The Energy Efficiency Gap in the Rental Housing Market: It Takes Both Sides to Build a Bridge

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ABSTRACT

We revisit the issue of the energy efficiency (EE) gap by explicitly acknowledging the two-sided nature of the rental housing market and two-sided asymmetries of information between tenants and landlords. Employing a theoretical matching model, we show that Energy Performance Certificates (EPCs) that signal a dwelling's energy performance induce optimal EE investments by landlords only if tenants pay their energy expenditures in full. When landlords pay part of the energy expenditures, they seek tenants who will conserve energy. Our model shows that asymmetry of information over tenant characteristics results in suboptimally low investments in EE. This may even render EPCs counterproductive. As a remedy, we show that tenant-side signaling needs to be rolled out jointly with EPCs and may even be sufficient when contracts include energy expenditures. Data from an original survey provides support for these insights and suggests that information on the tenants' side contributes to more EE investment.

Keywords: Energy efficiency gap, Split incentives, Rental housing market, Matching, Signaling, Energy performance certificates

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1. INTRODUCTION

There is ample evidence that households and organizations paradoxically fail to invest in energy efficiency (EE) 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 EE gap: (i) market failures such as incomplete contracts, (ii) behavioral anomalies such as present bias or loss aversion, and (iii) measurement errors.[1]

This paper focuses on the occurrence of market failure 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 to the energy

1. Measurement errors include unobserved or understated costs and benefits of EE technology adoption such as ignored product attributes; heterogeneity in costs and benefits across adopters; the use of incorrect discount rates; and uncertainty, irreversibility, and option value (Gerarden et al., 2015).

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performance of their dwellings) or characteristics available only to tenants (such as their typical energy consumption) (e.g. Giraudet, 2020).

First, because it is difficult for tenants to observe the energy performance of the dwellings in which they live, landlords may not be able to pass on the costs of EE investments such as insulation through higher rents to the beneficiaries of these measures (i.e. the tenants). Split incentives may therefore discourage landlords from investing in EE measures for rented dwellings. Indeed, numerous empirical studies suggest that the adoption of EE 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). The availability of a signaling device, such as an energy label, may help to overcome this so-called landlord–tenant problem. In fact, the empirical literature recently surveyed by Giraudet (2020) suggests that the costs of EE measures are at least partially passed through to the tenant when energy performance certificates (EPCs) are in place.

Second, because rental contracts may include energy expenditures, tenants with high energy consumption may choose to rent dwellings with contracts that include these costs. Indeed, the findings by Levinson and Niemann (2004) and Myers (2020) for the US are consistent with tenant self-selection into such rental contracts. For a landlord, this raises the difficult issue of how to screen potential tenants based on their expected energy 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 often assumes that when considering investing in EE, a landlord takes her tenant's characteristics as given, but in reality this is rarely the case. The lifetime of EE investments is typically much longer than the average tenure of a tenant. Therefore, when landlords make EE investments, they do not have perfect information about current or future tenants' energy consumption. This lack of information may be detrimental to EE investments. This information asymmetry on the tenant side has not been considered in the literature so far and, as we show, is also a source of inefficiency whenever landlords pay at least part of a dwelling's energy expenditures.

Together with individual metering, that is being rolled out in many parts of the world (Ito and Zhang, 2020) and allows consumption-based billing, EPCs help restore optimal matching and investment efficiency. Yet, several factors (costs of the meters and of metering, lack of information, behavioral biases, or landlords' marketing strategies) imply that a large share of rental contracts still include energy expenditures with a fixed payment scheme (Choi and Kim 2012). As we later show, these contracts do not guarantee optimal matching and investment efficiency. The issue is far from negligible, with 10% to 30% of rental contracts in developed economies still including at least some portion of the associated energy expenditures (Jessoe et al., 2020; US EIA, 2015; Ray et al., 2019; Santin et al., 2009). In the US, 60% of rental contracts include at least one source of energy expenses (Choi and Kim, 2012). The goal of this paper is to formalize this persistent inefficiency by recognizing that the rental housing market can be conceptualized as a matching problem with two-sided unobservables. This approach to modelling the split-incentive problem is novel and provides policy insights that have not been discussed so far.

Existing measures such as EPCs (certification on the landlords' side) may solve the problem of information asymmetry regarding landlord characteristics. We find, however, that these measures fail to restore optimality in the selection of tenants whenever landlords pay at least some of the energy expenditures and need to find adequate tenants—i.e. when the relevant information asymmetry lies on the tenants' side. Several empirical studies (Longhi, 2015; Rehdanz, 2007) report substantial heterogeneity in residential heating expenditures, even after controlling for ownership of a dwelling. This heterogeneity correlates with tenant-side characteristics such as household size, age, employment status and income of household members, and tenant-specific behavioral variables (Best et al., 2021). The present paper shows that the EE gap is attributable not only to the lack of signaling regarding landlord-side information but also to the lack of signaling regarding tenant-side information as a source of the EE gap. This latter case has been overlooked in the literature and does not have a regulatory answer as of yet. This paper sets itself the goal of remedying that deficiency.

