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Energy Performance Certificates and Investments in Building Energy Efficiency: a Theoretical Analysis

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Abstract

In the European Union, Energy Performance Certificates (EPCs) provide potential buyers or tenants with information on a property's energy performance. By mitigating informational asymmetries on real estate markets, the conventional wisdom is that they will reduce energy use, increase energy-efficiency investments, and improve social welfare. We develop a model that partly contradicts these predictions. Although EPCs always improve social welfare in the absence of market failures other than asymmetric information, their impact on energy use and investments is ambiguous and depends both on the time horizon considered and the distribution of energy needs in the population. This implies that, in a second-best world where energy externalities are under-priced, EPCs can damage social welfare.

Keywords: energy labeling, energy efficiency, buildings
JEL classification: Q48, Q58

1. Introduction

Improving energy efficiency is viewed as a major means to curb greenhouse gas emissions and, more generally, to limit the negative externalities generated by energy production, distribution, and use. This has led many countries to include ambitious energy efficiency objectives in their climate plans. As an illustration, the European

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[1]We are grateful to participants at MINES ParisTech, FAERE 2018, YEEES 2016, Montpellier, 18th Atlantic Workshop on Energy and Environmental Economics, and the 11th Conference on the Economics of Energy and Climate at TSE.

Union has set a binding target mandating a 20% reduction in energy use by 2020 relative to a business-as-usual scenario and current policy discussions focus on a 32% target for 2030.

Promoting energy efficiency of buildings is of major importance as they are responsible for 40% of total energy use in the EU. In addition to energy taxation, many countries grant tax credits and subsidies to energy retrofits of existing buildings. Building codes include energy performance provisions for new buildings. At the EU level, the building energy performance directive require to rely on so-called Energy Performance Certificates (EPCs).

EPCs provide potential buyers or tenants with information on housing energy performance. They display information on a property's typical energy use and energy cost, an energy efficiency rating from A (most efficient) to G (least efficient) and practical advice on improving such performance. Their publication is compulsory in all advertisements for the sale or rental of buildings since 2007 (for an example, see Figure A.5 in the appendix). In other countries, energy labeling is often voluntary (e.g. Energy Star, Leadership in Energy and Environmental Design).

The rationale for EPCs, and energy labeling more generally, is that buyers/tenants do not observe a dwelling's or an office's energy performance before moving in. In economic parlance, energy efficiency is an experience-good attribute. That is, a product characteristic which is difficult to observe in advance, but that will be revealed after the transaction. When considering a given property, a potential buyer or a tenant thus depends on the information provided by the seller/landlord who has incentives to manipulate this information by overstating the performance.

By limiting these information asymmetries on real estate markets, EPCs are primarily expected to improve the matching between properties with heterogeneous energy performance and households with heterogeneous energy needs. In particular, households with high energy needs – and thus a high willingness to pay for energy performance – will be able to choose energy-efficient properties, while households with lower needs will opt for cheaper, but less efficient properties. EPCs also raise the incentives to invest in energy efficiency as owners anticipate a higher price of energy-efficient properties when they will resell their property. These two mechanisms are expected to reduce energy use and GHG emissions in a cost-effective way.

We develop a dynamic model which examines the impact of EPCs on the level of energy use, investments and social welfare, and find results that partly challenge these conclusions. The model describes how the building stock of a city evolves over time. It includes two main characteristics. First, homeowners can make investments to upgrade their dwelling's energy performance.[2] Second, a fraction of dwellings is sold on a competitive real estate market in each period. We use this framework to identify the equilibrium investment paths in energy efficiency with and without mandatory energy certification, and the resulting impact on energy consumption.

We find that the introduction of EPCs improves social welfare in the absence of market failures other than asymmetric information. However, the impact on the level of energy use and on the volume of energy efficiency investments is ambiguous. In the short term, introducing EPCs clearly reduces energy use and increase investments because energy efficiency raises the dwelling's market value. The long-run pattern is totally different. In the absence of EPCs, imperfect matching on the real estate market means that a fraction of households with high energy needs inevitably move in *inefficient* dwellings. Once installed, they cannot but invest to reduce energy use. As mismatch persists until there is no longer any inefficient dwelling, so do investments, leading to the total renovation of the building stock.

This result has a very important policy implication. In policy circles, energy certification is primarily viewed as a tool for reducing energy externalities that are not sufficiently priced by other policy instruments. In this second best world, EPCs can damage social welfare in the long run. This calls for using EPCs in contexts where other imperfections are addressed by adequate instruments.

The remainder of the paper is organized as follows: section 2 reviews the literature on building energy certification, section 3 presents the model. We characterize the equilibriums with and without EPCs in section 4. Section 5 compares the two equilibriums and provides examples with simple simulations. In section 6, we discuss the case where energy externalities are under-priced and examine robustness issues in section 7. Section 8 includes the concluding remarks.

2. Literature on Building Energy Certification

We contribute to the economic literature on energy labeling of buildings with the first theoretical study dealing with its impact on energy use, retrofit investments and social welfare.[3] Almost all existing studies are empirical and concentrates on the impact on housing prices and rents (e.g., Brounen and Kok, 2011; Kok and Quigley, 2008; Fuerst and McAllister, 2011; Fuerst et al., 2015; Hyland et al., 2013; Jensen

[2]Although we cast the model in terms of residential homes, it equally applies to office buildings. We also consider the rental case in section 7.1.

[3]Note that, more generally, theoretical analyses of energy efficiency policies are seldom. For exceptions, see Fischer (2005), Nauleau et al. (2015), Wirl (2015).

et al., 2016; Kok and Jennen, 2012). They commonly find a positive impact with a price premium for higher energy performance although some studies are not able to identify whether this signals the effects of energy performance *per se* or the sole effect of labeling. The policy implications of these results are however limited. The ultimate objectives of energy labeling is to reduce energy use and GHG emissions in a cost-effective way. In theory, this can occur through at least two mechanisms: a better matching between heterogeneous households and dwellings and higher investment incentives. The existence of a price premium is a necessary condition for this to occur, but is not sufficient to test for these goal achievements.

An exception is the empirical study of Comerford et al. (2016) who examine the impact of EPCs on energy performance. Relying on UK data, they identify a threshold effect. After the introduction of the EPC, more homes have an energy rating just above the D grade and less homes have a rating just below in comparison to time before the EPC (the color-coded letter grade of the EPC overlaid a pre-existing 0-100 point scale). It illustrates a situation already identified by Dranove and Jin (2010): sellers might game the system when information is disclosed. Here, sellers seem to invest in a strategic way to reach the letter D. This leads to potential inefficiency issues as some sellers might over-invest to reach the letter D, some sellers might under-invest because their letter is already D or above.[4] We rule out these bunching issues in the model by assuming that the certificate yields perfect information (which is the case in practice). Qiu and Kahn (2019) have also recently provided evidence that voluntary energy certification in the U.S. has a significant negative impact on energy use.

A central component of our analysis is that households are assumed to have heterogeneous energy needs. This assumption is in line with Longhi (2015) and Bakaloglou and Charlier (2018) who provide evidence that family composition and preferences for comfort over energy savings do have significant impacts on energy consumption. Preferring comfort over economy or one additional degree of heating implies an average energy over-consumption of 10% and 7.8% respectively (up to 36% for high-income households). Miller et al. (2017) stress how important building energy performance can be for older people who have high energy needs because they spend more time at home.

Note that we only refer here to schemes which publicly disclose energy performance on real estate markets. There have been many studies on private signals providing home occupiers with informational feedbacks on their home energy con-

[4] In this respect, Sallee and Slemrod (2012) develops an interesting evaluation of the size of such inefficiencies in a different sector (the automotive industry).

sumption (see for instance Jessoe and Rapson, 2012). The underlying mechanisms are totally different since this information does not reduce information asymmetries on real estate markets. It is expected to mitigate behavioral biases. In this respect, EPCs can also affect salience and awareness of energy costs.

Finally, our theoretical approach relates more broadly to the microeconomics of real estate markets (see e.g. Fallis, 1985). The real estate literature is however mostly empirical, and interested on the one hand in macroeconomic aspects, in particular in the link with macroeconomic fluctuations and housing prices. On the other hand, analyses at the microeconomic level have raised a myriad of questions (see for instance Glaeser and Gyourko, 2018, for a recent overview on housing regulation). While several papers study dynamic adverse selection markets, to the best of our knowledge, the combination of market turnover, investment in quality and policies reducing asymmetric information has not been examined. Several authors have attempted to draw short term implications of matching frictions on the real estate market. In particular, the role of appraisal (see Quan and Quigley, 1991, for a seminal contribution) and time-on-the-market as a potential signal of quality (see Taylor, 1999, for a classic treatment) have been theoretically investigated. There is also a quite active theoretical literature on the dynamics of one-time sale in the lemons problem (i.e. non-durable goods), but it features neither quality investment nor certification in an open-ended horizon with successive sales as our model does.[5] Our model assumes instead simple market clearing in the short term to focus on the long term implications of policies reducing asymmetric information and fostering quality investment.

3. Model

The model describes the evolution of the building stock of a city. It has three main features. First, it includes a real estate market. At the beginning of each period, an exogenous share of households leave the city and sell their dwellings to incoming households who move in. Second, households can improve their dwelling's energy performance by investing in energy efficiency. As they look forward, this investment decision is driven by both their future energy expenditures and the future resale value of their dwelling. EPCs affect the level of investment by creating a price wedge between energy-efficient and inefficient dwellings. Third, households

[5] House and Ozdenoren (2008) study such a long-run dynamic housing market, but without informational issues. While other durable goods markets with adverse selection such as cars (Hendel and Lizzeri, 1999) have been studied theoretically, with an emphasis on the interaction between markets for used and new goods, the setting and research questions differ substantially.

have heterogeneous energy needs and dwellings have different (endogenous) energy performance levels. Total energy consumption will thus depend on how the real estate market matches households with dwellings. We now describe the model in more details.

3.1. Assumptions

We favor simpler assumptions whenever they do not change qualitatively the results in order to make the presentation clearer and highlight the key economic effects. The building stock consists of dwellings characterized by a level of energy performance θ. Each dwelling can either be energy-efficient ($\theta = 1$) or inefficient ($\theta = 0$). Relaxing the binary assumption would neither change the machinery of the model nor its qualitative results. The dwellings are owned and occupied by a continuum of households with heterogeneous energy needs. More specifically, each household consumes a quantity of energy $(1-\theta) \times e$ per period where e is distributed over $[0, +\infty)$ according to a cumulative distribution function F. Note here that this consumption level can incorporate a rebound effect. That is to say, the level e factors in all determinants of consumption and is best thought of the energy consumption differential of a given household occupying an energy inefficient dwelling (with $\theta = 0$) rather than an energy efficient one (with $\theta = 1$). The cumulative distribution function F is continuous, strictly increasing, and the overall level of energy consumption is bounded: $\int_0^{+\infty} e \, \mathrm{d}F(e) < +\infty$. We do not impose any other restrictions on F. We will see that the properties of this function have a decisive impact on some results.

