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PSL UNIVERSITÉ PARIS

THÈSE DE DOCTORAT
DE L'UNIVERSITÉ PSL

Préparée à MINES ParisTech

Essays on the Economics of Building Energy Performance in the Residential Sector

Essais sur l'économie de la performance énergétique des bâtiments dans le secteur résidentiel

Soutenue par

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Abstract

This PhD dissertation aims at better understanding some features of the market for building energy performance in the residential sector and at evaluating the effectiveness of three policy interventions to encourage energy retrofit: Energy Performance Certificates (EPCs), tax credit for energy retrofit, and energy taxation. In the European Union, EPCs provide potential buyers or tenants with information on a property's energy performance, thus mitigating informational asymmetries on real estate markets. The first chapter of the thesis surveys the literature on building energy performance certification. There is strong evidence that households value building energy performance when buying or renting a dwelling and limited evidence that the price premium for energy efficient dwellings in the housing market is higher due to certification. The second chapter provides a theoretical analysis of EPCs. We show that EPCs can either decrease or increase energy consumption depending on the time horizon and the heterogeneity of energy demand in the population. The third chapter develops a simulation based on the aforementioned model. Relying on French data, our simulations suggest that the scenario with energy consumption reduction under EPC is very much more likely. It also suggests that EPCs need to be supplemented by other policy instruments including carbon taxes, energy retrofit subsidies, and low-interest energy retrofit loans. Relying on French micro-panel data, the fourth chapter econometrically analyzes the impact of a tax credit rate increase on the decision to invest in home energy retrofit. I find that a tax credit rate increase substantially boosts expenditures for equipments targeted by the rate increase. I also find preliminary evidence that there is a substitution between investments targeted by the rate increase and other home energy efficiency investments. Also using French micro-panel data, the last chapter analyzes how energy prices affect households' decisions to invest in building energy performance. I do not find any statistical evidence that an increase in energy fuel price has an effect on the propensity to invest in building energy performance or on the amount spent on home energy efficiency expenditures.

Cette thèse de doctorat vise à mieux comprendre certaines caractéristiques du marché de la performance énergétique des bâtiments dans le secteur résidentiel et à évaluer l'efficacité de trois interventions publiques visant à encourager la rénovation énergétique : Diagnostics de performance énergétique (DPE), crédit d'impôt pour le développement durable (CIDD) et taxation de l'énergie. Dans l'Union européenne, le DPE fournit aux acheteurs ou locataires

potentiels des informations sur la performance énergétique d'une propriété, atténuant ainsi les asymétries d'information sur les marchés immobiliers. Le premier chapitre de la thèse passe en revue la littérature sur la certification de la performance énergétique des bâtiments. Il met en lumière des preuves empiriques solides montrant que les ménages valorisent la performance énergétique des bâtiments lorsqu'ils achètent ou louent un logement. Toutefois, les résultats démontrant une meilleure valorisation due à la certification sont plus limités. Le deuxième chapitre fournit une analyse théorique de l'impact du DPE. On démontre que le DPE peut diminuer ou augmenter la consommation d'énergie en fonction de l'horizon temporel considéré et de l'hétérogénéité de la demande en énergie de la population. Le troisième chapitre développe une simulation fondée sur le modèle du chapitre précédent. Il montre que la possibilité d'une augmentation de la consommaton d'énergie sous l'effet du DPE est peu probable si l'on calibre la modèle sur des données françaises. Il suggère également que le DPE a doit être combiné avec d'autres instruments de politique publique pour être efficace, dont des taxes sur le carbone, des subventions à la rénovation énergétique et des prêts à taux réduit. S'appuyant sur des données de panel françaises, le quatrième chapitre analyse économétriquement l'impact d'une augmentation du taux du crédit d'impôt pour le développement durable (CIDD) sur la décision d'investissement en rénovation énergétique. On montre qu'une hausse du taux du crédit d'impôt fait augmenter significativement les dépenses pour les équipements visés par l'augmentation du taux. L'analyse suggère également l'existence d'un effet de substitution entre les investissements visés par le crédit d'impôt et les autres investissements de rénovation énergétique. Toujours à l'aide de données de panel françaises, le dernier chapitre analyse comment les prix de l'énergie influencent la décision des ménages d'investir dans la performance énergétique des bâtiments. L'analyse ne met pas en évidence de preuve statistique qu'une augmentation du prix de l'énergie a un effet sur la propension à investir dans la performance énergétique des bâtiments ou sur le montant dépensé en rénovation énergétique.

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Contents

Acknowledgments 3

Introduction **8**

Buildings are strong contributors to climate change 8

Energy consumption and GHG emissions in the building sector 8

The inertia of energy consumption in buildings 9

The rational of building energy performance policies 11

Saving the planet while saving money? Buildings and the energy efficiency gap . 12

Improved energy performance and the rebound effect 13

Summary of the thesis 14

1 Effects of Energy Performance Labels And Ratings for Buildings: a Literature Review **18**

1.1 Introduction 19

1.2 Overview of the most popular Energy Performance Labels and Ratings for Buildings 21

1.3 The literature about certification and how it can be applied to building energy performance 21

1.3.1 Unraveling the energy performance ? 21

1.3.2 Disclosure, consumer choice and energy performance of the building stock 27

1.4 Energy Labels and Prices: an empirical perspective 29

1.4.1 Price, labels and energy performance 29

1.4.2 Cross-sectional data with a hedonic model 30

1.4.3 Repeat sales approach with panel data 33

1.4.4 Rental premium vs Sales premium 34
1.4.5 Prices and Beyond 35
1.5 Conclusion 36
1.6 Systematic review of empirical studies about the impact of building energy performance on transaction prices or rents 36

2 Energy Performance Certificates and Investments in Building Energy Efficiency: a Theoretical Analysis 52

2.1 Introduction 53
2.2 Literature on Building Energy Certification 56
2.3 Model 58
2.3.1 Setting 58
2.3.2 Policy objectives and evaluation 59
2.4 Equilibrium with an EPC 60
2.5 Equilibrium without EPC 64
2.6 Examples 68
2.6.1 Summer colony 68
2.6.2 Homogeneous residential community 69
2.7 Certification and other policy instruments 69
2.7.1 Certification and carbon tax 70
2.7.2 Certification and subsidy 72
2.7.3 Certification and Standards 72
2.8 Conclusion 72
2.9 Appendix 73
2.9.1 Alternative policy objectives 73
2.9.2 Rental case 77
2.9.3 Delayed EPC introduction 78
2.9.4 Proofs 80

3 Energy Performance Certificates and Investments in Building Energy Efficiency: a Simulation-Based Analysis **91**

3.1 Introduction 92

3.2 Model 96

3.2.1 Setting 96

3.2.2 Equilibrium 98

3.3 Parameters calibration 99

3.3.1 Investment cost I 101

3.3.2 Distribution of energy-saving benefits F 102

3.3.3 Discount factor δ 105

3.3.4 Housing market turnover m 106

3.3.5 Start time of EPC t_{EPC} 107

3.4 Results and discussion 110

3.4.1 Baseline 110

3.4.2 Mono-variate sensitivity analysis around the baseline 113

3.4.3 Limitations 123

3.5 Conclusion 124

4 Effects of a Tax Credit Rate Increase on Residential Building Energy Efficiency Investments: Evidence from France **128**

4.1 Introduction 129

4.2 Literature Review 132

4.3 Description of the tax credit scheme CIDD 134

4.3.1 Principles 134

4.3.2 Evolution of the CIDD 135

4.4 Data 137

4.4.1 Dataset 137

4.4.2 Descriptive statistics 138

4.5 Identification strategy 142

4.5.1 Extensive margin 145

4.5.2 Intensive margin 146
4.6 Results 146
4.6.1 Extensive margin 146
4.6.2 Intensive margin 148
4.7 Conclusion 152
4.8 Appendix 153
4.8.1 Intensive margin - Linear regression 153

5 Home Energy Efficiency Investments in Response to Energy Price Variations: an Empirical Investigation using French Data 158
5.1 Introduction 159
5.2 Literature Review 161
5.3 Data description 162
5.3.1 Dataset 162
5.3.2 Descriptive statistics 165
5.4 Econometric model 171
5.4.1 Extensive margin 171
5.4.2 Intensive margin 174
5.5 Results 175
5.5.1 Extensive margin 175
5.5.2 Intensive margin 175
5.6 Conclusion 178
5.7 Appendix 179
5.7.1 Moving average 179
5.7.2 Current price 179
5.7.3 Linear model for intensive margin 179
5.7.4 Map Climate Zones 185

Concluding Remarks 188
Summary of the main findings 188
Directions for future research 189

Introduction

Abstract

This chapter is an introduction to the thesis. We first provide an overview of the contribution of buildings to climate change. Then, we present the rational for building energy performance policies. Last, we provide a summary of the thesis.