This insight is, to the best of our knowledge, novel. Levinson and Niemann (2004) and Myers (2020) do find evidence that tenants self-select into certain types of contracts (whether energy expenditures are included in rent or not), but their empirical strategies do not allow for self-selection into certain levels of EE. This is our focus here, together with examining the impact of this selection process on landlords' incentives to invest in EE. Burfurd et al. (2012) show in a lab experiment with students that the relationship between landlord costs and tenants' energy use strongly affects landlords' propensity to invest in EE as well as the efficiency of such investments. Our theoretical model confirms these findings. While Burfurd et al. (2012) focus on landlord-side information disclosure as a tool for promoting efficient investment, we show that tenant-side information is also needed. As we noted earlier, the inefficiency we uncover applies to a significant share of the rental housing market.

Recent studies acknowledge that frictions in the rental housing market may have a significant impact on energy-related choices. Fabra and Bian (2020) explicitly model the search process to study incentives to disclose EPCs. Their model assumes, though, that tenants are homogeneous, investment in EE is exogenous, and there is no pairwise matching. Our paper is the first to model the EE gap issue formally as a matching problem. This makes it possible to bring to light and study in a common setting some of the main informational issues that apply in both directions of the tenant–landlord relationship. Data from an original survey provide some empirical support for the relevance of disclosing information about tenants.

The remainder of the paper is organized as follows. In Section 2 we propose a simple model of matching in the rental housing market and derive some formal propositions. In Section 3 we describe and discuss our 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 by 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,[2] 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 landlords, who may charge a fixed fee to tenants that is independent of actual energy consumption (e.g. a rental contract that includes energy expenditures). This happens for instance when there is no individual metering. We allow for intermediate θ to account for situations where landlords pay only for certain energy expenditures (e.g. a landlord does not pay for electricity but may provide central heating, or pays for heating in common areas only).

2. For convenience and consistency with the empirical section, we study the typical energy or heating consumption of a tenant. Our theoretical model, however, readily applies to any type of utility that may be consumed and enjoyed by the tenant but paid by the landlord (electricity, gas, heat, water, etc.).

Landlords are indexed by $l \in [0,1]$, which is a measure of their idiosyncratic cost of investment in EE. The higher l is, the cheaper it is for landlords to invest in EE. Prior to being matched with a tenant, they may invest in an EE level of $r \in [0,1]$, where $r = 0$ corresponds to no EE investment, and $r = 1$ corresponds to a zero-energy building. Following Mailath et al. (2017), an EE level of r is assumed to come at cost

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

We constrain landlords of type $l = 0$ to choose $r = 0$ (the costs of providing EE are infinite). k is an exogenous, strictly positive parameter. As k increases away from 0, landlords become more heterogeneous with respect to the cost they pay to invest in EE. Because we assume that landlords invest in EE only once, the investment choice r coincides with the level of EE. Hence r will be interchangeably referred to as a landlord's "investment in EE" and the "EE level" of a given dwelling.

Tenants are indexed by $t \in [0,1]$, which represents their typical consumption. For simplicity, we normalize energy prices to 1. A tenant t matched with a landlord with EE level r pays energy expenditures of $(1 - \theta)(1 - r)t$. The tenant's matched landlord pays the remaining $(1 - r)t$. Hence, the investment in EE level r generates a joint benefit of rt, which is called the 'premuneration value' (Mailath, Postlewaite, and Samuelson, 2013).

In the general model, we allow for personalized pricing: each landlord l may offer a specific rental 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:

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

The 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 utility the tenant obtains from having a dwelling. We assume this utility to be the same for all tenants and to be large enough so all prospective tenants seek a dwelling (equation 3 is always positive). Matching takes place in a competitive market. A match will materialize only if it maximizes landlords' utility (2) over all available tenants, maximizes tenants' utility (3) over all available landlords, and all agents have positive utility.[3]

2.2 Benchmark: perfect information

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

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

3. This theoretical model abstracts from the fact that in reality, agents may not be pure utility-maximizers but may have cognitive biases or make boundedly rational decisions and engage, for example, in satisficing.