Let q_t denote the share of efficient dwellings at the beginning of period t. For ease of presentation, we assume that $q_0 = 0$, that is, all dwellings are initially inefficient. We consider an extension with delayed implementation in subsection 7.2. Any household can then invest in any period to upgrade its property if $\theta = 0$. The cost is a one-time irreversible investment I that turns the inefficient dwelling into an efficient one for the entire time horizon.[6] The infinite lifetime is irrelevant as we just need that energy retrofit is still valuable when reselling the dwelling. The homogeneity assumption on energy retrofit cost I can be challenged in two ways. One way is to consider a dwelling-specific heterogeneity: some dwellings are more costly to retrofit than others. Introducing this type of heterogeneity does not change qualitatively the results. Another way is to consider heterogeneity across households: some households find more difficult to carry out energy retrofit than others. This second type of heterogeneity can have noteworthy consequences. They are examined in section Appendix C of the appendix.

[6] We thus ignore that energy efficient capital also depreciates.

In each period, m households exogenously and randomly move out and sell their dwelling to the same number of households who previously lived outside the area and who move in. Incoming and outgoing households are drawn from the same energy consumption distribution and every household has the same probability m of moving out at each period. The exogeneity of moving decisions captures the fact that most people decide to move in or out for professional or family reasons that are not related to home energy performance.[7] The real estate market is assumed to be competitive.

The precise timing of events within each period t is as follows:

1. m households move out and sell their dwellings to m households who move in.
2. Each household who lives in an inefficient dwelling decides whether to invest I or not.
3. Payoffs are realized.

In the scenario with EPCs, incoming households observe individual dwellings' energy performance before purchase. In the absence of EPCs, we simply assume that θ is observed after the transaction. That the EPC is perfectly informative, that a potential buyer has no information at all on the energy performance when there is no certification, and that her/his information is perfect after the transaction are all restrictive assumptions as shown empirically by Hardy and Glew (2019) or Myers (2019). They are however mostly innocuous assumptions: what ultimately matters is the information differential between the two scenarios, i.e. that incoming households are better informed when there is certification rather than not. Incoming households have a higher willingness to pay for a dwelling they believe more strongly to be energy efficient, and EPC precisely makes this belief more accurate.

Lastly, households form correct expectations about future housing prices in all scenarios. This assumption of full rational expectations simplifies the presentation and can be relaxed. What simply matters is that households anticipate an increase of the market value of their dwelling if they invest in energy efficiency in the EPC scenario.

3.2. Social optimum

We can now identify the socially optimal investment path and the allocation of households in the dwellings. Under our assumptions, the social optimum is obtained

[7] An equivalent setting is to allow moving decisions to be endogenous to energy issues but to assume that moving costs are greater than the investment cost I, so that households have no incentives to move for home-energy-performance-related reasons. While it may be the case very marginally that (local) moving can be triggered by energy-efficiency consideration, it this seems a reasonable assumption to neglect this at the aggregate level.

by minimizing the discounted sum of investments and energy expenditures over the entire time horizon. This cost is:

$$C = \sum_{t=0}^{\infty} \delta^t \left(\int_0^{+\infty} \mathbb{P}_t(\theta = 0|e)e \, \mathrm{d}F(e) + (q_{t+1} - q_t)I \right)$$

Let us first characterize the socially optimal allocation of the households across dwellings in period t at the beginning of which the share of energy efficient dwellings is q_t. In this context, perfect marching requires that households with the highest energy needs occupy the energy-efficient dwellings. Formally, let g_t^* denote this socially optimal allocation function $e \mapsto \theta$ which maps each household type to a dwelling's level of energy performance in period t. Perfect matching means that:

$$g_t^*(e_t^*) = \mathbb{1}_{\{e \geq e_t^*\}} \tag{1}$$

where e_t^* is the marginal type such that the city capacity constraint is binding: $1 - F(e_t^*) = q_t$.

Turning next to the socially optimal investment path, recall that the distribution of households' types e does not vary over time: incoming households are drawn from the same distribution as that of the initial population. As a result, an investment in a given dwelling should either be made in the first period or never, which in turn leads to a time-invariant threshold e_t^*. Ignoring the time index, the value of e^* is then obtained by considering that the investment decision in period 1 should be made as if the same household was staying forever. In this context, energy retrofit is socially optimal if the household e is such that the investment cost is lower than the net present value of the energy cost over the infinite time horizon:

$$I \leq \sum_{k=0}^{\infty} \delta^k e = \frac{e}{1-\delta} \tag{2}$$

where δ denotes the household discount factor. This completes the characterization of the social optimum.

Lemma 1 (Social optimum)**.** *In the first best social optimum, investments are only made in period $t = 1$ and the share of energy-efficient dwellings at the end of the period is $q^* = 1 - F(e^*)$ with $e^* = I(1 - \delta)$. The energy-efficient dwellings should then be occupied by households with types higher than e^*.*

4. Equilibrium analysis

4.1. Equilibrium with EPCs

In this section, we examine the equilibrium investment path when EPCs give perfect information on energy performance. From now on, let $u_t(e, \theta)$ denote the expected lifetime surplus of a household with energy consumption e living in a dwelling with performance θ at the beginning of period t. In the case where the dwelling is efficient ($\theta = 1$), this surplus is given by induction, according to:

$$u_t(e, 1) = \delta[mp^1_{t+1} + (1 - m)u_{t+1}(e, 1)] \tag{3}$$

where δ is the household's discount factor.[8] Indeed, the energy expenditure is zero in period t while the household moves out in the next period with probability m, thereby selling the dwelling at price p^1_{t+1}, or stays with probability $1-m$ and derives surplus $u_{t+1}(e, 1)$. Note that when a household leaves, we normalize the continuation values outside of the city to 0. This is without loss of generality since the future utility depends only on past housing quality through the price received upon selling.

When $\theta = 0$, the surplus depends on whether the homeowner invests or not. Denoting $u^I_t(e)$ the expected surplus when she invests and $u^\emptyset_t(e)$ when she doesn't, the expected utility is:

$$u_t(e, 0) = \max\{u^I_t(e), u^\emptyset_t(e)\} \tag{4}$$

where:

$$u^I_t(e) = -I + \delta mp^1_{t+1} + \delta(1 - m)u_{t+1}(e, 1) \tag{5}$$

$$u^\emptyset_t(e) = -e + \delta mp^0_{t+1} + \delta(1 - m)u_{t+1}(e, 0) \tag{6}$$

We now examine how incoming households are allocated in the different dwellings by the real estate market. To start with, perfect information implies a separating equilibrium with a price premium for the energy efficient dwellings: $p^0_t < p^1_t$. The outcome of trading is characterized by p^0_t, p^1_t, and the allocation function $g_t : e \mapsto \theta$ which satisfies two conditions:

- Market clearing: $\int_0^{+\infty} g_t(e)\mathrm{d}F(e) = q_t$.

[8]It is assumed that every household has the same discount factor δ. Relaxing this assumption to allow heterogeneous discount factor does not change qualitatively the results of the model, the investment threshold would however now depend jointly on e and δ. We further discuss comparative statics below, as well as the behavioral interpretation of δ.

- Incentive compatibility: $g_t(e) = \underset{\theta}{\operatorname{argmax}}\ u_t(e,\theta) - p_t^\theta$.

From the incentive compatibility condition easily follows that the market perfectly matches the households with the dwellings. That is, there is a threshold energy consumption $\tilde{e}_t$ such that all households with lower energy consumption purchase inefficient dwellings whereas the biggest energy consumers choose efficient ones. Hence $g_t = \mathbb{1}_{\{e \geq \tilde{e}_t\}}$.[9]

Lemma 2 (Perfect matching)**.** *Under perfect certification, all incoming households with energy consumption such that $e \geq \tilde{e}_t$ purchase energy-efficient dwellings, where $\tilde{e}_t$ is implicitly and uniquely defined by $F(\tilde{e}_t) = 1 - q_t$.*

Proof. See the appendix. □

Turning next to the investment decision in this market environment, we compare u_t^I with $u_t^\emptyset$. It is intuitive that investors are the households with the highest energy needs.

Lemma 3. *In period t, a household with energy consumption e living in an inefficient dwelling invests if $e \geq \breve{e}_t$ where $\breve{e}_t$ is the unique solution of the equation $u_t^\emptyset(e,0) = u_t^I(e,0)$.*

Proof. See the appendix. □

It is then very intuitive that investments are only made in period $t = 1$. Lemma 2 implies that investing households anticipate that, if they move out in a next period, their home will be purchased by the biggest energy consumers types. As incoming types are drawn from the same distribution, they invest as if they were going to stay forever in the dwelling, trading off the investment cost and the total discounted energy cost $e/(1-\delta)$. We are now able to state the main proposition of this section. The details of the proof are relegated in the appendix.

Proposition 1 (EPC equilibrium)**.** *The EPC policy is socially optimal in the absence of market failures other than information asymmetry on energy performance. All investments in energy efficiency are made in period $t = 1$. Upgraded dwellings are then occupied over the entire time horizon by households with energy needs higher than $e^* = I(1-\delta)$. The time-invariant quantity of efficient dwellings in the market*

[9] Relying on French data, Douenne (2018) shows that poor households consume less energy although they live in less energy-efficient dwellings, suggesting that our matching mechanism has some substance.

is $q^* = 1 - F(I(1-\delta))$ *and the time-invariant per-period energy consumption is* $E^* = \int_0^{I(1-\delta)} e \, \mathrm{d}F(e)$*.*

As expected, the quantity of efficient dwellings increases when energy consumption increases. In more formal terms, for two distributions F_1 and F_2 of energy consumption e, if F_1 first-order stochastically dominates F_2, then the quantity of efficient dwellings associated to F_1 will be greater than the one associated to F_2, *ceteris paribus*. The energy performance of the building stock also increases when the discount rate and/or the investment cost I diminish.

4.2. Equilibrium without EPCs

The main difference with the certification case is that we now have a pooling equilibrium on the real estate market with $p_t^0 = p_t^1$. The analysis is then somehow simpler as the real estate market gives zero value to energy retrofit ($p_t^0 = p_t^1$), so that no incentives for investment are provided by the price system, and incoming households are randomly assigned to the dwellings.