Ce chapitre est une introduction à la thèse. Nous commençons par un état des lieux de la contribution des bâtiments au réchauffement climatique. Nous présentons ensuite le rationnel derrière les politiques visant à améliorer la performance énergétique des logements. Nous terminons par un résumé de la thèse.

Buildings and climate change

Energy consumption and GHG emissions in the building sector

In 2010 buildings accounted for 32% of total global final energy use and 19% of energy-related greenhouse gas (GHG) emissions. Residential buildings alone accounted for 24% of total global final energy use. Figure 1 shows the evolution of GHG emissions in the building sector. They have more than doubled since 1970 to reach 9.18 GtCO2eq in 2010. (Intergovernmental Panel on Climate Change, 2014)

GHG emissions dynamics in the building sector vary a lot across regional areas (figure 2). Western countries accounted for about half of GHG emissons in 2010. However, their emissions tend to stabilize. In the meantime, emissions of emerging countries in Asia, Africa, Middle East,

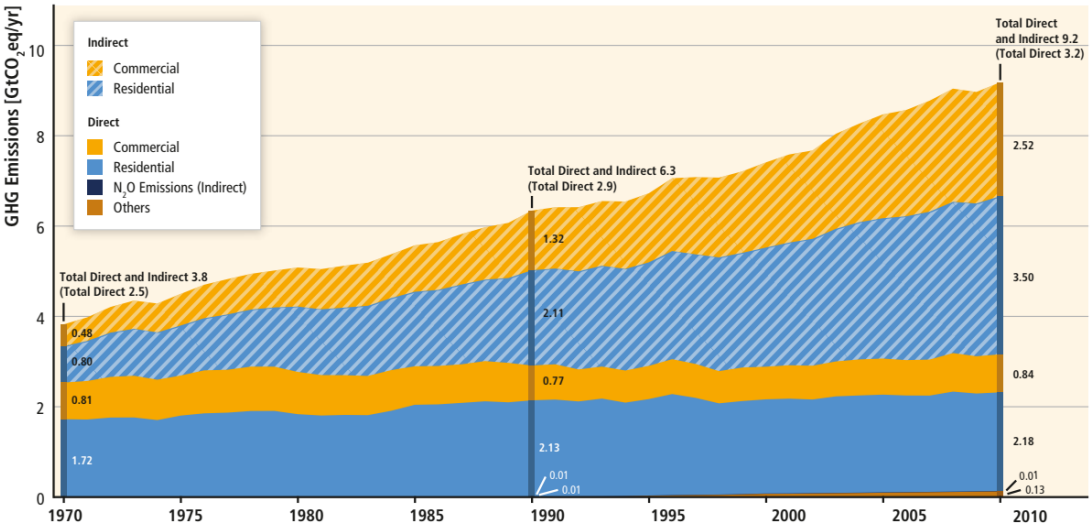

Figure 1: Direct and indirect emissions (from electricity and heat production) in the building subsectors (Intergovernmental Panel on Climate Change, 2014)

Latin America and Carribean have sharply increased. GHG emissions in the residential building sector are therefore a global challenge which involve both developing and developed economies.

The inertia of energy consumption in buildings

Among energy-consuming equipments and infrastructures, buildings have the longest lifespan (figure 3), typically between 40 and 120 years. Unlike lightbulbs and consumer electronics, the natural replacement of old buildings by new energy-efficient buildings would therefore take too long to curb CO2 emissions in the short and middle term. Besides, residential heaters also have a rather long lifespan, typically between 10 and 30 years. The level of insulation and the performance of heaters are especially important because heating is often the first energy consumption item in buildings, especially in cold climate (figure 4; about 70% of buildings energy consumption is for space and water heating in cold climates.).

Without immediate action, GHG emissions and energy consumption are likely to keep increasing, and may double or potentially even triple by mid-century. However, buildings also have a huge potential for GHG mitigation. In contrast to a doubling or tripling, final energy use may stay constant or even decline by mid-century, as compared to today's levels, if today's

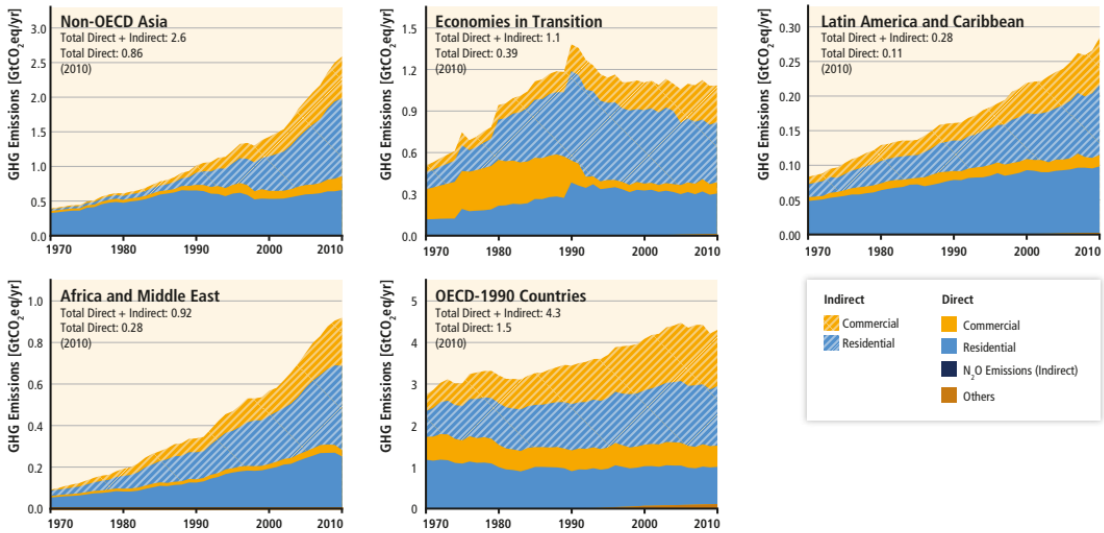

Figure 2: Regional direct and indirect emissions in the building subsectors (Intergovernmental Panel on Climate Change, 2014)

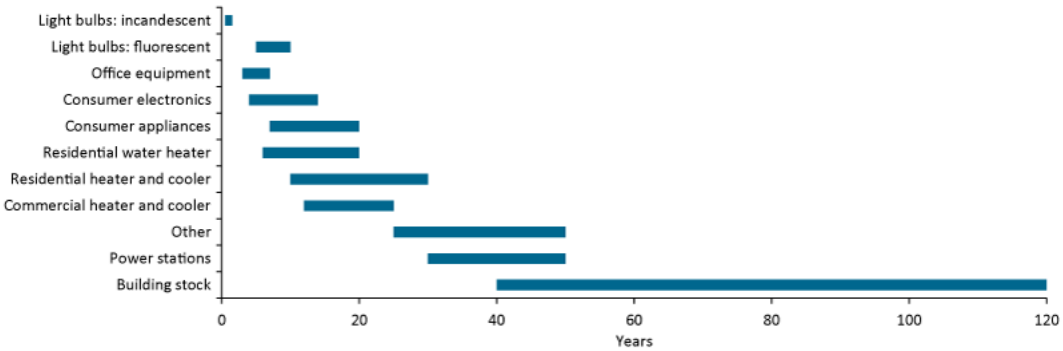

Figure 3: Economic life spans of energy-consuming equipment and infrastructure (IEA, 2013)