Individual rationality also imposes that (2) and (3) are positive for all agents in equilibrium. The supermodularity of the gross value rt created by a match between a tenant of type t and a landlord who invested in an EE level of r implies that efficient matching is positively assortative: tenants exhibiting the highest energy consumption are matched with landlords for whom investing in EE is cheapest: $t = l$.[4] In turn, we obtain, for the optimal EE investment:

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

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: (a) each tenant t is matched with the landlord l whose investment r maximizes the payoffs of equation (4), (b) each landlord l is matched with the tenant t who allows her to maximize payoffs and to make a payoff-maximizing investment r, and (c) 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:*

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

$$r^* = l$$

[proof] Our proof is detailed in the appendix and follows Mailath et al. (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 maximize the surplus. We observe that the equilibrium price depends on both r and t: in general, personalized pricing is a necessary condition of efficiency. Further, from the first term of equation (6), we observe that the clearing price corresponds to a complete pass-through of landlords' contribution to energy expenditures into rent: when landlords pay tenants' energy expenditures, they must be able to pass these expenditures through to the rent so that they can appropriate the benefit of their EE investments. The two last terms correspond to a partial pass-through of the costs of investment in EE. This is consistent with the finding in the literature that tenants are willing to support part of the additional investment cost through higher rents (Burfurd et al., 2012; Lang and Lanz, 2020). In equilibrium ($r = t = l$), the pass-through of capital costs corresponds to half of the gross surplus t^2 generated by the investment in EE: tenants and landlords share the gross surplus equally.[5]

2.3 Both landlords' and tenants' characteristics are private information

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 energy consumption $\mathbb{E}[t]$, which—to ensure

4. In the terminology of the mechanism design literature, high-type tenants are matched with high-type landlords.

5. An investment in r allows to save rt on energy expenditures. In equilibrium, we have $r=t$ (see Equation 6), which results in a gross surplus of t^2.

a uniform distribution—coincides with the energy consumption of the average tenant. A landlord's problem is to choose r to maximize:

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

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

[Proposition 2] *In the presence of strong matching frictions, the equilibrium investment is:*

$$r_1(l,k)=l^{\frac{k}{1+k}}\theta^{\frac{1}{1+k}}\mathbb{E}[t]^{\frac{1}{1+k}} \tag{8}$$

[proof] See appendix **[end of proof]**

Proposition 2 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 a match is sealed, investment in EE is inefficient: low-cost landlords fail to invest sufficiently in EE to attract tenants who are willing to pay all energy expenditures while inefficient landlords invest more than is needed to attract such tenants. Further, investment decreases as the share of energy expenditures paid by tenants increases because landlords fail to internalize the benefits of their investment. Overall, as shown in the proof of Proposition 2 in the Appendix, EE investment in the rental housing sector is on average too low compared to the benchmark of Proposition 1. We note that this mechanism does not presume that landlords are risk averse.[6]

2.4 Only landlords can signal their types (EPCs)

We now consider the case in which EE is public information. Prior to engaging in the matching process, landlords are endowed with EPCs, enabling them to signal their quality (here, the energy performance of their dwellings), but tenants' typical consumption is not observable by landlords. In that case, the price posted by landlords may depend on their investment r in EE but not on tenants' typical consumption t.

From equation (3), we infer that tenants choose the optimal rental contract such that $p'(r)=(1-\theta)\hat{t}(r)$, where $\hat{t}(r)$ denotes the typical consumption of a tenant who selects a landlord with EE investment r. Landlords choose $r(l)$ so as to maximize equation (2), assuming that $t=\hat{t}(r)$. Because matching remains efficient, $\hat{t}(r(l))=l$. 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:*

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

[proof] See appendix **[end of proof]**

6. Risk aversion may cause overinvestment by all landlords (including the inefficient ones), due to the uncertainty about the quality of a match.

Matching is efficient in the sense that efficient landlords are matched with high-consumption tenants. Investment in EE, however, is suboptimal: No closed-form solution to equation (9) is available, but we may note that optimality requires $\frac{\partial r_2(l,k)}{\partial l} > 0$, which by (9) makes investment $r_2(l,k)$ being lower than the optimal level l. 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 tenants to reveal their typical consumption to landlords prior to matching. Otherwise, high-demand tenants may self-select into high-efficiency dwellings, discouraging landlords from investing sufficiently in EE. With a numerical application, we show later in Figure 1 that the efficiency loss may be substantial.

In turn, EPCs may discourage investments in EE and harm social welfare. This echoes concerns already raised by Fleckinger et al. (2019). In their model, the mechanism through which EPCs may harm welfare is however different: random tenant–landlord matching in the absence of EPCs generates some poor matches where tenants with high energy needs are matched with inefficient landlords. In the long run, these tenants have no other option than to invest in EE themselves. The presence of an EPC stimulates more landlord investment but discourages tenant investments. The overall effect is ambiguous. In the present paper we do not allow tenants themselves to invest in EE (in our sample only 6% of the tenants are allowed to invest in thermal insulation). Instead, in our framework, the detrimental welfare effects of EPCs stem from adverse selection during the matching process.

This finding also echoes Levinson and Niemann (2004) and Myers (2020), who find that high- demand tenants self-select into utility-included contracts (θ large). This channel for adverse selection with respect to the type of contract θ is precluded in our case where all contracts have the same energy-expenditure policy θ. When the common policy settles on $\theta > 0$, however, Proposition 3 shows that some adverse selection with respect to the dwellings' EE r may arise. This drives landlords to strategically decrease their investment in EE relative to the optimal investment level.