When making an investment decision, households just need to compare the investment cost with the energy saved during their residence in the dwelling. A household with energy consumption e will thus invest if and only if:

$$I \leq \sum_{k=0}^{\infty} (\delta(1-m))^k e = \frac{e}{1-\delta(1-m)} \tag{7}$$

This condition shows a partial internalization of the investment benefit by the investor. As the household may move out and sell its dwelling with per-period probability m, investing households discount the future at rate $\delta(1-m)$, that is the conventional discount rate times the probability of staying in the next period. Hence, we have:

Lemma 4. *Without EPCs, in any period, a household with energy consumption* e *living in an inefficient dwelling invests if and only if* $e \geq \hat{e}$ *where* $\hat{e} = I(1-\delta(1-m))$*.*

Although individual investment incentives are lower than with certification, they persist over time in contrast with the EPC equilibrium where all investments are made in the first period. The reason is that the random market allocation implies that some large energy consumers inevitably move in inefficient dwellings in each period. Once installed, they cannot but invest to consume less energy. To be more precise, the process unfolds as follows:

- At $t = 0$, all households occupy inefficient dwellings.

- Households who consume more than $\hat{e}$ upgrade their home. As a result, the share of inefficient dwellings is $F(\hat{e})$ at the end of the period.
- At the beginning of period $t = 1$, m households randomly move out. A share $mF(\hat{e})$ of inefficient dwellings are thus (randomly) sold to incoming households. Households moving in these inefficient dwellings invest if their energy consumption is higher than $\hat{e}$. The share of efficient dwellings thus increases by $mF(\hat{e})(1 - F(\hat{e}))$.

The process goes on so that we have:

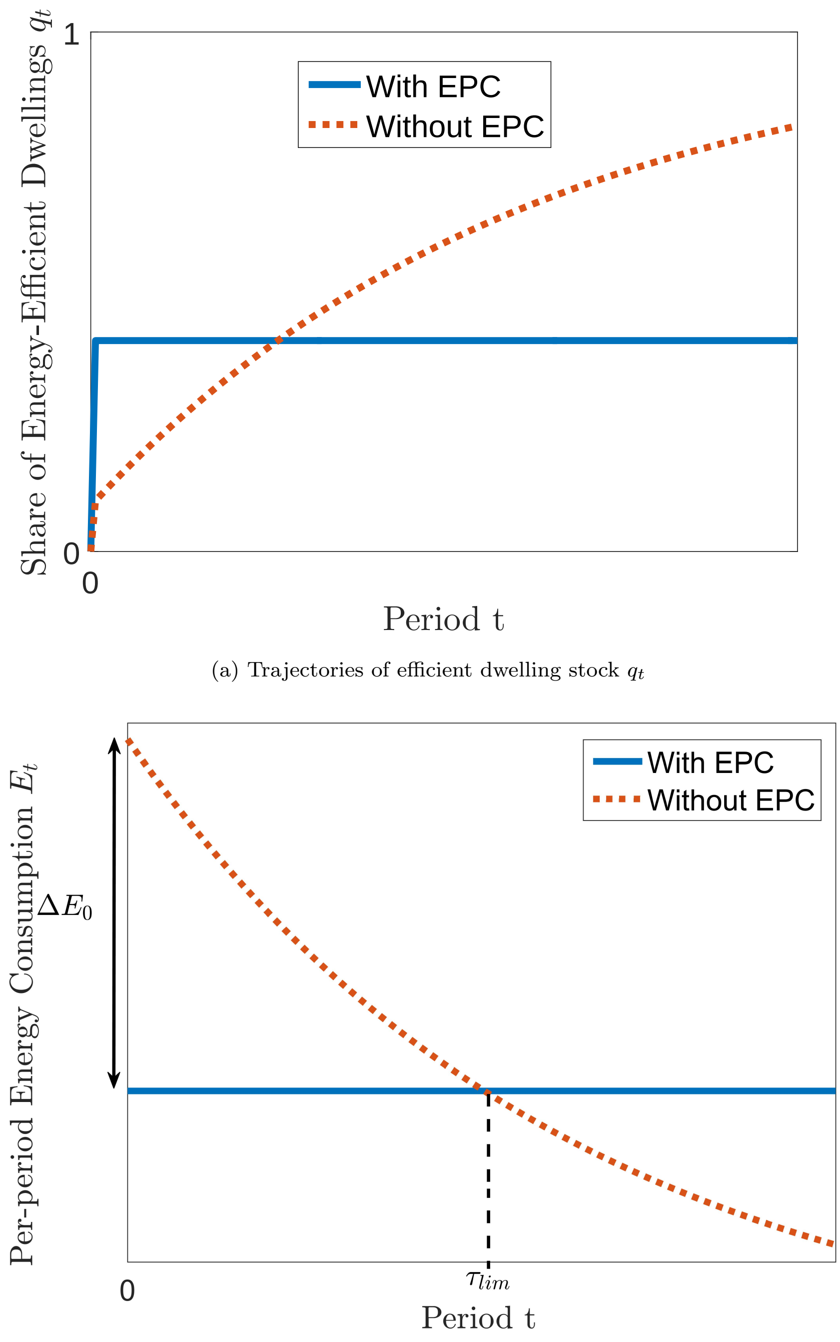
Lemma 5. *Without EPCs, the share of efficient dwellings is* $\hat{q}_t = 1 - F(\hat{e})[1 - m(1 - F(\hat{e}))]^{t-1}$ *and the overall level of energy investment flow is* $\hat{I}_t = mI(1 - F(\hat{e}))F(\hat{e})[1 - m(1 - F(\hat{e}))]^{t-1}$*. Moreover, the aggregate energy consumption is* $\hat{E}_t = [1 - m(1 - F(\hat{e}))]^t \int_0^{\hat{e}} e \, \mathrm{d}F(e)$ *(with* $t \geq 0$*) and* $I_0 = (1 - F(\hat{e}))I$*.*

From Lemma 5, we directly obtain the main proposition of this section.

Proposition 2 (Equilibrium without EPCs)**.** *When building energy performance is not certified, households never stop investing so that the share of efficient dwellings converges to 1 in the long run:* $\hat{q}_t \to 1$ *when* $t \to +\infty$*. The levels of per-period investments and energy use converge to zero:* $\hat{E}_t \to 0$ *and* $\hat{I}_t \to 0$*.*

This proposition gives the main result of the paper. Counter-intuitively, the absence of energy certification leads to more investments and less energy consumption in the long run than under perfect information. To grasp the intuition, consider Figure 1 which compares the evolution over time of the share of upgraded dwellings q_t and the per-period total energy use E_t with and without certification.

In the short term (i.e., in period 1), households invest more with EPC than without because they anticipate the market price premium. This leads to a higher share of efficient dwellings at the end of the first period ($q^* > \hat{q}_0$). This is the intuitive mechanism that investment incentives are higher when the real estate market values energy performance. The situation evolves totally differently in subsequent periods. In the EPC scenario, perfect matching on the real estate market ensures that efficient dwellings continue to be occupied by households with the highest energy needs. As a result, investments stop and energy consumption remains constant. In contrast, mismatch persists without EPCs, which to leads to a sustained rate of investments. The reason is that a fraction of the newcomers with high energy needs randomly purchase inefficient dwellings and then invest to reduce their energy consumption once installed. Since the stock of energy-efficient building increases, this effect fades over time.



(a) Trajectories of efficient dwelling stock q_t

(b) Trajectories of per-period energy use E_t

Figure 1: Comparison of equilibrium dynamics with and without certification

Real world energy efficiency policies are frequently structured by overall energy efficiency goals (e.g., a 20% reduction of energy use by 2020 in the European Union). Against this background, Proposition 2 says that, in the long run, the absence of EPCs may induce more energy efficiency gains. This suggests that introducing EPCs can make it more difficult to achieve long-term goals.

5. Equilibrium comparison

In this section, we push further the comparison of the scenarios with and without EPCs by deriving comparative statics results and examining examples.

5.1. The influence of the moving probability

The role of the moving probability m is crucial as it determines the building stock turnover speed. As shown in proposition 1, m does not affect the aggregate level of energy consumption when there is certification. In contrast, the level of energy efficiency investment in period 1 in the absence of certification is a decreasing function of this probability (lemma 5). That is, the shorter the expected duration of residence, the less households are willing to invest.

In the long term, the effect in the absence of EPCs of the moving probability on energy consumption is ambiguous. On the one hand, a higher m continues to lower investment incentives. On the other hand, more real estate transactions occur at each period, thereby creating more frequent opportunities to invest. It is possible that this mismatch effect more than compensates the price-incentive effect, leading to less energy consumption in the long term when m is high.

Let us illustrate this point with the uniform distribution $F \sim U([0, I])$. A straightforward extension of lemma 5 shows two regimes:

- When $m \leq \frac{1}{2}$, an increase in the moving probability induces an increase in energy consumption E_t at all periods. In this case, the decrease in investment incentives dominates the increase in investment opportunities.
- When $m \geq \frac{1}{2}$: an increase in m induces a decrease in the aggregate energy consumption E_t in the long term. In this case, the decrease in investment incentives is dominated by a higher mismatch effect and the associated increased investment opportunities in the long term.

These results are illustrated in figure 2 which shows that energy consumption trajectories do not cross each other when $m \geq \frac{1}{2}$ while per-period energy use in any period decreases with m. In contrast, when $m \leq \frac{1}{2}$, per-period energy use decreases with m in the first periods but increases with m in later periods.

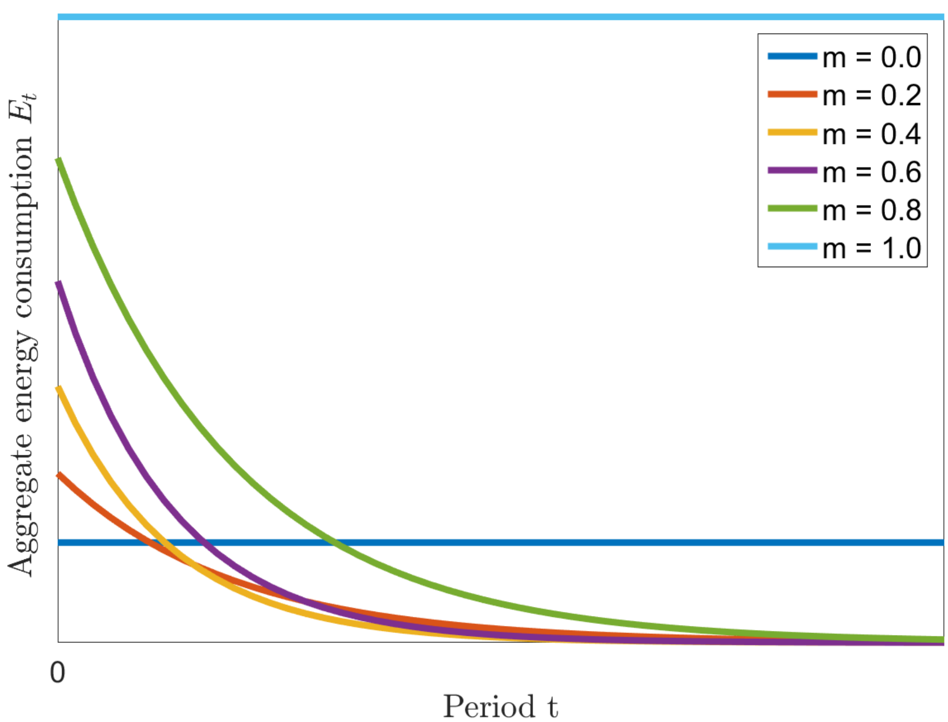


Figure 2: Aggregate energy consumption trajectories without EPC for a uniform distribution $F \sim U([0, I])$ and for various probabilities m of moving.