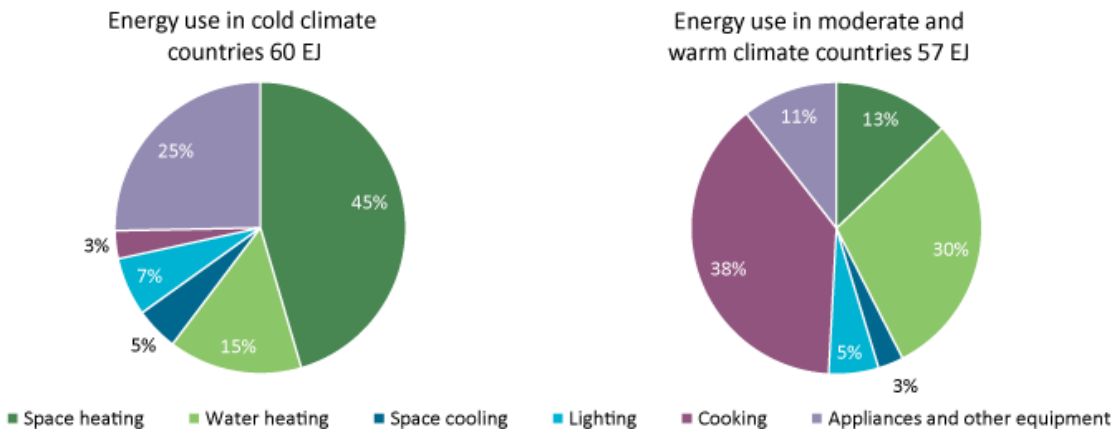

Figure 4: Buildings end-use energy consumption in 2010 (IEA, 2013)

cost-effective best practices and technologies, such as deep retrofits and energy efficient heaters, are broadly diffused. (Intergovernmental Panel on Climate Change, 2014)

The rational for building energy performance policies

The Paris agreement was adopted on December 12th, 2015 by the 21st Conference of the Parties (COP 21) to the United Nations Framework Convention on Climate Change (UNFCCC). As of November 2018, 195 UNFCCC members have signed the agreement, and 183 have become party to it. The Paris Agreement's long-term goal is to keep the increase in global average temperature to well below 2 °C above pre-industrial levels; and to limit the increase to 1.5 °C, since this would substantially reduce the risks and effects of climate change. Because of its substantial contribution to GHG emissions, the residential building sector is expected to be a key contributor to this effort.

There are two (non mutually exclusive) ways to reduce GHG emissions in the residential sector. First is to substitute fossil fuels with low-carbon energy sources. It requires to increase renewable energy (and/or other low-carbon energy sources such as nuclear energy) in the energy mix. A second way is energy conservation: reducing the energy consumption of buildings. This can be achieved either by using energy more efficiently (using less energy for a constant service) or by reducing the amount of energy service used (for example, by heating less). Improving building energy performance is in the former category.

Saving the planet while saving money? Buildings and the energy efficiency gap

From an economics perspective, a key challenge is to reach environmental policy goals in a cost-effective way. In this respect, energy efficiency (including better building energy performance) is particularly appealing. It is commonly believed at least since Hirst and Brown (1990) that there is a large untapped potential for improving energy efficiency which is due to several barriers. As a result, there would be a difference between the cost-minimizing level of energy efficiency and the level of energy efficiency actually realized. This difference is called the *energy efficiency gap*.

Gillingham and Palmer (2014) reviews the different barriers which could explain an energy efficiency gap. First are market failures: imperfect information, principal-agent issues, credit constraints and learning-by-using. All these market failures are likely to arise in building energy performance. Indeed, building energy performance is not easily observable by people who would like to buy or rent a dwelling, or who are willing to insulate their dwellings. Building energy performance is to some extent an experience good. Moreover, people who benefit from energy performance are not necessarily the one who pay for it. It might be the case when tenants do not pay for their energy bill or when energy consumption is measured at an aggregated level (multi-dwelling building without individual meters). Besides, insulation or boiler replacement require a substantial upfront cost that some households cannot afford without a credit, leading to potential credit constraints inefficiencies. Also, innovative home energy efficiency technologies might lead to a positive externality generated by early adopters which is called learning-by-using. Without public intervention, positive externalities might lead to under-investment.

A second type of barriers are behavioral anomalies and failures. Common behavioral anomalies mentioned for the energy efficiency gap are self-control problems, also known as myopia, and limited attention. Self-control problems arise when consumers have time-inconsistent preferences and therefore discount too heavily future energy savings. Because building energy performance trades off immediate spending for future energy savings, it is susceptible to be hurt by self-control issues. Also, improving building energy performance is a complex decision which involves several parameters. For instance, it requires to forecast future energy prices, which is not trivial. If consumers are unable to use sophisticated forecasting models because of bounded rationality,

they might end up doing suboptimal decisions and invest less (or more) in energy efficiency.

The size of the energy efficiency gap is heavily debated and is the topic of an abundant literature which is reviewed by Gerarden et al. (2015). They concude that although there are strong theoretical foundations to the existence of an energy effciency gap, there is limited evidence to support it. They call for a focus of the reseach effort on emirical analysis to assess the size of the gap and to evaluate the effectivess of the policies to reduce it. Besides explaining the mechanisms that could lead to the gap, Gillingham and Palmer (2014) also lists arguments in favor of a small energy efficiency gap. Understated large non monetary costs could explain the lack of adoption of energy efficiency measures, especially when building energy performance is concerned (Fowlie et al., 2015a). Also, energy savings due to energy retrofits might be largely over estimated (Fowlie et al., 2015b).

Policy instruments which aim at improving building energy performance have therefore at least two justifications. Independently of any environmental target, they can be justified by the existence of an energy efficiency gap and allow to achieve better economic efficiency. A second justification is that they can allow to achieve environmental policy targets. In this latter case, the policy instruments need to be evaluated both from a cost-effectiveness point of view (how much does it cost to abate one tonne of CO2) and also from a distributional point of view (who are the winners and losers of these policy instruments). Thus, building energy performance policies can be compared to alternative policies such as energy efficiency policies or policies in favor of low-carbon energy sources.

Improved energy performance and the rebound effect

An important feature of improved energy efficiency is the *rebound effect* which can be defined as the combination of the substitution effect and the income effect in the context of energy use. Indeed, in the absence of price change for final energy use, increased energy efficiency leads to a lower price for energy service. As a result, consumers might increase their consumption of energy service and consequently generates less energy savings than what would happen if the rebound effect is not taken into account. Thus, it is important to take this phenomenon into account when designing and evaluating energy efficiency policies. Gillingham et al. (2016) do a thorough

review of the mechanisms and literature of the rebound effect. They find that in most cases, the total microeconomic rebound has been found to be on the order of 20 percent to 40 percent when all substitution and income effects are included. They conclude that the existing literature does not support claims that energy efficiency gains will be reversed by the rebound effect.

Summary of the thesis

This PhD dissertation aims at better understanding some features of the market for building energy performance in the residential sector and at evaluating the effectiveness of three policy interventions to encourage energy retrofit: Energy Performance Certificates (EPCs), tax credit for energy retrofit, and energy taxation.

Chapter 1 surveys the economic literature on energy performance labels and ratings for buildings. We first study the underlying theoretical mechanisms that may justify quality certification and how they apply to building energy performance. We find that building energy performance does not fulfill the conditions for voluntary disclosure to emerge in equilibrium (unraveling) and we examine whether mandatory certification can be relevant. We then look at the literature on the impact of energy labels on consumer choice and improvement of building energy performance and we find almost no paper. Last, we survey the large body of literature on the effect of green labels on transaction prices and rents. Our survey of the literature tends to confirm that higher energy performance is valued in the real estate market, and certification seems to increase this valuation. Besides, the sale premium is usually higher than the rental premium. We offer demand-side hypothesis to explain this phenomenon.