Like Fabra and Bian (2020), we find that landlords may have an incentive to hide their EE investments. Our mechanism is however very different. In the Fabra and Bian (2020) model, efficient landlords may strategically hide their bad signals in a traditional Lemons issue (Akerlof, 1970). In our case, EE is a horizontal differentiation parameter that appeals particularly to high-consumption tenants. This paves the way for adverse selection, which encourages efficient landlords to hide their EPCs.

2.5 Only tenants can signal their types

We now consider the mirror case when r is unknown to tenants but t is publicly observable. This is a more exploratory case that the literature and regulation has hitherto overlooked. Such a case may for example occur if there is no EPC to enable landlords to signal their quality but tenants have access to a signaling device. The signaling device could inform landlords about prospective tenants' past record of paying their energy bills, or tenants' socio-demographic characteristics known to correlate with energy consumption (see references in the Introduction). In this case, prices cannot depend on r. A landlord's problem is to choose r and (t) to maximize:

$$\max_{r,t} p(t) - \theta t(1-r) - \frac{r^{2+k}}{(2+k)l^k} \tag{10}$$

In contrast to maximizing equation (2), the price may depend on t but not on r.

[Proposition 4] *When EE investments are unobservable by a tenant, matching is efficient (t = l) but investments are suboptimally low. The clearing price and equilibrium investment are:*

$$p_3(t) = t\theta\left(1 - \frac{t}{2}\theta^{\frac{1}{1+k}}\right)$$
$$r_3(l,k) = l\theta^{\frac{1}{1+k}} \leq r^* \tag{11}$$

[proof] See appendix. **[end of proof]**

Even though matching is efficient, investments in EE are too low whenever landlords do not pay all the energy expenditures: the equilibrium investment $r_3(l, k)$ is optimal (equation [6]) if and only if $\theta = 1$. This corresponds to the case where landlords pay all the energy expenditures, thereby fully internalizing the benefits of their investments. As θ decreases (tenants pay a larger share of the energy expenditures), EE investments become increasingly inefficient. If $\theta = 0$, no investment is made. This situation corresponds to the standard split incentive problem.

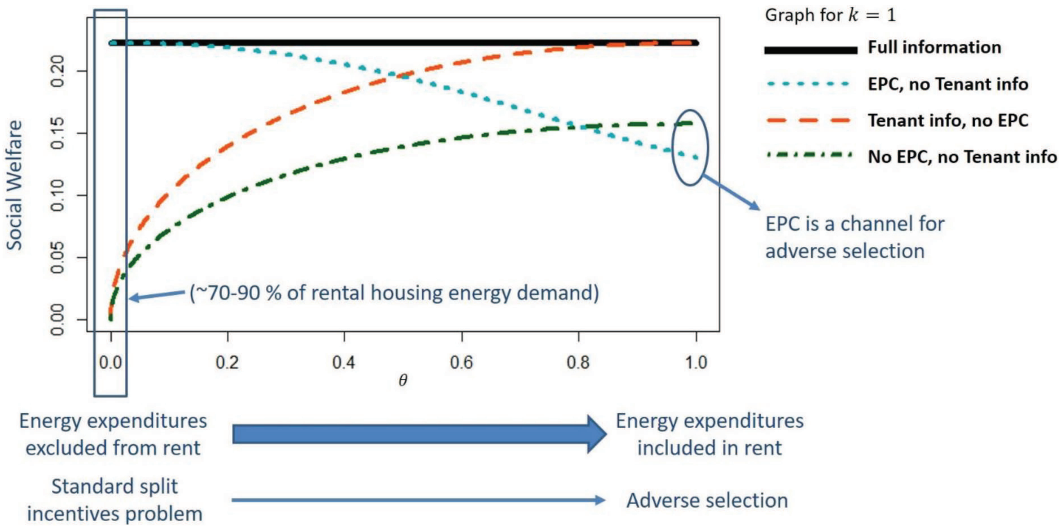
Comparing Proposition 2 and Proposition 4, we observe that landlords with low investment costs (l>E[t]) invest more in EE and landlords with high costs (l<E[t]) invest less than when both landlords' and tenants' characteristics are unknown (Proposition [2]). On average, landlords invest more in EE when tenants' characteristics are known.[7]

We finally note that $r_3(l, k)$ increases in k: the more differentiated the landlords are, the less homogenous the market is. We can therefore expect less fierce competition. As a consequence, landlords are able to extract more of the surplus that their investments generate, which results in more investments in EE.