Beyond the moving probability, comparative statics on other parameters of the model (investment cost I, discount rate δ) are in general ambiguous and centrally depends on the distribution F.[10] In order to develop intuitions and illustrate the machinery of the model, we develop two illustrative examples with contrasted distribution in the next subsection.

5.2. City examples

The homogeneous city. Let us consider a homogeneous residential community where the population has the same energy need e. For the sake of presentation, assume further an intermediate level of energy consumption: $e \in [I(1-\delta), I(1-\delta(1-m))]$. In this case, it is straightforward that certification always induces less energy consumption and more investments in the short run and in the long run. There is no mismatch between dwellings and households without EPCs which could compensate the low investment incentives. The result does not qualitatively change when considering a retirement community with high energy consumption $\bar{e} > I(1-\delta(1-m))$ because retired people spend a substantial amount of time at home or a college town with low energy consumption $\underline{e} < I(1-\delta)$ because students are more likely to trade a lower energy bill with a less cozy thermal comfort.

The summer colony. In contrast to the previous example, this example pictures a situation with strong heterogeneity in energy consumption among households. We have in mind a summer colony like Martha's Vineyard in the U.S. with two types of inhabitants:

- Permanent residents who live there all over the year, which implies a high energy consumption $\bar{e} > I(1-\delta(1-m))$. Investing in energy efficiency is profitable even if they only take into account energy savings.
- Seasonal residents who only come on vacation and therefore have a low energy consumption $\underline{e} < I(1-\delta)$.

Under these assumptions,[11] once installed in an inefficient dwelling, permanent residents invest whether it is certified or not. Symmetrically, seasonal residents never

[10] The empirical literature on residential energy efficiency provides evidence that energy users may be myopic in the sense that they under-estimate future private energy savings when making investment decisions (Gillingham and Palmer, 2014). The ambiguity of the comparative statics results on δ prevents drawing general lessons on the long-term impacts of such behavioral biases.

[11] This example features a discrete or bounded distribution F. Therefore, It does not satisfy the technical assumptions made for convenience on F (continuity and strict monotonicity over $[0, +\infty)$). However, results derived in section 4 can be straightforwardly adapted.

invest even with EPCs. Investment levels and energy consumption are thus the same at the end of the first period with and without certification. Furthermore, without EPCs, the mismatch between incoming permanent residents who have high energy consumption and energy-inefficient dwellings is potentially large. This induces sustained investments by incoming permanent residents. As a result, the absence of certification allows to attain lower energy consumption levels in the long term. The mismatch effect dominates the investment-incentive effect. This example illustrates that a high household heterogeneity promotes energy efficiency where there is no EPCs.

This example gives the opportunity to present a simulation which shows that the case where EPC leads to less energy consumption in the long run is not a hypothetical situation that would never happen in the real world. We are therefore considering a particular case that we are trying to make as realistic as possible. Our objective is not to examine the different cases of Proposition 3.

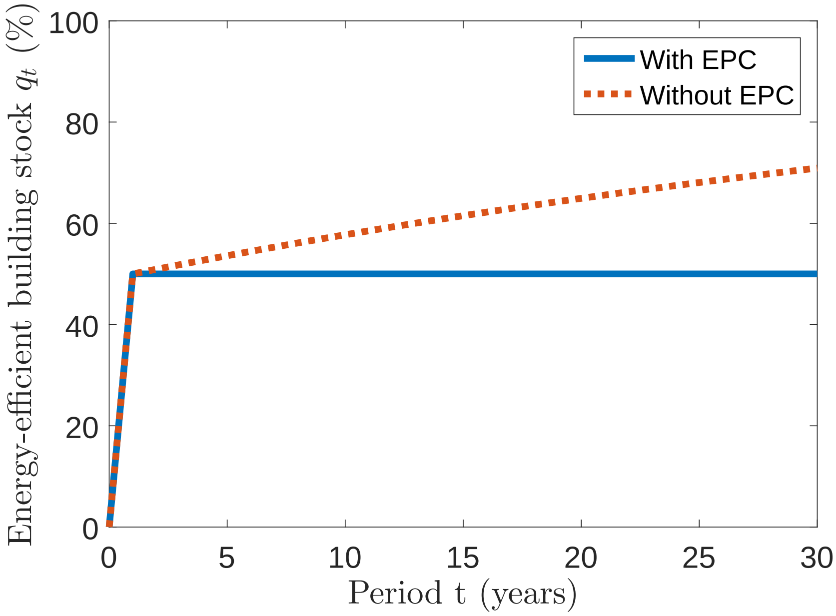
Since the simulation is generated using the model, we are however forced to simplify. We consider the case of a French summer colony where natural gas is used as a heating fuel. In order to make our point, we use the carbon tax rate projected for 2030 in France. In such a setting, permanent residents have incentives to invest in energy efficiency whether or not there is an EPC. On the contrary, seasonal residents (we assume that seasonal residents have an energy consumption equal to 20% of the one of permanent residents) are never willing to invest in energy efficiency. We also assume that the population is equally split between seasonal and permanent residents. Details of the calibration of the model for this example are provided in the appendix.

Results of the simulation are shown in figure 3. When there is an EPC, retrofits only concern the half of dwellings occupied by permanent residents, whereas retrofits' dynamic is maintained in the absence of EPC. In parallel, energy consumption is constant when there is an EPC while it keeps decreasing without EPC.

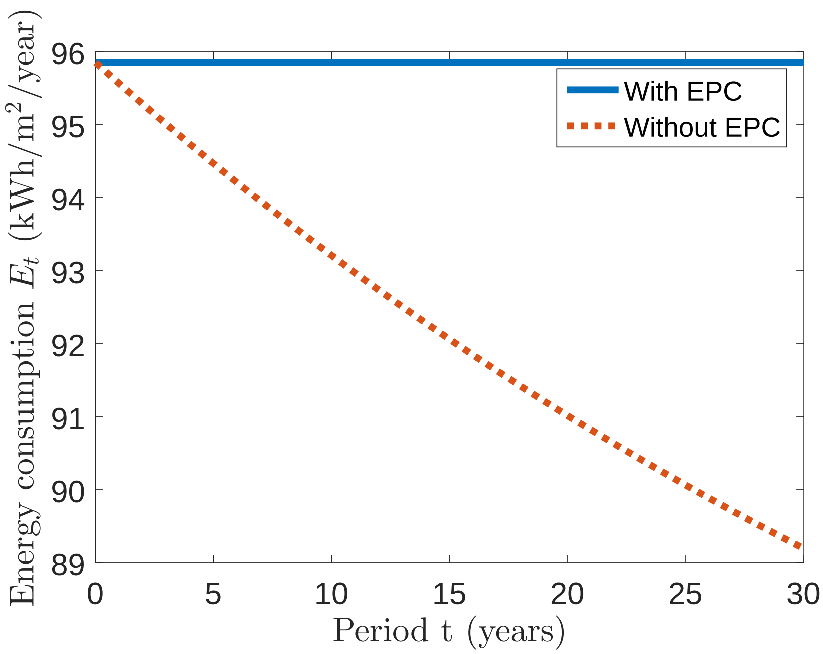
6. Under-priced externalities

Proposition 1 tells us that EPCs always improve welfare in a situation where all the other market failures have been properly mitigated. However, in policy circles, energy efficiency policies in general, and EPCs in particular, are generally viewed as tools to mitigate energy externalities that are not priced at the efficient level. In this section, we derive policy implications that are relevant in this context.

As introducing EPCs may lead to higher energy consumption and lower cumulative investments in the long term, certification may reduce welfare if energy externalities are not sufficiently internalized. Assume that energy expenditure e generates



(a) Trajectories of efficient dwelling stock q_t



(b) Trajectories of per-period energy consumption E_t

Figure 3: Example of a French summer colony with 2030 energy prices

an externality αe which is not internalized with a tax or another policy instruments. Households thus use too much energy under EPCs. More precisely, cumulative energy cost, excluding the externality, is now $\left(\int_0^{e^*} edF(e)\right)/(1-\delta)$ while it should be $\left(\int_0^{e^{**}} edF(e)\right)/(1-\delta)$ in the first best with a threshold $e^{**} = I(1-\delta)/(1+\alpha)$ which is lower than e^*.

Without EPCs, Lemma 5 say that cumulative energy use is:

$$\sum_{t=0}^{+\infty} \delta^t \hat{E}_t = \frac{1}{1-\delta[1-m(1-F(\hat{e}))]} \int_0^{\hat{e}} edF(e).$$

It is then clear that the difference with the EPC scenario is ambiguous. In particular, it depends on the cumulative F. If most households consume between e^* and $\hat{e}$ (the population has intermediary energy needs), they will not invest in the absence of EPCs, leading to a higher energy use.[12] This is just the opposite if most of the households have high energy needs so that $e > \hat{e}$. Their propensity to invest is identical in the first period, but a fraction of incoming households continue to invest in the next periods without EPCs because they move in inefficient dwellings.

Depending on the size of the externality, this can lead to a higher social cost with EPCs. Straightforward calculation yields that EPCs improve welfare iff:

$$\begin{aligned}
&(1+\alpha)\left(\frac{\int_0^{\hat{e}} e\,\mathrm{d}F(e)}{1-\delta(1-m(1-F(\hat{e})))} - \frac{\int_0^{e^*} e\,\mathrm{d}F(e)}{(1-\delta))}\right) \\
&+ I\left[\frac{1-\delta(1-m)}{1-\delta(1-m(1-F(\hat{e})))}(1-F(\hat{e})) - (1-F(e^*))\right] > 0
\end{aligned}$$

The sign of this (cumbersome) welfare difference is ambiguous. If α is very small, the EPC scenario converges to the first best. If α is large, EPCs may damage welfare if q_t without EPC quickly converges towards 1. And we have seen that this depends on the distribution F (among other factors). We collect these insights in a new proposition.

Proposition 3. *When energy consumption generates an externality of size α per unit, introducing EPCs may damage social welfare. This ultimately depends on the sets of parameters m, δ, I, α and on the distribution of energy needs F.*

[12] Formally, $F(\hat{e}) \to 1$, implying that the first multiplicative tends to be equal across scenarios $(1/(1-\delta))$ while the integral tends to 0 in the EPC scenario.