Chapter 2 deals with Energy Performance Certificates (EPCs), an EU certification scheme which provides potential home buyers or tenants with information on a property's energy performance. By mitigating informational asymmetries on real estate markets, the conventional wisdom is that EPCs will reduce energy use and greenhouse gas emissions, and increase energy-efficiency investments. We develop a dynamic model that partly contradicts these predictions. Although EPCs minimize total private costs, 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. Last, our model analyzes the interaction of EPCs with other policy instruments

such as a carbon tax and subsidies, and studies conditions when these instruments are substitutes or complements.

Chapter 3 continues the analysis of the EPC with a simulation-based approach. We perform the first simulation-based analysis which focuses on the evaluation of the effects of an EPC policy on the energy performance of the building stock and on the residential energy consumption in the short and long term in the French context. We find that an EPC policy requires moderate investment cost, moderate to high energy savings, and a low discount rate to reduce energy consumption. Besides, the more heterogeneous is individual energy demand, the lower energy consumption is under EPC. Our simulations also suggest that the scenario with energy reduction under EPC is very much more likely. These findings support the idea that EPC needs to be supplemented by other policy instruments including carbon taxes, energy retrofit subsidies, and low-interest energy retrofit loans.

Chapter 4 considers the impact of a tax credit scheme named "Crédit d'Impôt pour le Développement Durable" which is implemented in France since 2005 and which aims at encouraging households to invest in building energy efficiency equipments. We perform an econometric analysis of the effect of a 15-point tax credit rate increase implemented for a subgroup of the population using a difference in difference approach. We find that the 15-point tax credit rate increase induces additional expenditures of €1,650 (+ 49%) on average for investments targeted by the rate increase. We also find preliminary evidence that there is a substitution between eligible and non-eligible investments. As a result, we find that expenditures on non-eligible equipments are reduced by €420-650 on average. Our findings support the effectiveness of the CIDD to increase the amount spent by households in building energy efficiency investments and suggest that policymakers could use successfully differences in tax credit rates to target particular home energy efficiency investments.

Chapter 5 studies how energy prices affect households decisions to invest in home energy efficiency using micro panel data from France. To do so, we exploit the fact that households use different energy fuels for heating and that these energy fuels have distinct price trends. We do not find evidence that an increase in energy fuel price has an effect on the propensity to invest or on the amount spent in energy efficiency. These results call for a continuation of the research effort to evaluate the impact of energy prices on households' decision to invest in home energy

efficiency.

We finish the thesis with some concluding remarks where we provide a summary of the main findings in the thesis along with some directions for future research.

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Chapter 1

Effects of Energy Performance Labels And Ratings for Buildings: a Literature Review

Abstract

We survey the economic literature on energy performance labels and ratings for buildings. We first study the underlying theoretical mechanisms that may justify quality certification and how they apply to building energy performance. We find that building energy performance does not fulfill the conditions for voluntary disclosure to emerge in equilibrium (unraveling) and we examine whether mandatory certification can be relevant. We then look at the literature on the impact of energy labels on consumer choice and improvement of building energy performance and we find almost no paper. Last, we survey the large body of literature on the effect of green labels on transaction prices and rents. Our survey of the literature tends to confirm that higher energy performance is valued in the real estate market, and certification seems to increase this valuation. Besides, the sale premium is usually higher than the rental premium. We offer demand-side hypothesis to explain this phenomenon.

Nous examinons la littérature sur les effets des labels de performance énergétique pour les bâtiments. Nous étudions d'abord les mécanismes de certification de la qualité et comment ils peuvent être appliqués à la performance énergétique des bâtiments. Nous montrons que la performance énergétique des bâtiments ne remplit pas les conditions de divulgation volontaire et nous nous demandons si la certification obligatoire peut être pertinente dans ce cas. Nous examinons ensuite la littérature sur l'impact direct des labels énergétiques sur le choix des consommateurs et l'amélioration de la performance énergétique des bâtiments et nous ne trouvons presque pas d'études sur le sujet. Enfin, nous passons en revue l'abondante littérature sur l'effet des labels énergétiques sur les prix des logements et des loyers. Notre examen de la littérature tend à confirmer qu'une performance énergétique supérieure est valorisée sur le marché immobilier, et que la certification semble augmenter cette valorisation. En outre, la prime de vente est généralement plus élevée que la prime de location. Nous proposons des hypothèses du côté de la demande pour expliquer ce phénomène.

1.1 Introduction

Energy consumed in the building sector consists of residential and commercial end users and accounts for 20.1% of the total delivered energy consumed worldwide (U.S. Energy Information Administration, 2016). This figure is doubled in the US and in Europe. In 2015, about 40% of total U.S. energy consumption was consumed in residential and commercial buildings according to the U.S. energy information agency (eia). In the EU, buildings are responsible for 40% of energy consumption and 36% of CO2 emissions according to the European Commission. Thus, the building sector is seen as important for energy reduction policies by policy makers. The European Commission estimates that improving the energy efficiency of buildings could reduce total EU energy consumption by 5% to 6% and lower CO2 emissions by about 5%.

Furthermore, the buildings sector is subject to the so-called energy efficiency gap: the difference between the cost-minimizing level of energy efficiency and the level of energy efficiency actually realized. As a result, it means that it could be possible to improve buildings energy performance in a cost-effective way. Buildings face at least three barriers to energy efficiency identified by Hirst and Brown (1990): risks of energy-efficiency investments, misplaced incentives and information gaps. Building energy retrofits are risky because there are uncertainties on the

energy savings once investments are made. Besides, investment incentives can be sub-optimal when buildings are shared among several occupiers and energy bills are not individualized: free riding undermines the level of investments. Last, building energy performance is often imperfectly known by prospective tenants or buyers which leads to an information asymmetry problem (Akerlof, 1970).

Several policy instruments to tackle these barriers are proposed by Hirst and Brown (1990) and largely implemented today such as construction standards and subsidies. One of them is the expansion of energy performance labeling and rating programs. Those are very common nowadays for usual energy-intensive home appliances such as fridges, washing-machines, dishwashers or lights. In 2002, the European Commission passed the Energy Performance of Building Directive (EPBD) which requires all EU members to implement an energy performance certification scheme for all buildings put on sale or for rent. In the US, there is no federal mandatory program of certification. However, there exists several voluntary building energy performance labels which the two most famous are LEED (Leadership in Energy and Environmental Design) and Energy Star. Similar certification schemes are implemented in other parts of the world such as Singapore, Australia or Japan.

In this paper, we survey the literature concerning the effects of energy performance labels and ratings for buildings. We first study the mechanisms behind quality certification and how they can be applied to building energy performance. We find that building energy performance does not fulfill the conditions for voluntary disclosure and we question if mandatory certification can be relevant in this case. We then look at the literature concerning the impact of energy labels on consumer choice and improvement of building energy performance and we find almost no paper. Last, we survey the large body of literature on the effect of green labels on transaction prices and rents. Our survey of the literature tends to confirm that higher energy performance is valued in the real estate market, and certification seems to increase this valuation. Besides, the sale premium is usually higher than the rental premium. We offer demand-side hypothesis to explain this phenomenon.

The rest of the paper is organized as follows. Section 1.2 presents a short list of the most popular energy labels and ratings. Section 1.3 presents the main concepts and results of the literature about quality disclosure and explores how it can be adapted to building energy per-

formance. Section 1.4 reviews the empirical literature about energy ratings and buildings prices. Section 1.5 concludes.

1.2 Overview of the most popular Energy Performance Labels and Ratings for Buildings

Several energy performance labels and ratings have been developed over the world. Table 1.1 references a short list of the most popular ones with their specific features. While Europe has chosen to implement a mandatory certification theme, other countries like the US let building-owners free to get a certification or not. In the latter case, only the most energy-efficient buildings are certified as it is required to exceed a given threshold in energy performance to get the label, whereas in Europe buildings with a low energy efficiency performance also get a rating. In both cases, information provided is usually twofold: a numeric score and a letter grade or a distinction (silver, gold, platinum). Besides, while Energy Performance Certificates (EPC) and Energy Star label almost exclusively focus on energy efficiency performance[1], other labels and ratings like LEED or BREEAM also take into account other criteria like water efficiency, waste management or indoor air quality. Figure 1.1 provides an example of EPC.