Figure 1 offers a graphical illustration of the main findings of this section in terms of social welfare, which is defined as the sum of all landlords and tenants' energy expenditures (equations 2 and 3) expressed in monetary units. It reveals that EPCs alone restore welfare-optimal investment and matching if and only if all energy expenditures are excluded from rent (see the left side of the graph: $\theta = 0$). If this is not the case (see the right side of the graph, $\theta > 0$), an EPC needs to be complemented by tenant-side information. EPCs may even lower social welfare if all energy expenditures are included in the rent, as they allow for tenant-side adverse selection. In this case, the paradigm without any information is preferable to having EPCs alone. Tenant-side information suffices to restore optimal matching and investment. The graph also shows that providing tenants with tools that they can use to signal their type is a no-regret policy: combined with EPCs, such tools make it possible to achieve optimality with all types of contracts (the black solid line is always above the blue dotted line). If EPCs are unavailable, tenant-side signaling improves welfare whenever a rental contract includes some of the energy expenditures (the orange line is always above the green line). Figure 2 in the Appendix displays equilibrium investment in EE as a function of landlord type and the type of contract.

7. Propositions 2 and 4 also show that when there is no landlord-signaling, utility-included rental contracts increase welfare relative to individual metering. Our model, however abstracts away from the (potentially strong) effect of moral hazard on the tenant side.

Figure 1: Social welfare as a function of contract type. (k=1, tenant and landlord types follow a standard uniform distribution).



3. INDICATIVE EMPIRICAL EVIDENCE

In this section we first derive a set of conjectures from the theoretical model presented in Section 2. We then test these conjectures employing original data from a recent survey conducted among landlords in Germany.

3.1 Predictions derived from the conceptual model

In Section 2 we showed that imperfect information about landlords' EE investments generates a split-incentive problem. Further, when, in addition, tenants' characteristics are unknown to landlords prior to investing, EE investment is suboptimal. From this, we derive three testable hypotheses:

1) When landlords can signal their EE investments through an EPC, they invest more in EE.
2) Landlords' information about their tenants affects their investment in EE.
3) Imperfect matching (e.g. demand and supply are unbalanced) reduces investment in EE.

The first conjecture derives from the comparison of Proposition 1 on the one hand and Propositions 2 and 3 on the other hand. When landlords can signal EE investments, efficiency may be restored (Figure 1) and overall investment in EE increases (Figure 2, in appendix). The second conjecture derives from the fact that landlords get to know their tenants' characteristics over time. As tenants stay longer, landlords receive more accurate information about their tenants' energy consumption. More importantly, when tenants stay in their rental dwellings longer, landlords likely do not expect tenants' characteristics to change much in the coming years.[8] The comparison of Propo-

8. We made the simplifying assumption that the typical energy consumption of a given tenant is persistent over time. We acknowledge, though, that events such as changes in professional or family situations may induce shocks in consumption. We note that these large shocks often induce tenants to move and search for new dwellings, which we believe makes this persistent consumption assumption credible.

sitions 1 and 3 shows that when there is an EPC, better knowledge of tenants' characteristics in the future results in more EE investment (see Figure 2, in appendix).

The third conjecture may seem counterintuitive as one may suspect that landlords would be more strongly inclined to invest in EE and signal the quality of their rental properties in a case where finding tenants is difficult. Our model shows that, on the contrary, informational frictions imply that landlords do not know with which types of tenants they will be matched in the future. Overall, they invest less in EE, as the return on investment is insufficient to cover the costs.

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 of 416 landlords in Germany (each of whom owns 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 a discrete choice experiment on hypothetical technology adoption, which is not used in the present analysis. The survey included items pertaining to building characteristics, energy costs, past EE investments, tenant characteristics, and household socio-economic characteristics.

Our variable of interest is "Landlord_has_invested", which equals 1 if a landlord ever invested in thermal insulation in the rented dwelling and 0 otherwise.[9] We regress this variable against several covariates in a logistic regression model:

$$\begin{aligned}\mathrm{Landlord\_has\_invested}_i = {} & Intercept + Heating\_included_i + Low\_baseline_i \\ & + Market\_frictions_i + EPC_i + Market\_frictions_i * EPC_i \\ & + Tenant\_tenure_i + Friend_i + X_i + \epsilon_i\end{aligned}$$

"Heating_included" equals 1 if a landlord pays the heating expenditures and 0 otherwise. A positive value corresponds to a large θ in the model presented in Section 2. "Tenant_tenure" is the tenure in years of a tenant in the currently occupied dwelling and "Friend" takes the value 1 if the tenant is a friend of the landlord and 0 otherwise. These two variables may represent the quality of information a landlord has about her current tenant's energy consumption. "Market_frictions" equals 1 if a landlord declared that it would be difficult to find a new tenant should the current lease be terminated and 0 otherwise. "EPC" is a binary variable that equals 1 if a dwelling has an EPC, which enables a landlord to signal its EE level. The interaction term "Market-frictions * EPC" captures whether an EPC is more effective when there are market frictions compared to a situation where there are no market frictions. "Low_baseline" takes discrete values ranging from 1 if a landlord declared that she thought her tenant was energy-inefficient to 5 if she thought he conserved energy. We add various controls X_i such as the dwelling size (in m^2), the monthly rent (in euros), how long the landlord has owned the dwelling, whether the dwelling is in a collective building or not and how many dwellings the landlord rents out. We assume that the distribution of the error term ϵ_i is logistic. Table 1 displays the main descriptive statistics.

