may induce a shock on this baseline. We note that these large shocks often induce tenants to move and search for a new dwelling, which we believe makes this assumption credible.

Our main results are summarized in Table 1. Column (1)report the findings of estimating Linear Probability Models while (2) is the Logit Regression counterparts. To allow findings to be compared across models and for results to be easily interpreted, column (2) presents marginal and discrete probability effects rather than the coefficients of the latent objective function.

Table 1: Regressions of investments on dwelling and tenant characteristics

	Dependent variable:	
	Landlord_has_invested	
	OLS	*logistic*
	(1)	(2)
Utilities_included	0.265***	0.267***
	(0.062)	(0.058)
EPC	−0.056	−0.066
	(0.102)	(0.101)
Market_frictions	−0.023	−0.026
	(0.036)	(0.039)
Market_frictions*EPC	0.097**	0.101**
	(0.043)	(0.044)
Tenant_tenure	0.004**	0.004**
	(0.002)	(0.002)
Low_baseline	0.020	0.023
	(0.025)	(0.026)
Household_size	0.001***	0.001***
	(0.0004)	(0.0004)
Location : isolated	0.046	0.044
	(0.121)	(0.127)
Location : small town	−0.022	−0.021
	(0.060)	(0.057)
Location : suburban area	0.100*	0.102*
	(0.060)	(0.058)
Constant	0.001	−2.391
	(0.134)	
Observations	416	416
R^2	0.165	
Adjusted R^2	0.144	
Log Likelihood		−246.927
Akaike Inf. Crit.		515.855
Residual Std. Error	0.458 (df = 405)	
F Statistic	7.978*** (df = 10; 405)	
Note:	*p<0.1; **p<0.05; ***p<0.01	

Several observations are in order. First, in line with our model and the broader literature on split incentives, we find that when landlords pay some of the energy expenditures, they tend to invest more (coefficient on Utilities_included is positive and strongly significant).

Second, a longer tenure of tenants is associated with more investments in EE. While some degree of reverse causality cannot be excluded, our interpretation is that when a landlord has more certain information about her tenants for the coming years, she is more inclined to invest into an adequate level of EE. Another, equivalent interpretation is that tenants who often switch homes typically reside in dwellings that were not retrofitted recently.

Third, a landlord's investment is not correlated to her belief about her tenant's energy consumption. This effect, which is present independently of whether the landlords pays some of the heating expenditures or not, is a clear sign of a market failure. In our model, we explain this by the fact that investment is made when future tenant characteristics are unknown, which may decrease average investment in EE (see Section 2.5).

Interestingly, the difficulty to find a new tenant does not appear to be associated with more investment in EE when there is no EPC. This null result is coherent with the findings of Proposition 4, which established that matching frictions cause a *decrease* in average investment in EE.[3] In general, an EPC is ineffective, unless there are strong matching frictions ("l_difficulty" takes value 1), which is consistent with the results of Section 2.4.

4- Conclusion

The previous literature focused on split incentives *after* landlords and tenants are matched as a main market failure driving the energy efficiency gap. This research offered a new mechanism (i.e. imperfect matching in the house rental market because of market frictions) as an explanation for the EE gap in the rental housing market. We clarified the intricate interactions between these two market failures. We provided a simple conceptual model, which allows analyzing the effect of private information on landlords (their idiosyncratic cost to invest in EE) and tenants (baseline energy consumption) when landlords may pay a share of tenants' energy expenditures. The model allows for a rich set of insights that call for a targeted certification of stakeholders of the house rental market.

First, we showed that EPCs (certification on landlords side) are fully effective only when utilities are excluded from the rent. If instead the rent includes utilities, then a more information on the tenant side would be needed. In other words, the side that should be certified is the one that does not pay for actual energy consumption. Second, when no certification is available at all, it is best that rents include utilities so that landlords are residual claimants of the energy savings derived from their EE investment. However, even in that case, as a direct consequence of inefficient landlord-tenant matching, investment is highly inefficient. . It is too low on average.

[3] Our failure to find a meaningful effect may also be due to a lack of statistical power. Future research on a larger sample may therefore be needed.

Our work could be extended in at least two directions. First, allowing for moral hazard on the tenant side would probably uncover practical difficulties for tenant certification and reinforce the need for rental contracts that exclude utilities (and in turn, reinforce the need for EPCs). Second, our empirical study allowed to test a few simple conjectures. Future empirical analyses may employ a larger sample size to confirm the results and analyse frictions on the tenant side of the market. Ideally, the matching of landlords with their actual tenants may provide a more complete picture of rental market frictions and allow for a structural estimation of search frictions in the house rental market.