1.3 The literature about certification and how it can be applied to building energy performance

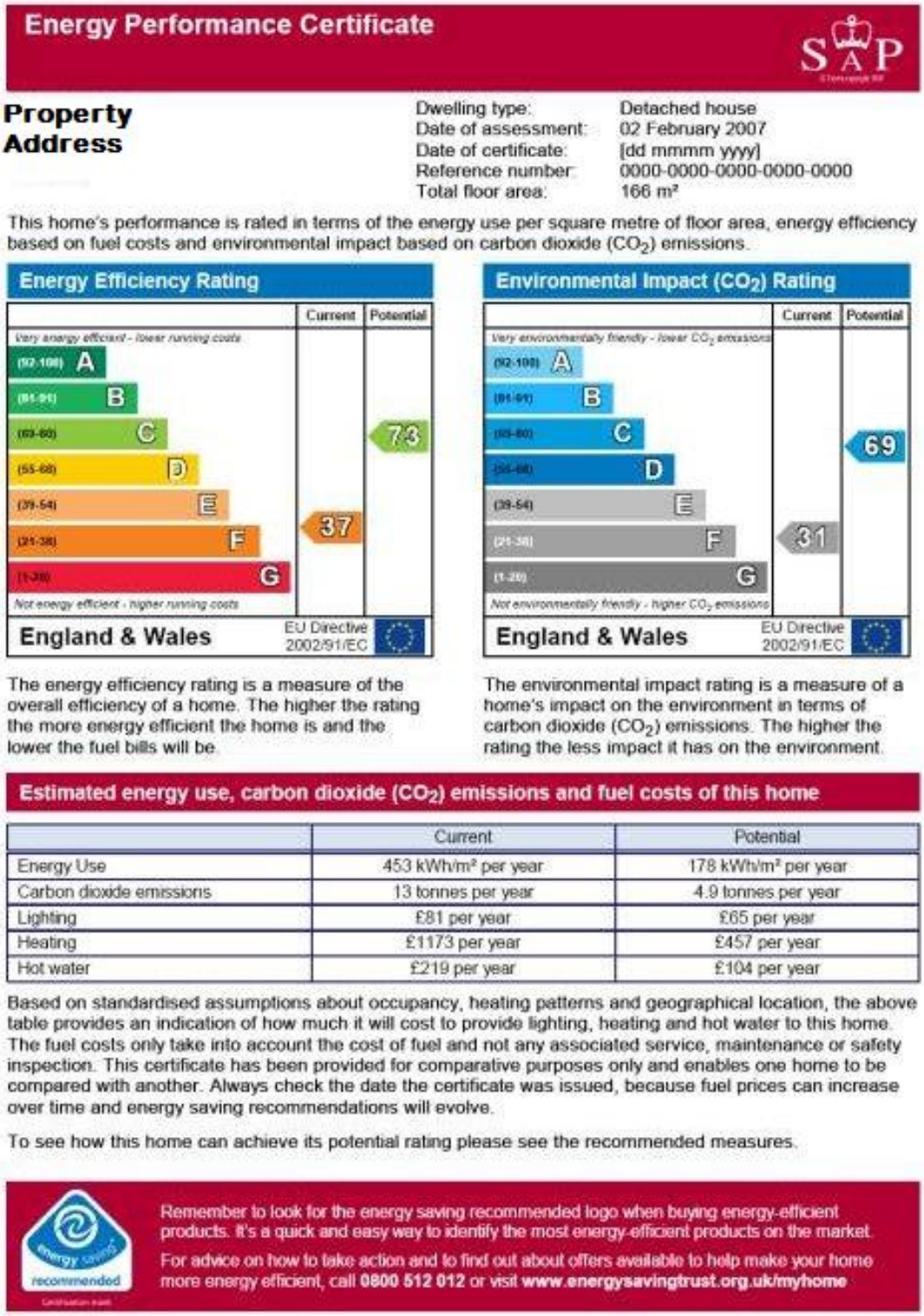
1.3.1 Unraveling the energy performance ?

Dranove and Jin (2010) offer an excellent review of the literature about quality disclosure and certification. In their paper, they first recall the so-called "unraveling result": the process whereby the best quality firm is first to disclose as a way to distinguish itself from lower quality firms. Once the best firm discloses, the second best firm has the same incentive to disclose, and so forth

[1]Energy Star for homes now requires applicants to respect a comprehensive package of best building practices and materials in order to protect roofs, walls, and foundations from water damage and help ensure durability and prevent moisture-related indoor air quality problems. Energy Performance Certificates also provide information about projected CO_2 emissions besides projected energy consumption (see figure 1.1).

Name	Country	Mandatory / Voluntary	Type of rating	Starting year	Operating Agency	Comments
Energy Performance Certificate	Europe	Mandatory	Usually letter grades + numeric metric	gradually after 2002	European countries administration	Implementation might vary between countries. Focus only on energy performance and CO_2 emissions.
Energy Star	USA	Voluntary	Label obtained if energy performance score high enough	1999	US Environmental Protection Agency (EPA)	Annual certification for commercial buildings. Only top performers (typically the top 25% for commercial buildings) are certified.
LEED	Worldwide (mostly US)	Voluntary	Score and distinction (certified, silver, gold, platinum)	1994	US Green Building Council (USGBC, nonprofit organization)	Energy accounts for 30% of the score. Other items are by order of importance: location and transportation, indoor environmental quality, materials and resources, water efficiency, sustainable sites, innovation, regional priority
Green Mark	Singapore	Voluntary	Score and distinction (certified, gold, gold plus, platinum)	2005	Singapore Building Construction Authority	Energy efficiency accounts for half of the score. Other items are by order of importance: sustainable operation and management, water efficiency, indoor environmental quality, innovative green features
BREEAM	Worldwide (mostly UK)	Voluntary	Score and distinction (unclassified, pass, good, very good, excellent, outstanding)	1990	Building Research Establishment (private organization, former UK government establishment)	2,260,000 buildings registered for assessment. Assesses several other categories besides energy such as water use, health, waste, land use and ecology, pollution.
GreenPoint	California	Voluntary	Score and distinction (new home: certified, silver, gold, platinum; existing home: element label, whole house label)	2013	Build It Green (BIG, nonprofit organization)	Energy efficiency acounts for 44% of the score. Other items are by order of importance: water conservation, indoor air quality, resource conservation, community.

Table 1.1: Overview of the most popular Energy Performance Labels and Ratings for Buildings



Energy Performance Certificate

SAP

Property Address

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.

Energy Efficiency Rating

Current: 37 — Potential: 73

Very energy efficient - lower running costs
(92-100) A
(81-91) B
(69-80) C
(55-68) D
(39-54) E
(21-38) F
(1-20) G
Not energy efficient - higher running costs

England & Wales — EU Directive 2002/91/EC

Environmental Impact (CO_2) Rating

Current: 31 — Potential: 69

Very environmentally friendly - lower CO_2 emissions
(92-100) A
(81-91) B
(69-80) C
(55-68) D
(39-54) E
(21-38) F
(1-20) G
Not environmentally friendly - higher CO_2 emissions

England & Wales — EU Directive 2002/91/EC

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.

energy saving recommended

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**

Figure 1.1: A typical EPC in the UK

until all but the worst firm discloses. In the context of buildings, it would mean that all but the most energy-inefficient buildings get an energy performance score. However, we can easily observe that voluntary disclosure is incomplete in buildings (otherwise the European Commission would not have made it mandatory). Dranove and Jin (2010) also recall the assumptions behind the basic unraveling result. Let us review them one by one and see how they hold in the context of buildings.