7. Extensions

In this section, we consider two variations of the model in order to assess the robustness of our results.

7.1. The rental case

The base model features owner-occupiers. What if dwellings are owned by landlords who rent to tenants? This extension is straightforward and results are in line with the literature on the so-called split-incentive problem ((Gillingham et al., 2012)). Unlike the owner-occupier case, we show there is no long-term downside to the introduction of an EPC because certification is a necessary condition for investments to occur.

Assume that the owner makes the investment decision while s/he also pays the energy bill. The analysis of this first scenario is immediate. When owners pay the energy bill, tenants do not have any willingness to pay for a higher energy performance on the rental market. As a result, information conveyed by energy certification has no value, so that the building stock and overall energy consumption are identical with and without certification. Note however that owners have incentives to invest. As they fully internalize energy savings in any case and as tenants are randomly matched, they do so in the first period if the investment cost is lower than the expected flow of energy expenditures over the entire horizon:

$$I \leq \frac{\int_0^{+\infty} e \, \mathrm{d}F(e)}{1-\delta}$$

When tenants pay the energy bill, they obviously prefer to move in energy-efficient dwellings. Without EPCs, landlords cannot however charge a premium for a higher energy performance. As a result, they never invest in energy efficiency. This is the so-called split-incentive problem. In contrast with the owner-occupier case, households with high energy needs discovering energy performance after moving in cannot invest.

With certification, the rental market is perfectly competitive with no information asymmetry, prices thus fully capture the energy performance and the long run equilibrium corresponds to the social optimum described in Lemma 1. As a result, certification always induces more investments and less energy consumption. We collect these findings in:

Proposition 4. *In the rental case where potential investors are owners who do not occupy the dwellings, certification only implements the social optimum if they pay the energy bill and there is always more investments and less cumulative energy* *consumption than when there is no certification. If tenants pay the bill, owners never invest with and without certification.*

7.2. Delayed EPC introduction

Until now, it has been assumed that EPCs are introduced at $t = 0$ (when $q_0 = 0$). From a policy perspective, it is more realistic to consider that certification is introduced in period $t_{EPC} > 0$. We now investigate this case, introducing two additional assumptions. First, owners do not anticipate the introduction of certification. Before t_{EPC}, their investment behavior is thus not influenced by future signals on the real estate market.[13] Second, at the beginning of period t_{EPC}, the share $q_{t_{EPC}}$ of energy-efficient buildings and the allocation of the occupiers across the dwellings correspond to those of the trajectories described in lemma 5.

Under these assumptions, we establish in the appendix the following result:

Proposition 5 (Delayed EPC introduction)**.** *In the case where the EPC is introduced at the beginning of period t_{EPC}, all investments are immediately made. This leads to a constant share of efficient dwellings such that $1 > q_{t_{EPC}} > q_{EPC}$. After t_{EPC}, per-period energy consumption E_t decreases towards a value E_∞ which verifies $E_{EPC} > E_\infty > 0$.*

Figure 4 represents the evolution of energy consumption with and without a delayed certification. The intuition is straightforward. At the beginning of period $t_{EPC} > 0$, there remains a share $q_{t_{EPC}}$ of inefficient dwellings, which can be lower or higher than the first best. Suddenly, a price gap between efficient and inefficient dwellings appears on the real estate market. The households occupying inefficient dwellings whose type lies between $\hat{e}$ and $e*$ thus decide to invest. At the end of the period, the allocation of households across dwellings remain partly sub optimal as some low types continue to occupy efficient dwellings. This imperfect matching progressively vanishes in the next periods when these low types will move out and sell their property to high types. Note that this result decisively hinges upon the assumption that moving decisions are exogenous. That is, we rule out the possibility that low types living in efficient dwellings would all move in inefficient dwellings in the city, thereby increasing their surplus by selling at a high price to high types.

[13] For technical simplicity, we assume that households anticipate the introduction of the EPC at period $t_{EPC} - 1$ after the sale and before the investments. This assumption does not change qualitatively the results of this section. As long as households do not anticipate the introduction for more than one period, the exact timing of the introduction of the EPC does not matter.

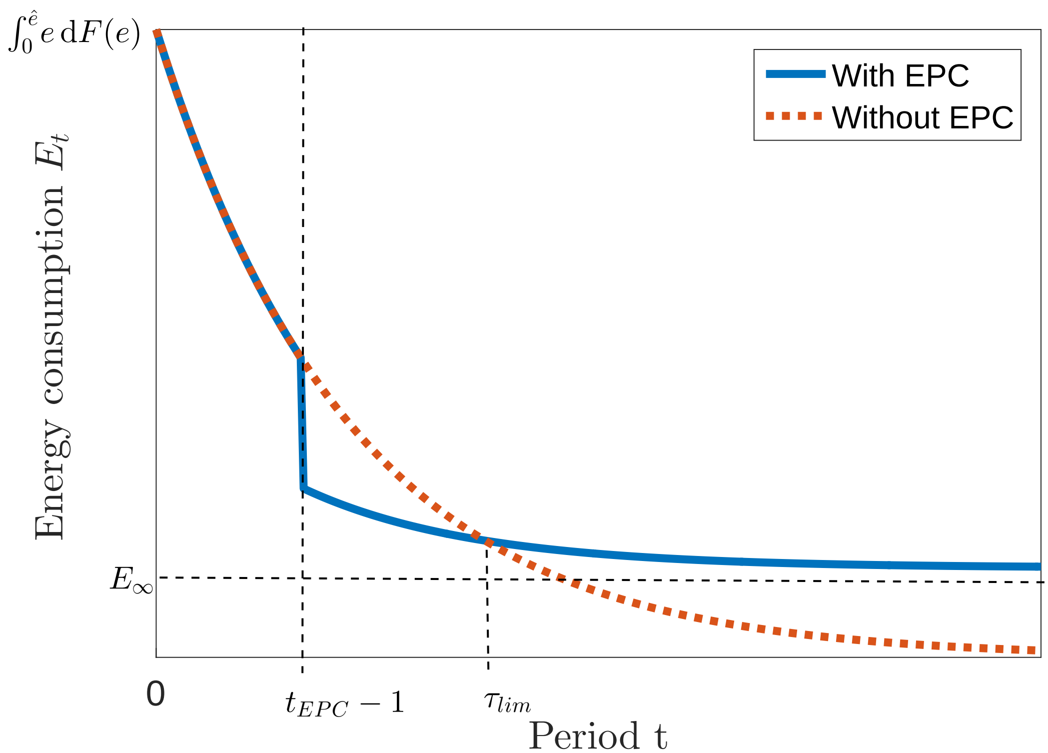


Figure 4: Trajectories of per-period energy use E_t with a delayed EPC introduction

8. Concluding remarks

To the best of our knowledge, we are the first to offer a dynamic housing market model to study the impact of mandatory energy labeling. The theoretical approach put the emphasis on individual investment incentives and informational frictions as the main determinants of the energy efficiency of the housing stock. This allows us to understand the inter-temporal trade-offs inherent to dynamic investment in energy performance and the market effects of such a policy.

We find drastic differences in the dynamics of the building stock with and without EPCs. The real estate market under certification implements a socially-efficient path in the absence of other market failures, in which the introduction of EPCs front-load energy efficiency investments and does not induce long-term investment patterns. On the contrary, in the absence of EPCs, individual incentives are lower, but persist in the long run, through the imperfect matching between dwellings and high energy-needs consumers. It leads to a more energy-efficient building stock and to less energy consumption in the long term compared to a scenario with EPCs.

Perhaps surprisingly, this means that, in the absence of well-calibrated policy instruments mitigating other market failures (in particular, energy externalities and household behavioral anomalies), introducing EPCs might not improve welfare in the long run.

Moreover, our model indicates that the dynamics of the market is substantially altered by informational policies in non-trivial ways. In particular, introducing EPCs brings about benefits that are highly dependent on the distribution of energy needs and moving rate. In order to evaluate the relative desirability of such policy, it is hence necessary to precisely take into account the characteristics of the market (e.g. high-turnover rates city centers vs rural stable population). Doing so would require performing multiple simulations using microdata is left to future research. From this point of view, this paper should be seen as a first step in revealing mechanisms that deserve empirical analysis.

In addition to EPCs, real-world energy efficiency policies feature a mix of policy instruments (energy taxation, energy education, investment subsidies, tax credits, building codes). The distinctive effect of EPCs is to make it possible for real estate markets to react to housing energy performance. How will this response affect the effectiveness of other instruments?

The overall effect of the other components of the policy mix amounts to an upward exogenous shock on the stock of energy-efficient dwellings q_t at a given period t. With EPCs, a higher q_t lowers the price premium for energy efficient buildings as it increases the supply of efficient dwellings on the market. Consequently, investment incentives fall. Without EPCs, a higher q_t does not have any short-term effect on investment incentives because there is no price premium. EPCs hence induce a particular form of "rebound" effect driven by price adjustments on the real estate market.

In the long term, the situation becomes more complex. Without EPCs, the exogenous shock on the building stock change the subsequent investment path by lowering the occurrence of mismatch between large energy consumers and energy-inefficient dwellings. As a result, the long-term effect is unclear and the differential effect of EPCs will depend, inter alia, on m as discussed in subsection 5.1.

9. Acknowledgments

The authors gratefully acknowledge the financial support of Conseil Français de l'Energie (French Energy Council).