9. The exact question in the survey is: "Have you ever invested in thermal insulation of the dwelling while it was rented (e.g., changed windows or insulated ceilings or walls)?"

Table 1: Descriptive statistics.

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Landlord_has_invested	416	0.43	0.50	0	0	1	1
Heating_included	416	0.17	0.37	0	0	0	1
Tenant_tenure	416	6.99	7.46	0	2	10	36
Friend	416	0.23	0.42	0	0	0	1
Low_baseline	416	3.60	0.93	1	3	4	5
Dwelling_size	416	137	62	≤ 25	75	175	> 250
EPC	416	0.62	0.49	0	0	1	1
Market_frictions	416	2.11	1.14	1	1	3	5
Rent_price	389	778	674	≤ 300	450	800	> 3,000
Collective_housing	416	0.67	0.47	0	0	1	1
Duration_ownership	416	11.95	11.40	0	4	18	60
Number_of_rented_dwellings	416	1.58	0.87	1	1	2	4

Amongst the landlords in our sample, 43% had invested in EE in the past, while 17% pay the energy expenditures, which is in line with most estimates in developed countries. Extrapolated to the whole country and taking into account that 56% of households in Germany rent their dwelling, this would represent around 3.6 million households with rental contracts that include heating expenditures. Current heating cost regulation in Germany requires at least 50% of a household's heating costs to be charged based on metered data. Metering heating consumption for tenants is not required if, for example, landlord and tenant reside in the same building which comprises of two apartments only, and if costs for implementing meters and measuring heating consumption exceed cost savings. According to our data, tenants stay in a given dwelling on average for 7 years, which is significantly shorter than the average duration of a landlord's ownership tenure (12 years).

3.3 Results

Table 2 displays our main results. All models include information on tenants, landlords and market frictions as well as a number of controls such as dwelling-specific characteristics (location, collective dwelling or not) and landlord-specific characteristics (age, gender, number of dwellings rented out). Compared to the base Model (1), in Model (2) we add the interaction between EPC and market frictions. Model (3) includes the same covariates as Model (2) with a Linear Probability Model, as a robustness check pertaining to the underlying distributional assumptions. To allow comparison of the findings across models and for easy interpretation of the results, we present marginal and discrete probability effects for Models (1) and (2).

Several observations are in order. First, in line with our theoretical model and the broader literature on split incentives, Models (1) to (3) the findings show that when landlords pay some of the energy expenditures for a dwelling, they tend to invest more in EE (the coefficient on "Heating_included" is positive and statistically significant).

Second, longer tenant tenure and friendship between landlords and tenants are associated with more investments in EE. We believe it is reasonable to assume that tenant tenure and friendship between the landlord and the tenant are somewhat correlated with the degree of information the landlord may have on the tenant's heating consumption. 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 near future, she is more inclined to invest to achieve an adequate level of EE. Another, equivalent, interpretation is that tenants who often switch homes typically reside in dwellings that were not recently retrofitted.

Table 2: Regressions of EE investments on dwelling and tenant characteristics.

	Landlord_has_invested		
	Logistic	*Logistic*	*OLS*
Dependent variable:	(1)	(2)	(3)
Heating_included	0.200***	0.208***	0.199***
	(0.064)	(0.064)	(0.067)
Tenant_tenure	0.004*	0.004*	0.004*
	(0.002)	(0.002)	(0.002)
Friend	0.153***	0.126**	0.131**
	(0.058)	(0.059)	(0.063)
Low_baseline	0.021	0.024	0.019
	(0.025)	(0.025)	(0.026)
Dwelling_size	0.001*	0.001**	0.001**
	(0.001)	(0.0005)	(0.001)
EPC	0.133***	–0.100	–0.078
	(0.049)	(0.105)	(0.108)
Market_frictions	0.039*	–0.037	–0.032
	(0.021)	(0.038)	(0.038)
Market_frictions*EPC		0.111**	0.103**
		(0.044)	(0.046)
Dwelling-specific controls	yes	yes	yes
Landlord-specific controls	yes	yes	yes
Constant	yes	yes	yes
Observations	416	389	389
Log Likelihood	–255.199	–221.096	
Akaike Inf. Crit.	522.397	484.192	
McFadden's Pseudo R^2	0.101	0.169	
R^2			0.205
Adjusted R^2			0.162

Note: * p > 0.1; ** p > 0.05; *** p > 0.01. Standard errors are in parenthesis.