- *Products are vertically differentiated along a single, well-defined dimension of quality.* This assumption does not hold at all as buildings are a typical example of a multi-attribute good: location, size, orientation, architectural site, amenities, etc. Furthermore, energy efficiency is a relatively minor purchasing criterion as it is shown by Amecke (2012). Hotz and Xiao (2013) provide a setting with multi-attribute products and heterogeneous consumers where the unraveling result may not hold. The failure of information unraveling arises when providing consumers with more information results in more elastic demand, which triggers more intensive price competition and leads to lower prices and profits for competing firms. One can wonder what happens when customers have the possibility to selectively gather information about the quality of a multi-attribute good. Bar-Isaac et al. (2012) argue that the choice of characteristics that are assessed might affect firms' incentives to invest in quality. Mandatory disclosure of energy performance information could therefore have an impact both on building energy performance and on other building characteristics (or on the value of these other characteristics).

- *Sellers have complete and private information about their own product quality.* Because a homeowner (who lives in her house) knows her energy use and her energy consumption, this assumption seems quite verified (at least in the case of owner-occupied dwellings), even if the homeowner has no technical knowledge about buildings. Because landlords are responsible for the general state of their buildings, they are also likely to have good knowledge about their energy performance.

- *Disclosure is costless.* Realizing an EPC in France costs between €85 and €140 according to the comparator website ViaDIAGNOSTIC[2] and the inspection lasts between 30 and 120

[2] `http://www.viadiagnostic.fr/tarif-diagnostic-immobilier.html`

minutes[3] (both time and price mainly depend on the size of the dwelling).

- *Monopoly or competitive market with no strategic interaction among competing sellers.* With a large number of sellers who do not typically coordinate their action, the real estate market seems to verify quite easily this assumption.

- *Consumers are willing to pay a positive amount for any enhancement of quality.* Because of the energy savings in high energy performance building, this assumption is also quite easily satisfied[4]. However, the willingness to pay for energy efficiency might vary between consumers as we shall see in the next point.

- *Consumers are homogeneous.* It is easy to identify a couple of reasons why this assumption cannot hold in the building sector. Retired households are more likely to spend a substantial amount of day time in their dwellings than working-age households. As a result, they should get more benefits from high energy performance, and therefore have a higher willingness to pay for it. Environmental awareness can also play a role (Mandell and Wilhelmsson, 2011). Also, if consumers have heterogeneous discount rates, they will value differently the benefits of investment in energy efficiency. Relaxation of the homogeneity assumption alone has not been much studied in the certification literature[5]. However, when it is relaxed with another assumption such as the single attribute assumption (which also does not hold in the building sector), we saw earlier that it could lead to a failure of the unraveling result (Hotz and Xiao, 2013).

- *Consumers hold a rational expectation on the quality of non-disclosed products.* A necessary condition for this assumption to hold is that consumers pay attention to the available information and understand the disclosed content. Otherwise, lower quality sellers may not disclose because at least some consumers do not perceive nondisclosure as a signal of the lowest quality. (Amecke, 2012) suggests that the understanding of the EPC is not

[3]Wikipedia - `https://fr.wikipedia.org/wiki/Diagnostic_de_performance_%C3%A9nerg%C3%A9tique%#.C3.89tablissement`

[4]We consider a setting where it is possible to disentangle the pure energy performance from all the other attributes such as maintenance costs for example. It might no be the case in reality as a higher energy performance can come with higher maintenance costs (due to a more complex heating system for instance). We adopt the traditional approach in economics where we look at a change in pure energy performance *ceteris paribus*.

[5]In a competitive market, if quality is vertical, the heterogeneity of consumers does not change the reasoning behind the unraveling result.

perfect. 42% of the respondents in their survey did not have a good understanding of the information provided by the certificate. Indeed, energy performance metrics are not easy to understand and process. Usually, a standardized energy consumption per meter square and per year is provided. Then, consumers have to infer from this figure the quantity of interest for them. Let us assume for instance that consumers are only interested in energy saving. They have to determine where their energy use stands compared to the standardized measure and then multiply by the expected price of energy. This computation is not necessarily straightforward and therefore can discourage some consumers. As a result, the informational content of the label might be discarded and consequently, the incentives to disclose information are reduced.

- *The distribution of available quality is public information.* Developed countries usually have an administrative branch which is in charge of collecting energy-related information. This is the energy information administration (eia) in the US or ADEME (Agence de l'environnement et de la maîtrise de l'énergie) in cooperation with INSEE (Institut natinal de la statistique) in France. From reports provided by these agencies, it is usually possible to infer a distribution of the energy performance of the building stock.

In summary, the conditions for the "unraveling result" to hold are not present in the case of building energy performance. Indeed, buildings are multi-attribute goods, consumers (households and firms) are heterogeneous in their preferences for energy efficiency, and energy performance information provided by labels is not always taken into account by consumers. In practice, certification is relatively rare when it is not mandatory. However, it does not mean that mandatory certification is always desirable. On the one hand, it can stimulate competition along the energy performance dimension. On the other hand, it may encourage homeowners to invest in energy performance and cut back in other dimensions, leading to potential reduction in consumer welfare. To the best of our knowledge, the question of whether energy performance should be mandatory or voluntary has not been settled in the literature yet.

1.3.2 Disclosure, consumer choice and energy performance of the building stock

In their survey, Dranove and Jin (2010) also study two questions: does disclosure improve consumer choice and does it improve quality? From a welfare and an energy policy perspective, these two questions are very important for the building sector. Indeed, if there is a better match between consumer preferences and building energy performance, the social welfare increases. Moreover, because consumers with a strong willingness to pay for energy efficiency attributes are likely to have a high usage of energy services, improved matching can also lead to decreased energy consumption and therefore reduced CO_2 emissions. Similarly, if quality improves to better match consumers' demand in energy efficiency, social welfare might increase, energy consumption might decrease, and CO_2 emissions might be reduced.

It is worth mentioning here the rebound effect phenomenon which can undermine energy consumption (and therefore CO_2 emissions) reduction. Because energy efficiency improvement lowers the (marginal) price of energy service, it can lead to an increase in energy service consumption which leads to energy savings lower than if energy consumption is inelastic to price: this is called the rebound effect. In their review, A. Greening et al. (2000) give a range between 10% and 30% for the rebound effect for residential space heating. It means that a 10% improvement in fuel efficiency for space heating generates between 7% and 9% of energy saving instead of 10% if the rebound effect was absent.

Concerning consumer choice, Dranove and Jin (2010) conclude that consumers respond to quality disclosure when rankings differ from preconceptions. The nature of the response depends on whether the disclosed information is easy to access and understand, and whether consumers pay attention to disclosure. In this respect, Amecke (2012) casts some doubts on the effectiveness of the EPC. We have already mentioned the difficulties for consumers to understand energy labels and their inattentiveness. On top of that, results of Amecke (2012) question the informational added value of an EPC compared to available alternatives for prospective buyers and tenants. In his survey, EPCs were found to be less useful than own visits of dwelling or energy utility bills in disclosing energy efficiency information.

This trend is also supported by Olaussen et al. (2015). In their study of the Norwegian

housing market, the researchers look at the impact of EPCs on prices. Indeed, quality disclosure is expected to increase price discrimination: high energy performance dwelling can sell at a relatively higher price. They first apply a cross sectional framework to measure the impact of an increase in the letter of EPC and they find a premium. Then, they use a repeat sales model to see if this premium was already present before the introduction of the EPC (there are several transactions for the same dwelling, at least one of them is before the introduction of the EPC and at least one of them is after): they are unable to reject the zero premium hypothesis. Their conclusions suggest that energy ratings might inform already informed consumers, which challenges their effectiveness in improving matching between consumers and dwellings. We notice here the importance of the price signal triggered (or not) by the label for consumer choice. It also matters a lot for quality improvement. We will dedicate the entire section 1.4 to the survey of the large body of empirical literature concerning the impact of energy performance labels on prices. To the best of our knowledge, literature which directly investigates the impact of energy labels on the matching between consumers and buildings is non-existent.