Appendix A. An example of EPC

Appendix B. Proofs

Appendix B.1. Proof of Lemma 2

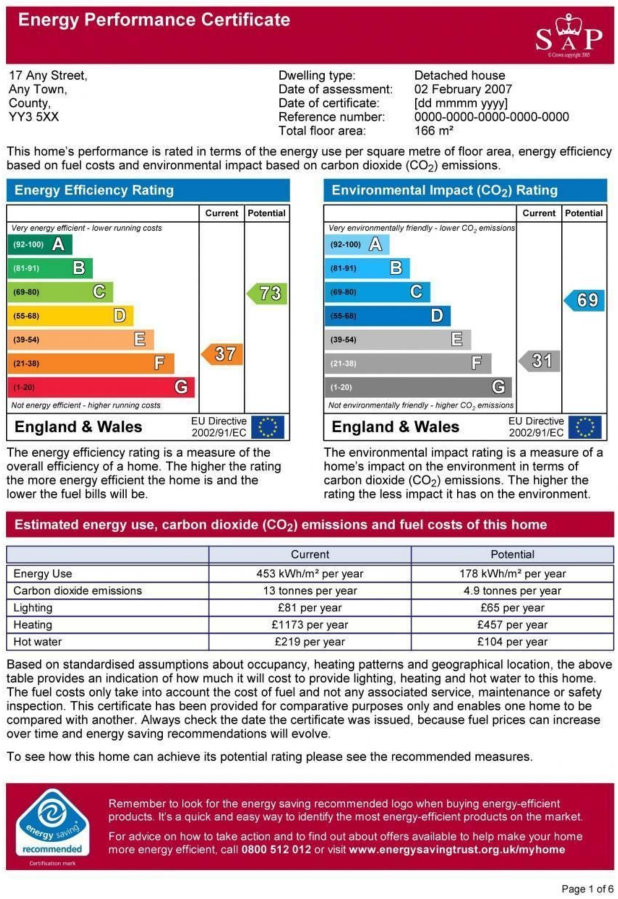
By contradiction, assume there exists $e_1 < e_2$ such that $g_t(e_1) = 1$ and $g_t(e_2) = 0$. From the incentive compatibility, this would imply that

$$u_t(e_1, 1) - p_t^1 \geq u_t(e_1, 0) - p_t^0$$
$$u_t(e_2, 1) - p_t^1 < u_t(e_2, 0) - p_t^0$$

This is not possible because the function $u_t(e, 1) - p_t^1 - u_t(e, 0) + p_t^0$ is non-decreasing with e. To see this, note first that p_t^1 and p_t^0 do not vary with e because the market is competitive. This also holds true for $u_t(e, 1)$ which only depends on the price trajectory as shown by equation (3). Last, from equation (4) follows that $u_t(e, 0)$ is non-increasing with e as $u_t^{\emptyset}(e)$ is non-increasing with e and $u_t^I(e)$ does not vary with e. The market clearing condition directly gives the value of the threshold $\tilde{e}$.

Appendix B.2. Proof of Lemma 3

u_t^I does not vary with e while $u_t^{\emptyset}$ is continuous and strictly decreasing with e. When $e \to +\infty$, we have $u_t^{\emptyset} \to -\infty$, implying that $u_t^I > u_t^{\emptyset}$. Last, we show that $u_t^I(0) \leq u_t^{\emptyset}(0)$ when $e = 0$ by contradiction. Assume that $u_t^I(0) > u_t^{\emptyset}(0)$. This implies that we have $u_t^I(0) = u_t(0, 0) = -I + u_t(0, 1)$, and thus $u_t(0, 1) - u_t(0, 0) = I$. We know that $u_t(e, 1) - u_t(e, 0)$ is increasing with e, meaning that $u_t(0, 1) - u_t(0, 0) < u_t(\tilde{e}, 1) - u_t(\tilde{e}, 0)$. Corollary **??** then implies that $I < p_t^1 - p_t^0$, which is absurd.



Energy Performance Certificate

17 Any Street,
Any Town,
County,
YY3 5XX

Dwelling type:	Detached house
Date of assessment:	02 February 2007
Date of certificate:	[dd mmmm yyyy]
Reference number:	0000-0000-0000-0000-0000
Total floor area:	166 m²

This home's performance is rated in terms of the energy use per square metre of floor area, energy efficiency based on fuel costs and environmental impact based on carbon dioxide (CO_2) emissions.

The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills will be.

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

	Current	Potential
Energy Use	453 kWh/m² per year	178 kWh/m² per year
Carbon dioxide emissions	13 tonnes per year	4.9 tonnes per year
Lighting	£81 per year	£65 per year
Heating	£1173 per year	£457 per year
Hot water	£219 per year	£104 per year

Based on standardised assumptions about occupancy, heating patterns and geographical location, the above table provides an indication of how much it will cost to provide lighting, heating and hot water to this home. The fuel costs only take into account the cost of fuel and not any associated service, maintenance or safety inspection. This certificate has been provided for comparative purposes only and enables one home to be compared with another. Always check the date the certificate was issued, because fuel prices can increase over time and energy saving recommendations will evolve.

To see how this home can achieve its potential rating please see the recommended measures.

Remember to look for the energy saving recommended logo when buying energy-efficient products. It's a quick and easy way to identify the most energy-efficient products on the market.

For advice on how to take action and to find out about offers available to help make your home more energy efficient, call **0800 512 012** or visit **www.energysavingtrust.org.uk/myhome**

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Figure A.5: Example of an energy performance certificate

Appendix B.3. Proof of proposition 1

Let us denote $\Delta_t(e) = u_t^I(e) - u_t^{\emptyset}(e)$ the utility gain of investing at period t for a household of type e. By definition of $\breve{e}_t$ in lemma 3, we have $\Delta_t(\breve{e}_t) = 0$. Moreover:

$$\begin{aligned}
\Delta_t(e) &= -I + \delta m p_{t+1}^1 + \delta(1-m)u_{t+1}(e,1) - (-e + \delta m p_{t+1}^0 + \delta(1-m)u_{t+1}(e,0)) \\
&= e - I + \delta m(p_{t+1}^1 - p_{t+1}^0) + \delta(1-m)(u_{t+1}(e,1) - u_{t+1}(e,0)) \\
&= e - I + \delta m(u_{t+1}(\tilde{e}_t,1) - u_{t+1}(\tilde{e}_t,0) + \delta(1-m)(u_{t+1}(e,1) - u_{t+1}(e,0)) \text{ (corollary ??)}
\end{aligned}$$

Let us also observe that:

$$\Delta_t(e) \geq 0 \Rightarrow (u_t(e,1) - u_t(e,0) = I$$

$$\Delta_t(e) \leq 0 \Rightarrow (u_t(e,1) - u_t(e,0) = \Delta_t(e) + I$$

We can then rewrite:

$$\Delta_t(e) = e - I(1-\delta) + \delta(1-m)\min(0, \Delta_{t+1}(e)) + \delta m \min(0, \Delta_{t+1}(\tilde{e}_{t+1})) \quad \text{(B.1)}$$

We now derive two intermediate results.

Lemma 6. *When incoming households are perfectly informed about dwellings' energy performance,* $\breve{e}_t \geq \tilde{e}_{t+1}$.

Proof. By definition of $\breve{e}_t$, there is at least $1 - F(\breve{e}_t)$ energy efficient buildings at the beginning of period $t+1$ so $q_{t+1} \geq 1 - F(\breve{e}_t)$. Moreover, $F(\tilde{e}_{t+1}) = 1 - q_{t+1}$ (lemma 2). Thus: $F(\breve{e}_t) \geq F(\tilde{e}_{t+1})$. F being strictly increasing on $[0, +\infty)$ and $F(0) = 0$, F is a bijection from $[0, +\infty)$ to $[0, 1]$ whose inverse function is also (strictly) increasing; therefore, $\breve{e}_t \geq \tilde{e}_{t+1}$. □

Lemma 7. *When incoming households are perfectly informed about dwellings' energy performance,* $\Delta_t(e)$ *is non increasing in* t.

Proof. It is straightforward to see that the following property holds:

$$\forall x, y \in \mathbb{R}, \min(0, x) - \min(0, y) \leq \max(0, x - y) \quad \text{(B.2)}$$

Lets us arbitrarily pick $E \in [\tilde{e}_1, +\infty)$. Given $t \in \mathbb{N}$ and $e \in [0, E]$, it follows from equation B.1 and the above property:

$$\begin{aligned}\Delta_{t+1}(e) - \Delta_t(e) =& \delta(1-m)\left(\min(0, \Delta_{t+2}(e)) - \min(0, \Delta_{t+1}(e))\right) \\ &+ \delta m \left(\min(0, \Delta_{t+2}(\tilde{e}_{t+2})) - \min(0, \Delta_{t+1}(\tilde{e}_{t+1}))\right) \\ \leq& \delta(1-m) \max(0, \Delta_{t+2}(e) - \Delta_{t+1}(e)) \\ &+ \delta m \max(0, \Delta_{t+2}(\tilde{e}_{t+2}) - \Delta_{t+1}(\tilde{e}_{t+1}))\end{aligned} \tag{B.3}$$

$\Delta_{t+2}(e)$ is increasing in e. Because $\tilde{e}_{t+2} \leq \tilde{e}_{t+1}$ (q_t is non decreasing and therefore $\tilde{e}_t$ is non increasing from lemma 2), it follows $\Delta_{t+2}(\tilde{e}_{t+2}) \leq \Delta_{t+2}(\tilde{e}_{t+1})$. Equation B.3 becomes:

$$\begin{aligned}\Delta_{t+1}(e) - \Delta_t(e) \leq& \delta(1-m) \max(0, \Delta_{t+2}(e) - \Delta_{t+1}(e)) \\ &+ \delta m \max(0, \Delta_{t+2}(\tilde{e}_{t+1}) - \Delta_{t+1}(\tilde{e}_{t+1}))\end{aligned} \tag{B.4}$$

Let us define the sequence a_t by:

$$a_t := \sup_{e \in [0,E]} \{\max(0, \Delta_{t+2}(e) - \Delta_{t+1}(e)) : e \in [0, E]\} \tag{B.5}$$

Because for any $t \in \mathbb{N}$, $-I \leq \Delta_t(e) \leq e \leq E$ (straightforward from equation B.1), a_t is real and $\forall t \in \mathbb{N}, 0 \leq a_t \leq E + I$. From equation B.4, it follows that for any $e \in [0, E]$:

$$\Delta_{t+1}(e) - \Delta_t(e) \leq \delta(1-m)a_{t+1} + \delta m a_{t+1} = \delta a_{t+1}$$

Therefore:

$$a_t \leq \delta a_{t+1}$$

By induction, it follows:

$$\forall n \in \mathbb{N}, a_t \leq \delta^{t+n} a_{t+n}$$

Because $\forall t \in \mathbb{N}, a_t \leq E + I$, we also have:

$$\forall n \in \mathbb{N}, a_t \leq \delta^{t+n}(E + I)$$

When n goes to infinity, it yields: $a_t \leq 0$ and therefore $\Delta_t(e)$ is non increasing in t for any $e \in [0, E]$. Because we can pick E arbitrarily large, the result can be extended to all $e \in [0, +\infty)$. □

Corollary 1. *When incoming households are perfectly informed about dwellings' energy performance,, $\breve{e}_t$ is non decreasing.*

Proof. Straightforward from lemma 7, definition of $\breve{e}_t$, and $\Delta_t(e)$ being strictly increasing in e. □

We are now ready to prove the first part of proposition 1:

Proposition 6 (One-shot investment)**.** *When incoming agents are perfectly informed about dwellings' energy performance, all investments are made at time $t = 0$. The stock of energy-efficient dwellings remains constant from period $t = 1$.*

Proof. Let us note that when information is perfect, no investments are made at time t if $\breve{e}_t \geq \tilde{e}_t$. Then, we use lemma 6, corollary 1 and the fact that $\tilde{e}_t$ is non increasing to show that the previous condition is valid for all $t \in \mathbb{N}^*$. □

Lemma 8. *When incoming households are perfectly informed about dwellings' energy performance, $\Delta_t(e)$, and therefore $\breve{e}_t$, are constant over time t.*

Proof. Lemma 7 shows that $\Delta_t(e)$ is non increasing. From proposition 6, it follows that $\tilde{e}_t$ is constant over time (at $t = 0$, it is not defined): $\forall t \in \mathbb{N}^*, \tilde{e}_t = \tilde{e}$. Then, a proof similar to the one of lemma 7 allows us to show that $\Delta_t(e)$ is non decreasing in t. □

From now on and until the end of this section, we drop the index t whenever it is unnecessary. We are now ready to prove the second part of proposition 1.