Third, there is no statistical evidence that landlords' EE investments are significantly correlated with their belief about their tenants' energy consumption. This finding, which is present independently of whether landlords pay some of the heating expenditures or not, would be a clear sign of market failure. It may, however, need to be confirmed with a larger sample. With respect to our model, we explain this by citing the fact that investment is made when future tenant characteristics are unknown, which may decrease average investment in EE (see Section 2.5).

Fourth and in line with our theoretical model, EPC in model (1) is statistically significant, suggesting that the EPC indeed allows landlords to signal information about the quality of their dwelling in terms of energy consumption. Market frictions are associated with more investment in EE, which is consistent with the idea that landlords strategically invest in quality when attracting a tenant is difficult. As Models (2) and (3) suggest, the EPC is related with higher EE especially when landlords declare that there are strong matching frictions ("Market_frictions" equals 1), i.e. when landlord-side signaling is most needed. This is consistent with the results reported in Section 2.4.[10]

4. CONCLUSION AND POLICY IMPLICATIONS

The previous literature that analyzes investments in EE in the rental housing market conceptually and empirically has focused on split incentives after landlords and tenants are matched

10. We also estimated a model where we include the interaction between EPC and tenant information (i.e. Tenant_tenure) which led to a null result. All other findings remained virtually unchanged.

as a main source of market failure that drives the EE gap. This study offered a new mechanism (i.e. imperfect matching in the rental housing market because of two-way asymmetry of information between landlords and tenants) as an explanation for the EE gap in the rental housing market. We clarified the intricate interactions between these two sources of market failure using a novel modeling framework. We use a matching model—an intuitive and realistic framework in which to think about the real estate market—to analyze the effects of private information on landlords (their idiosyncratic costs when investing in EE) and tenants (their typical energy consumption) when landlords may pay a share of tenants' energy expenditures. Above all, the main policy recommendation that the study generates is that in this case energy certification in the rental market should account for both demand-side and supply-side characteristics. In particular, because EE investments are often made when a landlord is searching for a new tenant, tenants should be able to signal their energy performance, which could then be accounted for by landlords. At present, policies such as EPCs enable landlords to signal information only about EE. We have shown in Proposition 3 that EPCs are fully effective only when all energy expenditures are excluded from rent. If instead rent includes (even only some) energy expenditures, then more information on the tenant side is needed. In other words, the side that should be certified is the one that does not pay for actual energy consumption. Our study confirms that when effective EPCs are in place, policies encouraging individual metering such as the one described in Ito and Zhang (2020) go in the right direction, because these policies enable landlords to exclude energy expenditures from the rent and implement consumption-based billing. However, because various market frictions cause many rental contracts (10 to 30%) to still include energy expenditures in a fixed payment system, signaling the tenant type is also needed.

We acknowledge that the practical implementation of such a signaling device on the tenant side may prove challenging. Ideally, tenants would be encouraged to show their past energy bills to potential landlords. This could form the basis of a more ambitious and informative "energy passport" wherein tenants would record their past energy performance and other characteristics relevant to forming a prediction of their future energy use. This would be the tenant-side counterpart to EPCs. Rental agencies or past landlords could also be allowed to provide such information, with adequate privacy safeguards. House search websites may also incentivize tenants to declare some of these characteristics and use them as input in search results.

Because of practical or privacy considerations, these recommendations may seem difficult to implement. However, a few initiatives indicate that tenant-side signaling may be realistic. First, solutions have become common practice in other domains facing similar signaling issues: insurance companies for instance request their potential clients to truthfully report past damages and to provide insurance-relevant information such as the practice of dangerous sports. Similarly, employers request truthful information from potential recruits, including referrals, past achievements, and proofs of qualification. Second, in most rental housing markets, landlords already gather some information about potential renters (credit checks in particular). In Germany (where the empirical study was conducted), potential renters are often asked to fill in a voluntary self-descriptive questionnaire ("Mieterselbstauskunft") including questions about rent payment capacity but also about being a good caretaker and a good neighbor. Further, in many countries, landlord associations have launched "ratemytenant" initiatives in which they gather and share information about their tenants (see for instance the site myrental.com in the USA). So far, these questionnaires or websites do not include information about energy consumption; however, this information could be added if deemed relevant by the landlords.

Our work could be extended fruitfully in at least two directions. First, allowing for moral hazard and the possibility of a rebound effect on the tenant side would likely uncover practical difficulties for tenant certification and reinforce the need for rental contracts that exclude energy expenditures (and, in turn, reinforce the need for EPCs). Second, our empirical study allowed us to test a few simple conjectures. Future empirical analyses may employ a larger sample to confirm the results and analyze frictions on the tenant side of the market. Ideally, matching 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 rental housing market.