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Appendix

Proof of Proposition 1

We look for a personalized price function $p(t,r)$ such that every landlord (tenant) is matched with the tenant (landlord) that maximizes its utility. Hence we need that :

$$\forall\, l \in [0,1],\quad r(l)\,,t(r) = \underset{r,t}{argmax}\quad p(r,t) - \theta(1-r)t - \frac{r^{2+k}}{(2+k)l^k}$$

$$r(t) = \underset{r}{argmax}\quad \bar{u} - p(r,t) - (1-\theta)(1-r)t$$

We also want that all agents make non-negative payoff. This translates into :

$\frac{\partial p(r,t)}{\partial r} = \frac{r^{1+k}}{l^k} - \theta t$, $\frac{\partial p(r,t)}{\partial t} = \theta(1-r) - \frac{\partial r(\,t)}{\partial t}\frac{r^{1+k}}{l^k}$, $\frac{\partial p(r,t)}{\partial r} = (1-\theta)t$. In equilibrium landords and tenants are matched efficiently, such that $l = t(l)$. It immediately derives that $r(l) = t(l) = l$, and the equilibrium personalized price is $p(r,t) = \theta(1-r)t + rt - \frac{t^2}{2} + C$ where C is a constant we set to 0 without loss of generality, so tenants with no energy demand pay no fee for energy.

Proof of Proposition 2

When energy efficiency r is unobservable, the price set by landlords may only depend on tenants characteristics, which are public information p(t). The maximization problem is :

$$\forall\, l \in [0,1],\quad r(l)\,,t(r) = \underset{r,t}{argmax}\quad p(t) - \theta(1-r)t - \frac{r^{2+k}}{(2+k)l^k}$$

$$t(r) = \underset{\tilde{t}}{argmax}\quad \bar{u} - p(\tilde{t}) - (1-\theta)(1-r(\tilde{t}))t$$

First order conditions are $\theta t = \frac{r^{1+k}}{l^k}$ and $\frac{\partial p(t)}{\partial t} = \theta(1-r)$. From the first one, in equilibrium we have that $l = t$, which translates into $r_2(l) = l\,\theta^{\frac{1}{1+k}}$. Integrating the second relation, we have $p(t) = \theta t\left(1 - \frac{t}{2}\theta^{\frac{1}{1+k}}\right)$, up to a constant normalized to 0 so tenants with no energy demand pay no fee for energy.

Proof of Proposition 3

When tenants characteristics are private information, landlords cannot condition their price on these characteristics. They may, however, post a price $p(r)$ that depends on their energy efficiency , which is public information. Tenant t chooses the price-landlord bundle that maximizes his utility. The first order condition is :

$$\frac{\partial p(r)}{\partial r} = (1-\theta)t$$

The first order condition for the utility of landlord l is:

$$\frac{\partial p(r)}{\partial r} + \theta t(r) - \theta(1-r)\frac{\partial t(r)}{\partial r} - \frac{r^{1+k}}{l^k}$$

From these equations and $t = l$ we derive:

$$\frac{r^{1+k}}{l^k} = l - \theta(1-r)\frac{\partial t(r)}{\partial r}$$

We observe that the first term corresponds to the efficient benchmark. The second term is the distortive term, which relates to the adverse selection of high-demand tenants into high-efficiency landlords. This drives landlords into investing less, so as to reduce their attractiveness for high-demand tenants.

Proof of Proposition 4

We now assume that no agent-specific information is public. This results in prices $\bar{p}$ being independent of both landlord's energy efficiency and tenant's baseline consumption. In these conditions, a match can only be random. The expected utility of landlords becomes:

$$\Pi_l(r,l) = \bar{p} - \theta(1-r)\,\mathbb{E}[t] - \frac{r^{2+k}}{(2+k)l^k}$$

Which results in the optimal investment $r_3 = (\theta\,\mathbb{E}[t]\,l^k)^{\frac{1}{1+k}}$. Recalling that $r_1(l) = l\theta^{\frac{1}{1+k}}$, we derive the expression of the proposition.

Rewriting the equilibrium investment as:

$$r_3(l,k) \quad = l^{\frac{k}{1+k}}\mathbb{E}[t]^{\frac{1}{1+k}}\theta^{\frac{1}{1+k}}$$

we derive the expected investment :

$$\mathbb{E}_l[r_3(l,k)] \quad = \frac{1+k}{1+2k}\left(\frac{1}{2}\right)^{\frac{1}{1+k}}\theta^{\frac{1}{1+k}} \equiv f(k)\theta^{\frac{1}{1+k}} \tag{11}$$

We observe that $lim_{k\to+\infty}f(k) = f(0) = \frac{1}{2}$: when k is very small or very large, the average investment coincides with the case in which pricing is personalized to tenants, and landlords' characteristics are unknown to tenants $\mathbb{E}_l[r_1(l,k)] = \frac{1}{2}\theta^{\frac{1}{1+k}}$.

$$\frac{\partial f(k)}{\partial k} = \frac{(2\ln(2) - 1)k + \ln(2) - 1}{(k+1)(2k+1)^2 \cdot 2^{\frac{1}{k+1}}}$$

This expression is negative when k is small, and positive when k is large. It has a single root in $k = \frac{1-ln(2)}{2ln(2)-1} \approx 0.8$. Hence $\mathbb{E}_l[r_3(l,k)]$ is bounded from above at $\mathbb{E}_l[r_1(l,k)]$.