Proposition 7 (Investment threshold)**.** *When incoming households are perfectly informed about dwellings' energy performance, the final share of energy-efficient dwellings q_1 is given by $q_1 = 1 - F(\tilde{e})$ where $\tilde{e} = \breve{e} = I(1 - \delta)$.*

Proof. From proposition 6, it follows: $q_1 = 1 - F(\breve{e})$. From lemma 2, it also holds: $q_1 = 1 - F(\tilde{e})$. Because F is a bijection (recall that F is strictly increasing), it follows: $\breve{e} = \tilde{e}$, and therefore $\Delta(\tilde{e}) = \Delta(\breve{e}) = 0$. Lemma B.1 yields:

$$0 = \Delta(\tilde{e}) = \tilde{e} - I(1 - \delta)$$

□

Appendix B.4. Proof of Proposition 5

We assume that households anticipate the introduction of the EPC at period $t_{EPC} - 1$ after the sale and before the investments. Before the announcement of the EPC, we have $\mathbb{P}_t(\theta = 0|e) = 0$ for$e \geq \hat{e} = I(1 - \delta(1 - m))$ and $\mathbb{P}_t(\theta = 0|e)) = (1 - m(1 - F(\hat{e})))^t$ for $e < \hat{e}$.

Like in section 4.1, the announcement of the EPC induces a one-shot investment dynamics. We will call again $\breve{e}$ the type threshold from which households invest in period $t_{EPC} - 1$.

The announcement of the EPC changes the benefits of investing in energy retrofit. Before the announcement, benefits of investing for a household of type e were $\frac{e}{1-\delta(1-m)}$. After the announcement, it will receive an additional benefit which is the sale price premium. Consequently, we have $\breve{e} < \hat{e}$. Similarly to section 4.1, the sale price premium is equal to the benefits of a marginal buyer of type $\tilde{e}$ who would stay forever in the dwelling: $\frac{\tilde{e}}{1-\delta}$. This marginal buyer is such that $F(\tilde{e}) = 1 - q_{t_{EPC}}$ (this property corresponds to lemma 2). The expected discounted sale price premium is therefore: $\frac{\delta m}{1-\delta(1-m)} \cdot \frac{\tilde{e}}{1-\delta}$. Thus, the total benefits of investing after the EPC announcement for a household of type e is:

$$\frac{e}{1-\delta(1-m)} + \frac{\delta m}{1-\delta(1-m)} \frac{F^{-1}(1-q_{t_{EPC}})}{1-\delta} \tag{B.6}$$

The stock of energy-efficient dwellings from period t_{EPC} is equal to the stock of energy efficient dwellings at the beginning of period t_{EPC} in the no certification policy, that is: $1 - F(\hat{e})(1 - m(1 - F(\hat{e})))^{t_{EPC}-1}$ (lemma 5), to which we add the new investments made by households of type $e \in [\breve{e}, \hat{e})$, that is: $(F(\hat{e}) - F(\breve{e})) \cdot (1 - m(1 - F(\hat{e})))^{t_{EPC}-1}$. Thus:

$$q_{t_{EPC}} = 1 - F(\breve{e})(1 - m(1 - F(\hat{e})))^{t_{EPC}-1} \tag{B.7}$$

Inserting equation B.7 in the expression B.6 and subtracting the cost of investment I, we obtain a net gain of investing for a household of type e equal to:

$$-I + \frac{e}{1-\delta(1-m)} + \frac{\delta m}{(1-\delta(1-m))(1-\delta)} F^{-1}\left(F(\breve{e})(1 - m(1 - F(\hat{e})))^{t_{EPC}-1}\right) \tag{B.8}$$

Because the household of type e is the marginal investor, its net gain of investing is equal to zero. Thus, $\breve{e}$ verifies the following equation:

$$I = \frac{\breve{e}}{1-\delta(1-m)} + \frac{\delta m}{(1-\delta(1-m))(1-\delta)} F^{-1}\left(F(\breve{e})(1 - m(1 - F(\hat{e})))^{t_{EPC}-1}\right) \tag{B.9}$$

Also, $\tilde{e}$ depends on $\breve{e}$ via the following equation:

$$\tilde{e} = F^{-1}(1 - q_{t_{EPC}}) = F^{-1}(F(\breve{e})(1 - m(1 - F(\hat{e})))^{t_{EPC}-1}) \tag{B.10}$$

Suppose now that $q_{t_{EPC}} \leq q_{EPC}$. It implies $\tilde{e} = F^{-1}(1-q_{t_{EPC}}) \geq F^{-1}(1-q_{EPC}) = I(1-\delta)$. From equation B.6 applied to $e = I(1-\delta)$, it follows that the benefits of investing for a household of type $e = I(1-\delta)$ after the announcement of the EPC are larger than I. It implies that $\breve{e} \leq I(1-\delta)$, and using B.7, it follows $q_{t_{EPC}} > q_{EPC}$, which contradicts our initial assumption. Thus, we have shown: $q_{t_{EPC}} < q_{EPC}$. We also showed: $\tilde{e} < I(1-\delta)$.

By denoting $A = 1 - m(1 - F(\hat{e}))$, straightforward calculation leads to (for $t \in [t_{EPC} - 1, +\infty)$:

$$E_t = \int_0^{\tilde{e}} e \, \mathrm{d}F(e) + (1-m)^{t+1-t_{EPC}} \left(A^{t_{EPC}-1} \int_0^{\breve{e}} e \, \mathrm{d}F(e) - \int_0^{\tilde{e}} e \, \mathrm{d}F(e) \right) \tag{B.11}$$

Thus, E_t is decreasing and converges to $E_\infty = \int_0^{\tilde{e}} e \, \mathrm{d}F(e) < E_{EPC} = \int_0^{I(1-\delta)} e \, \mathrm{d}F(e)$ because $\tilde{e} < I(1-\delta)$.

Let us recall the trajectory of energy consumption when there is no EPC:

$$E_t = A^t \int_0^{\hat{e}} e \, \mathrm{d}F(e) \tag{B.12}$$

Finally, we define τ_{lim} as the unique intersection point between the two trajectories in the interval $[t_{EPC} - 1, +\infty)$, i.e. as the unique solution of the equation (in t):

$$\int_0^{\tilde{e}} e \, \mathrm{d}F(e) + (1-m)^{t+1-t_{EPC}} \left(A^{t_{EPC}-1} \int_0^{\breve{e}} e \, \mathrm{d}F(e) - \int_0^{\tilde{e}} e \, \mathrm{d}F(e) \right) = A^t \int_0^{\hat{e}} e \, \mathrm{d}F(e) \tag{B.13}$$

The existence of a solution to this equation is obtained via the intermediate value theorem. The uniqueness is a consequence of the study of the variation on the interval $[t_{EPC} - 1, +\infty)$ of the following function:

$$g : t \mapsto \int_0^{\tilde{e}} e \, \mathrm{d}F(e) + (1-m)^{t+1-t_{EPC}} \left(A^{t_{EPC}-1} \int_0^{\breve{e}} e \, \mathrm{d}F(e) - \int_0^{\tilde{e}} e \, \mathrm{d}F(e) \right) - A^t \int_0^{\hat{e}} e \, \mathrm{d}F(e)$$

Indeed, g is continuous, $g(t_{EPC} - 1) < 0$, $\lim_{t \to \infty} g(t) > 0$, and g is either strictly increasing or decreasing and then strictly increasing.

Appendix C. Heterogeneity among households on energy retrofit cost

What if we replace the heterogeneity on energy consumption by an heterogeneity on the investment cost I among households? Such an heterogeneity can be justified by the importance of non-monetary costs in energy retrofit (Fowlie et al., 2015). It is easy to imagine that these non-monetary costs which include time can be very heterogeneous among households[14]. Let us explore through an example how it changes the results of our model.

Unlike the rest of the paper, we consider a continuum of households with the same energy consumption e. 10% of the households have an energy retrofit cost equal to 0 and 90% of the households have an energy retrofit cost equal to $+\infty$. One the one hand, the high-cost households have zero incentives to invest in energy retrofit. On the other hand, the zero-cost households have zero incentives to pay a premium to purchased an energy-efficient dwelling.

Without EPCs, zero-cost households who end up in energy-efficient dwellings will invest in energy efficiency. The equilibrium without EPCs will be symmetric to the situation where energy consumption is heterogeneous: in one case investments are made by energy-intensive households who purchase energy-inefficient dwelling, in the other case investments are made by low-energy-retrofit-cost households.

With EPCs, zero-cost households have incentives to purchase energy-inefficient dwellings instead of energy-efficient ones. While the allocation of households was random without EPCs, it is now determined by the cost of energy retrofit for households. This allocation efficiency induces more investments compared to a situation without EPCs because all zero-cost households can now buy energy-efficient dwellings (as long as there are enough of them). As a result, the introduction of the EPC increases the rate of investments and decreases the aggregate energy consumption in both the short and long terms.

When there is hetereogeneity in households' energy retrofit cost, the introduction of an EPC has the same two effects as when there is heterogeneity in energy consumption: increased incentives and allocation efficiency between households and dwellings. However, the allocation efficiency has opposite consequences depending on what dimension the heterogeneity is on. When heterogeneity is on energy consumption, EPCs reduce investments in the long term by allowing energy-intensive households to directly purchase energy-efficient dwellings. When hetereogeneity is on energy retrofit cost, EPC increased investment in the long term by allowing low-energy-retrofit cost to purchase energy-inefficient dwellings and retrofit them.

[14]Considering time, the cost opportunity of time typically depends on the hourly wage which is heterogeneous in the population

		Final EPC Grade					
		F	E	D	C	B	A
	G	76	136	201	271	351	442
	F		63	130	204	287	382
Initial EPC grade	E			70	146	232	331
	D				79	169	271
	C					93	199
	B						110

Table D.1: Cost matrix in e/m^2 used in the RES-IRF model in Branger et al. (2015)

Appendix D. Calibration of the summer colony example presented in section 5.2

To calibrate the model, we mainly use data from Branger et al. (2015) as the RES-IRF model is a reference in the French context. We also use the results of the PHEBUS survey[15].