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APPENDIX

Proof of Proposition 1

We seek 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:

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

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

We also want all agents to earn non-negative payoffs. 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, landlords and tenants are matched efficiently, such that $l = t(l)$. It implies 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

We now assume that no agent-specific information is public information. This results in prices $\bar{p}$ varying independently of both landlords' EE and tenants' typical consumption. In these conditions, a match can only be random. The expected utility of landlords becomes:

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

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

Rewriting the equilibrium investment as:

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

We derive the expected investment:

$$\mathbb{E}_l\left[r_1\left(l,k\right)\right] = \frac{1+k}{1+2k}\left(\frac{1}{2}\right)^{\frac{1}{1+k}}\theta^{\frac{1}{1+k}} \equiv f\left(k\right)\theta^{\frac{1}{1+k}}$$

We observe that $lim_{k\to+\infty} f\left(k\right) = f\left(0\right) = \frac{1}{2}$: when k is very small or very large, the average EE investment coincides with the case in which pricing is personalized to tenants and landlords' characteristics are unknown to tenants $\mathbb{E}_l\left[r_3\left(l,k\right)\right] = \frac{1}{2}\theta^{\frac{1}{1+k}}$.

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

This expression is negative when k is small but positive when k is large. It has a single root in $k = \frac{1-ln(2)}{2ln(2)-1} \approx 0.8$. Hence $\mathbb{E}_l\left[r_1\left(l,k\right)\right]$ is bounded from above by $\mathbb{E}_l\left[\ddot{u}_3(\ ,\ )\right]$.

Proof of Proposition 3

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

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

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

$$\frac{\partial p\left(r\right)}{\partial r} + \theta t\left(r\right) - \theta\left(1-r\right)\frac{\partial t\left(r\right)}{\partial r} - \frac{r^{1+k}}{l^k} = 0$$

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

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

Proof of Proposition 4

When the EE level r is unobservable, the price set by landlords may depend only on tenants' characteristics, which are public information p(t). The maximization problem is:

$$\forall l \in [0,1],\quad r_3(l)\,,\, t(r) = \arg\max_{r,t}\ \ p(t) - \theta(1-r)t - \frac{r^{2+k}}{(2+k)l^k}$$

$$\forall t \in [0,1],\quad t(r) = \arg\max_{\tilde{t}}\ \ \bar{u} - p(\tilde{t}) - (1-\theta)(1-r(\tilde{t}))t$$

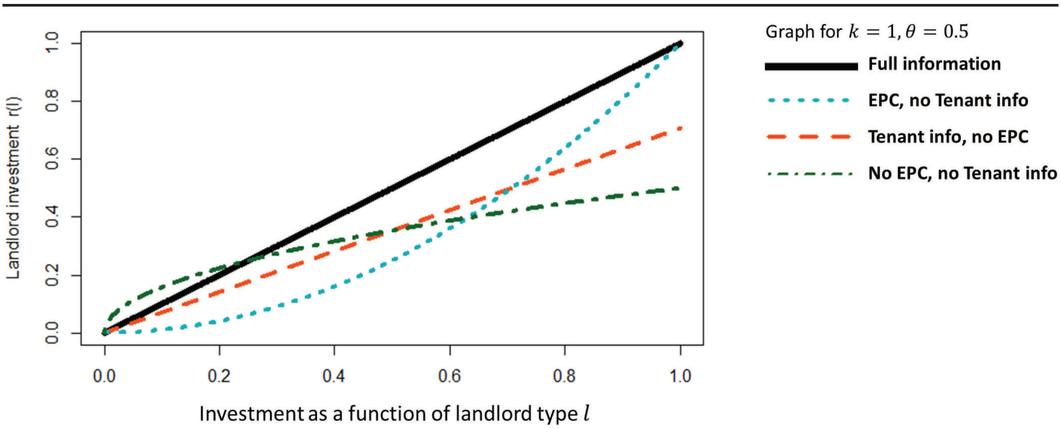
First-order conditions are $\theta t = \frac{r^{1+k}}{l^k}$ and $\frac{\partial p(t)}{\partial t} = \theta(1-r)$.

From the first equation above, in equilibrium we obtain $l = t$, which translates into $r_3(l) = l\,\theta^{\frac{1}{1+k}}$. Integrating the second relation, we have $\ddot{u}(\ ) = \theta\left(1 - \frac{t}{2}\theta^{\frac{1}{1+k}}\right)$, up to a constant normalized to 0 so tenants with no energy demand pay no fee for energy. As shown in the proof of Proposition 2, $\mathbb{E}_l\left[r_3(l,k)\right] > \mathbb{E}_l\left[r_1(l,k)\right]$: average EE investment is greater when tenants can signal their types than it is in a no-signaling situation.

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 in EE, reducing their attractiveness to high-demand tenants.

Graphical representation of EE investment as a function of landlord type

Figure 2: Landlords' investment in EE as a function of their types, and the type of contract. (k=1, tenant and landlord types follow a standard uniform distribution).



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