As far as quality improvement is concerned, Dranove and Jin (2010) conclude that from both a theoretical and empirical point of view, quality disclosure has strengths and pitfalls. On the one hand, quality disclosure is likely to motivate sellers to improve quality. If higher energy performance can claim a higher price in the real estate market, it might be worth investing in building energy retrofit. The effect of energy labels on prices is studied in section 1.4. On the other hand, when goods have multiple attributes, the overall effect of one-dimensional quality disclosure is unclear (Bar-Isaac et al., 2012). However, in the building sector, we might argue that other important attributes such as location, size or building type are easily observable by consumers. Thus, the risk of cutting back investments in other dimensions of quality at the expense of consumers and social welfare is lower. In the same spirit, we might expect a higher investment in energy efficiency for buildings which are weak on other attributes such as the building style, view or orientation. We can already notice that this interaction might pose a challenge when using a hedonic price model (Rosen, 1974): building style, view or orientation are observable by consumers but typically not present in databases. As a result, econometric analysis is likely to face an omitted variable bias.

Empirical evidence of an impact of labels on building supply is scarce. The only paper we

identified on this topic is Comerford et al. (2016). However, the paper is only able to 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 (the color-coded letter grade of the EPC overlayed a pre-existent 0-100 point scale. It illustrates a situation already identified by Dranove and Jin (2010): sellers might want to game the system when information is disclosed. Here, sellers seem to invest in a strategic way to reach the letter D (which is the last grade to pass an exam in the UK system). This leads to potential inefficiency issues: some sellers might over-invest to reach the letter D, some sellers might under-invest because their letter is already D or above. However, the paper does not allow to identify these effects.

In summary, literature about the impact of energy labels on consumer choice and improvement of building energy performance is very scarce. The importance of this impact strongly depends on the extent to which energy labels improve consumers information. Another important dimension to take into account is the strategic reaction of sellers who might want to game the rating system, especially if energy efficiency information is coded in a non-neutral way (like color-coded grades). Besides, price signal triggered by labels is crucial for better consumer choice and quality improvement. Literature about the impact of energy labels on building prices is far more abundant as we will see in the next section.

1.4 Energy Labels and Prices: an empirical perspective

1.4.1 Price, labels and energy performance

From a policy and welfare perspective, it would be more interesting to directly study the impact of labels on matching between consumers and buildings and on energy performance improvement of the building stock. However, information on matching and on energy performance improvement are difficult to obtain. This is not the case for transaction prices and rents of green-labeled buildings. In the US for instance, the company CoStar has a database with more than 4.5 million commercial real estate properties and the presence or absence of a LEED or Energy Star label is mentioned. In Europe, the introduction of the EPC has encouraged several notarial databases to reference the energy rating of the EPC. Moreover, as EPC is mandatory in housing

advertisement since the 2010 Energy Performance of Building Directive, it is even possible to get information about property listings and energy ratings (along with other building characteristics) on real estate websites.

Besides, housing markets are very local and energy labels differ among countries. Thus, it is difficult to extend empirical results outside the region studied and it legitimates the realization of similar studies with different data sets. We believe that this context of data availability and local markets features mainly explains the state of the current literature which consists for the larger part of numerous empirical papers which study the relationship between energy labels and prices. A systematic review of the papers in our survey can be found in section 1.6.

It is important to distinguish between two effects: the effect of energy performance on price and the effect of energy performance *certification* on price. To study the former effect, energy labels can be used as an indicator for building energy performance. To study the latter effect, it is necessary to control for building energy performance without using the label. Two different approaches are used in the literature: one which relies on cross sectional data and a hedonic model, and one with panel data and repeat sales. We present the two approaches and their results in the following paragraphs.

1.4.2 Cross-sectional data with a hedonic model

Rosen (1974) introduced the hedonic regression which is widely used today in real estate economics. In this setting, we assign to a multi-attribute good of price p a vector of attributes X (for instance, X can contain the size of the dwelling, its location, the number of rooms, etc.). A hedonic model has the form:

$$p = f(X, \varepsilon) \tag{1.1}$$

where ε is the error term. For the studies that we reviewed, the functional form is typically such that the model becomes:

$$\log(p) = \alpha EnergyRating + \beta X + \varepsilon \tag{1.2}$$

where $EnergyRating$ is an indicator of energy performance and X controls for the other non-energy-related attributes. $EnergyRating$ can be of two types: a numeric energy performance

indicator such as the standardized annual energy consumption per meter square, or a categorical energy performance such as a dummy variable to indicate the presence or absence of an Energy Star label.

EnergyRating **is a numeric energy performance indicator**

In this case, the empirical analysis investigates the effect of energy performance on prices and not the effect of certification, even if the energy performance indicator comes from a label. In the latter case, it requires that all buildings are labeled. This is verified when label is mandatory like with the EPC or when only green-labeled buildings are considered. For Energy Star and LEED offices, Eichholtz et al. (2010) find that a 10% decrease in energy consumption leads to an increase in value of about 1%, over and above the rent and value premium for a labeled building. In Berlin, Kholodilin and Michelsen (2014) find that for each additional kWh/m2/year of energy needed, the transaction price is reduced by €1.81 and the rent is decreased by roughly €0.2 per m2. In Sweden, Högberg (2013) finds that a 1% reduction in standard energy consumption leads to 0.04% increase in selling price. However, in another study on the Swedish residential real estate market, Wahlström (2016) does not find a premium. Nonetheless, the econometric framework is different as she uses energy-efficiency attributes in the control variables X such as the type of heating or cooling system. Thus, there is not one unique variable which corresponds to energy efficiency. As a result, the interpretation of the coefficient α is more ambiguous.

The expansion of energy labels allows to build larger databases to investigate the effect of energy performance on prices. However, such empirical studies were already performed in the 80s with a smaller number of observations and with alternative indicators of energy efficiency such as the energy bill or the thermal integrity factor (Johnson and Kaserman, 1983; Laquatra, 1986; Dinan and Miranowski, 1989); they already found a sale premium for an increase in energy efficiency.

EnergyRating **is a categorical energy performance indicator and certification is mandatory**

This is typically the case in Europe where the EPC is usually accompanied with a grade. Since the inception of the EPC, many studies fit in with this framework[6]. Most of them find a price premium associated to a one-letter improvement in energy rating. Fregonara et al. (2014) fail to find a premium for house listing prices in the Turin market and suggests that agents in this market are not yet aware of the benefits of building energy performance. Fuerst and McAllister (2011c) also fail to find evidence of a premium for the UK commercial real estate market. They mention as possible explanations the relatively small size of their sample (606 observations) and the lack of attention of prospective tenants.

EnergyRating **is a categorical energy performance indicator and certification is voluntary**

In this case, *EnergyRating* is usually a dummy variable (or a vector of dummy variable when the voluntary label has several categories) to indicate the presence or the absence of a label. This approach does not allow to disentangle the effect of certification from the effect of energy performance: one connot say if the premium found is due to the superior energy performance of labeled buildings or to the certification of these buildings. The empirical literature using this approach is sizable[7]. All but two papers find a premium for the presence of an energy label. Jaffee et al. (2012) do not find any additional premium when they control for total expenses per square foot which include energy expenditures[8]. This result suggests that certification alone does not play a significant role in the price premium. The other paper finds a negative premium (Yoshida and Sugiura, 2010). The author offers two possible explanations: maintenance costs for

[6](Bio Intelligence Service et al., 2013; Brounen and Kok, 2011; Cajias and Piazolo, 2013; Cerin et al., 2014; DINAMIC, 2015; Fregonara et al., 2014; Fuerst and McAllister, 2011c; Högberg, 2013; Jensen et al., 2016; Kholodilin and Michelsen, 2014; Kok and Jennen, 2012; Ramos et al., 2015)

[7](Addae-Dapaah and Chieh, 2011; Bloom et al., 2011; Bond and Devine, 2016; Chegut et al., 2014; Deng et al., 2012,?; Eichholtz et al., 2010, 2013; Fuerst and McAllister, 2011b,a; Hyland et al., 2013; Jaffee et al., 2012; Kahn and Kok, 2014; Miller et al., 2008)

[8]This approach does not strictly fit in with our framework where control variables on vector X are non-energy related. The other paper which also uses energy-related controls with cross-sectional data and a voluntary categorical energy performance label is Soriano (2008) for Australia. He controls for the presence of double/glazed windows, wall/ceiling insulation, and largest window facing north. He finds a 1.7% premium for a star level improvement when controlling for insulation and a 1.9% premium otherwise. Because insulation captures a part of the energy performance indicated by the label, this result makes sense.

green buildings are higher and an omitted variable bias (e.g.: choice to build a green building to mitigate some negative factors such as location or developer characteristics). We will come back on the omitted variable bias in the following paragraph.