Investment cost I

The cost of an energy retrofit I depends on building characteristics (including size, age, initial energy performance, architecture), final energy performance targeted, local market conditions, policy instruments in place (in particular subsidies) and several other factors. Thus, comparisons are difficult and average estimates need to be taken with caution. Branger et al. (2015) use the matrix cost presented in table D.1 as an input of their model. This matrix has been established with the help of experts insights.

Energy consumption e

Table D.2 shows an updated version of energy consumptions by EPC grades in the Res-IRF model used in Branger et al. (2015). With these figures, the average consumption in a B-graded building is 2.5 times the average consumption in a D-graded building.

To compute monetary energy savings, we use natural gas price as a reference as it is the most used heating energy fuel in France (ADEME, 2014). The aver-

[15]Enquête Performance de l'Habitat, Équipements, Besoins et Usages de l'énergie. Survey realized in France in 2013 on building energy performance and energy use in French households and mandated by the French administration.

EPC Grade	Average consumption (kWhEP/m^2/year)
G	596
F	392
E	280
D	191
C	125
B	76
A	40

Table D.2: Average consumption by EPC grade in the Res-IRF model. kWEP (kWh of Primary Energy) is a unit used in the French regulation for buildings. KWhEP takes into account the energy used in the production and transport of electricity. There is a conventional coefficient of 2.58 between the electricity consumption in kWhEP and the final electricity consumption billed. This coefficient is 1 for natural gas, oil and firewood.

age marginal price over the period 2010-2016 according to the Pegase database[16] is €0.0543/kWh[17].

Housing market turnover m and Discount factor δ

The average annual housing market turnover rate in France is 3.7% according to INSEE (INSEE, 2017). Besides, Lebègue (2005) uses the Ramsey rule with a calibration specific to the French context and recommends a 4% risk-free discount rate.

Additional assumptions and summary of the calibration

Based on the results of the PHEBUS survey , we consider the case of a building which has an initial EPC grade D-E and a final EPC grade A-B-C[18]. We then use tables D.1 and D.2 to compute the average investment costs and energy savings when coming from an EPC grade D-E to an EPC grade A-B-C.

[16]Pegase is the French reference database for time series statistics about energy.

[17]Note that it is close to the marginal price for electricity when computing in €/kWhEP (kWh primary energy), which is how energy savings are computed in table D.2. Indeed, primary energy and final energy are considered identical for natural gas while there is a factor 2.58 for electricity. As a results, while the average marginal price of electricity for French households over the period 2010-2016 is €0.131/kWh, it becomes €0.0508/kWhEP when using primary energy consumption.

[18]Phebus shows that buildings with an EPC grade D-E are most concerned by energy retrofits and buildings with EPC grade A-B-C are least concerned.

Parameter	Baseline Value
Investment cost I	€204.67/m^2
Average annual energy savings e	€155kWh/m^2
Energy price	€0.1070/kWh
Housing market turnover m	3.7 %
discount rate $\frac{1}{\delta} - 1$	4 %

Table D.3: Input parameters for the French summer colony example in section 5.2

To make our point in the paper, we consider natural gas price in 2030 for France. To extrapolate energy prices, we only consider the carbon pricing trajectory computed for France by the Quinet commission (Quinet, 2019). Carbon tax in 2016 was €22 /tCO_2. The Quinet commissions suggest a carbon value of €250 /tCO_2 in 2030. As a result, it represents an increase of €0.0527/kWH for the natural gas (i.e. the natural has price is almost doubled compared to the 2010-2017 average value).

To run the simulations for a summer colony, we make two additional assumptions. Firstly, we assume that seasonal residents have an energy consumption which is equal to 20% of the permanent resident's energy consumption. Secondly, we assume that seasonal residents represent 50% of the total population.

Input parameters values used for our simulation are gathered in table D.3.

References

ADEME, 2014. Baromètre 10 000 ménages 2013. Tech. rep.

Bakaloglou, S., Charlier, D., 2018. Energy Consumption in the French Residential Sector: How Much do Individual Preferences Matter?
URL www.faere.fr

Branger, F., Giraudet, L.-G., Guivarch, C., Quirion, P., aug 2015. Global sensitivity analysis of an energy–economy model of the residential building sector. Environmental Modelling & Software 70, 45–54.
URL https://www.sciencedirect.com/science/article/pii/S1364815215001097{#}appsec1

Brounen, D., Kok, N., 2011. On the economics of energy labels in the housing market. Journal of Environmental Economics and Management 62 (2), 166–179.
URL http://www.sciencedirect.com/science/article/pii/S0095069611000337

Comerford, D., Lange, I., Moro, M., jan 2016. The Supply-side Effects of Energy Efficiency Labels.
URL http://econpapers.repec.org/RePEc:mns:wpaper:wp201601

Douenne, T., 2018. The vertical and horizontal distributive effects of energy taxes: A case study of a french policy. FAERE Working Paper 2018.10.

Dranove, D., Jin, G. Z., dec 2010. Quality Disclosure and Certification: Theory and Practice. Journal of Economic Literature 48 (4), 935–963.
URL https://www.aeaweb.org/articles.php?doi=10.1257/jel.48.4.935

Fallis, G., 1985. Models of the housing market, chapter 4. In: Fallis, G. (Ed.), Housing Economics. Butterworth-Heinemann, pp. 73 – 90.
URL http://www.sciencedirect.com/science/article/pii/B9780409829402500071

Fischer, C., jan 2005. On the importance of the supply side in demand-side management. Energy Economics 27 (1), 165–180.
URL https://www.sciencedirect.com/science/article/pii/S0140988304000969

Fowlie, M., Greenstone, M., Wolfram, C., 2015. Are the Non-Monetary Costs of Energy Efficiency Investments Large? Understanding Low Take-up of a Free Energy Efficiency Program. American Economic Review: Papers & Proceedings 105 (5), 201–204.

Fuerst, F., McAllister, P., 2011. The impact of Energy Performance Certificates on the rental and capital values of commercial property assets. Energy Policy 39 (10), 6608–6614.
URL http://linkinghub.elsevier.com/retrieve/pii/S0301421511006021

Fuerst, F., McAllister, P., Nanda, A., Wyatt, P., mar 2015. Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England. Energy Economics 48, 145–156.
URL http://www.sciencedirect.com/science/article/pii/S0140988314003296

Gillingham, K., Harding, M., Rapson, D., 2012. Split Incentives in Residential Energy Consumption. The Energy Journal 0 (Number 2).
URL https://ideas.repec.org/a/aen/journl/33-2-03.html

Gillingham, K., Palmer, K., jan 2014. Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. Review of Environmental Economics and Policy 8 (1), 18–38.
URL https://academic.oup.com/reep/article-lookup/doi/10.1093/reep/ret021

Glaeser, E., Gyourko, J., 2018. The economic implications of housing supply. The Journal of Economic Perspectives 32 (1), 3–30.
URL http://www.jstor.org/stable/26297967

Hardy, A., Glew, D., 2019. An analysis of errors in the energy performance certificate database. Energy Policy 129, 1168 – 1178.
URL http://www.sciencedirect.com/science/article/pii/S0301421519301867

Hendel, I., Lizzeri, A., 1999. Adverse selection in durable goods markets. The American Economic Review 89 (5), 1097–1115.
URL http://www.jstor.org/stable/117049

House, C. L., Ozdenoren, E., 2008. Durable goods and conformity. The RAND Journal of Economics 39 (2), 452–468.
URL http://www.jstor.org/stable/25474377

Hyland, M., Lyons, R., Lyons, S., 2013. The value of domestic building energy efficiency—evidence from Ireland. Energy Economics.
URL http://www.sciencedirect.com/science/article/pii/S0140988313001655

INSEE, 2017. Les conditions de logement en France. Tech. rep.

Jensen, O. M., Hansen, A. R., Kragh, J., jun 2016. Market response to the public display of energy performance rating at property sales. Energy Policy 93, 229–235.
URL http://www.sciencedirect.com/science/article/pii/S0301421516300696

Jessoe, K., Rapson, D., 2012. Knowledge is (less) power: Experimental evidence from residential energy use. American Economic Review 104 (4), 1417–1438.
URL http://pubs.aeaweb.org/doi/abs/10.1257/aer.104.4.1417{%}5Cnhttp://www.nber.org/papers/w18344

Kok, N., Jennen, M., 2012. The impact of energy labels and accessibility on office rents. Energy Policy 46, 489–497.
URL http://linkinghub.elsevier.com/retrieve/pii/S0301421512003151

Kok, N., Quigley, J. M., 2008. Doing Well by Doing Good? Green Office Buildings. The American Economic Review 100 (December), 2494–2511.
URL http://www.jstor.org/stable/41038771

Lebègue, D., 2005. Révisions du taux d'actualisation des investissements publics. Tech. rep.
URL http://metroauxrigollots.fr/archives/pdf/SW54/Rapport{_}Lebegue{_}Revision{_}Taux{_}Actualisation{_}Investissements{_}Publics.pdf

Longhi, S., 2015. Residential energy expenditures and the relevance of changes in household circumstances. Energy Economics 49, 440 – 450.
URL http://www.sciencedirect.com/science/article/pii/S0140988315001103

Miller, W., Vine, D., Amin, Z., 2017. Energy efficiency of housing for older citizens: Does it matter? Energy Policy.
URL http://www.sciencedirect.com/science/article/pii/S0301421516306553

Myers, E., May 2019. Are home buyers inattentive? evidence from capitalization of energy costs. American Economic Journal: Economic Policy 11 (2), 165–88.
URL http://www.aeaweb.org/articles?id=10.1257/pol.20170481

Nauleau, M.-L., Giraudet, L.-G., Quirion, P., dec 2015. Energy efficiency subsidies with price-quality discrimination. Energy Economics 52, S53–S62.
URL https://www.sciencedirect.com/science/article/pii/S0140988315002479

Qiu, Y., Kahn, M. E., 2019. Impact of voluntary green certification on building energy performance. Energy Economics 80, 461 – 475.
URL http://www.sciencedirect.com/science/article/pii/S0140988319300507

Quan, D., Quigley, J., 1991. Price formation and the appraisal function in real estate markets. The Journal of Real Estate Finance and . . . .
URL http://link.springer.com/article/10.1007/BF00173120

Quinet, A., 2019. La valeur de l'action pour le climat. Tech. rep., France Stratégie. URL https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-2019-rapport-la-valeur-de-laction-pour-le-climat{_}0.pdf

Sallee, J. M., Slemrod, J., 2012. Car notches: Strategic automaker responses to fuel economy policy. Journal of Public Economics 96 (11-12), 981–999.

Taylor, C. R., 1999. Time-on-the-market as a sign of quality. The Review of Economic Studies 66 (3), 555–578.
URL http://www.jstor.org/stable/2567014

Wirl, F., may 2015. White certificates — Energy efficiency programs under private information of consumers. Energy Economics 49, 507–515.
URL https://linkinghub.elsevier.com/retrieve/pii/S0140988315001188