Limits of the cross-sectional approach

An important limitation of the cross-sectional is the omitted variable bias. As we have already mentioned in the previous section, different attributes like building style, view or orientation are observable by consumers but typically not present in databases. The problem is that these variables might be correlated with energy performance or the presence of a label. For instance, it could be that owners try to compensate a poor building style with higher energy performance that they will certify. The omitted variable bias is a likely explanation for the negative sale premium found in Oxford by Bio Intelligence Service et al. (2013) where many stylish buildings are old and poorly insulated. Another limit of the cross-sectional approach is that it does not usually allow to disentangle the effect of certification from the effect of energy performance. To cope with these limitations, one might want to use panel data with several sales or rent periods for the same building.

1.4.3 Repeat sales approach with panel data

The fixed-effect econometric model can usually be written with the following form:

$$\log p_{it} = x_i + \delta_t + \alpha Label_{it} + \varepsilon_{it} \tag{1.3}$$

where p_{it} is the transaction price or rent of building i at time t, x_i is the building fixed effect, δ_t is a time fixed effect and $Label_{it}$ is a dummy for the presence of the energy label (it can be a vector when the label has several categories). Assuming that the energy performance of the building (and its other attributes) does not change over time, this framework allows to measure the effect of certification and not the effect of energy performance.

Premiums found with this approach are typically lower than with the cross-sectional approach. It suggests that consumers are already partially informed about building energy performance. Olaussen et al. (2015) find a significant premium when using the cross-sectional which

disappears when using the repeat sales approach with the same data. Similarly, when applying a cross-sectional approach, Fuerst et al. (2015b) find positive premiums for dwellings in EPC bands A and B (11.3%) or C (2.1%) compared to dwellings in band D. When switching to a repeat sales approach, the estimated price premium for band A/B dwellings drops to 4.5%. The price premium for band C dwellings decreases to less than 1%. Deng and Wu (2014); Fuerst et al. (2015a); Reichardt et al. (2012); Das et al. (2011) all use a panel data approach and find certification premiums, although lower than those found in similar papers with a cross sectional approach [9].

Using panel data instead of cross sections also comes with some limitations. The most important one is the assumption of time invariance for the building fixed effect which might be challenged. Indeed, databases do not usually specify if work has been done on buildings during the sample period. If it is the case, the coefficient α is biased and overestimates the effect of certification.

1.4.4 Rental premium vs Sales premium

Over around ten papers reviewed which study the effect of labels both on transaction prices and rents [10] , only Chegut et al. (2014) find an effect which is higher (in percentage) on rents than on transaction prices (19.7% for rents and 14.7% for sales transactions); the others systematically find a stronger premium for sales. We can offer at least three explanations to this phenomenon. One is that the population of renters and buyers, and therefore their demands, have different characteristics. For example, it could be that on average renters have a higher discount rate than buyers. Another explanation relies on expectations of future energy costs and energy performance regulations. If buyers anticipate higher energy prices in the coming years or stringer regulations on building energy performance, it can have an influence on prices, whereas tenants only consider current energy prices. Last, it is also possible that renters spend less time assessing more minor attributes of dwellings as they don't expect to rent the building for a long time or they can

[9] For example, on the one hand, Miller et al. (2008) find a 10% premium for LEED buildings and a 5.8% premium for Energy Star buildings using a cross sectional approach. On the other hand, Reichardt et al. (2012) find a 2.9% premium for LEED buildings and a 2.5% premium for Energy Star buildings using a panel data approach.

[10] (Bio Intelligence Service et al., 2013; Chegut et al., 2014; Eichholtz et al., 2010, 2013; Fuerst and McAllister, 2011b,c,a; Hyland et al., 2013; Kholodilin and Michelsen, 2014; Pivo and Fisher, 2010; Wiley et al., 2010)

more easily move out if they are not satisfied with their building's features. To the best of our knowledge, a deep investigation of the energy performance premium gap between rents and sales in presence of certification is still lacking in the literature.

1.4.5 Prices and Beyond

Looking at price differences between buildings with different energy performance and which are certified or not is a good way (and relatively easy to carry out from an econometric point of view) to see if energy performance is valued by consumers and if certification has an impact. It does not directly analyze the effect of certification on consumer choice and on building stock energy performance evolution. However, price differences are expected to improve matching between consumers and buildings, and increase incentives to invest in building energy efficiency.

Our survey of the literature tends to confirm that higher energy performance is valued in the real estate market. Moreover, certification seems to increase this valuation even if empirical evidence suggests that consumers were already partially informed in absence of certification. Besides, certified high performance buildings are more valued by buyers than by renters. We offer demand-side hypothesis to explain this phenomenon which is not yet studied in the literature to the best of our knowledge.

It would also be interesting to compare the short term price premium after the introduction of a label to the long term price premium. Indeed, if certification leads to an increase of investments in building energy efficiency, the change in the supply is expected to decrease the price premium (provided that the demand remains the same). Such a study could be relevant in the coming years in Europe when databases are available over longer periods.

Last, Wiley et al. (2010) show that energy labels have not only an effect on prices, but also on the occupancy rate. They find in their analysis that estimated occupancy levels are higher by approximately 10% to 11% for Energy Star properties and 16% to 18% for LEED-certified properties. This suggests that prices only represent a part of the green premium or green value. For the residential sector, it could be that green-labeled buildings are sold or rent quicker. This can also be a topic for future research.

1.5 Conclusion

In this paper, we surveyed the literature concerning the effects of energy performance labels and ratings for buildings. We started by looking at the rational behind certification and whether it should be mandatory or not. We reviewed the main assumptions which led to the "unraveling result" and show that they are not all verified in the case of building energy performance. This explains why we don't see full disclosure in practice for the building sector when certification is mandatory. It does not mean however that mandatory certification is necessarily welfare improving. To the best of our knowledge, the question of whether energy performance should be mandatory or voluntary has not been settled in the literature.

We then looked at the literature concerning the impact of energy labels on consumer choice and improvement of building energy performance and we found almost no paper. We speculate that this void is due to the lack of data to properly study these topics. However, an indirect way to study the effects of energy performance certification is to look at the effect of green labels on transaction prices and rents. Databases which allow such studies are more abundant, and so is the literature. Our survey of the literature tends to confirm that higher energy performance is valued in the real estate market, and certification seems to increase this valuation. Besides, the sale premium is usually higher than the rental premium. We offer demand-side hypothesis to explain this phenomenon which is not yet studied in the literature to the best of our knowledge.

1.6 Systematic review of empirical studies about the impact of building energy performance on transaction prices or rents

Reference	Location	Label	Segment	Panel/Cross section	Period	Sample size	Name of database
Addae-Dapaah, K. & Chieh, S., 2011. Green Mark certification: does the market understand? Journal of Sustainable Real Estate.	Singapore	Green Mark	Residential	cross section	2005 - 2009	34 projects (21 000 dwelling units)	Building and Construction Authority data on rated properties matched with the Urban Redevelopment Authority's Real Estate Information System
Bio Intelligence Service, Lyons, R. & Ieep, 2013. Energy performance certificates in buildings and their impact on transaction prices and rents in selected EU countries	Europe	EPC	Residential	cross section	Austria: 2012 France: 2011-2012 Belgium: 2012 Ireland: 2008-2012 UK: 2012	Austria: 1189 sales; 1026 rents Flanders: 15,011 sales; 6,931 rents Brussels-Capital: 1,145 sales; 620 rents Wallonia: 986 sales, 250 rents Marseille: 1,263 sales Lille: 1,915 sales Ireland: 19,094 sales: 26,647 rents Oxford: 236 sales	Austria: immobilien-net.net Belgium: commercial websites France: notaires database BIEN and Perval Ireland: daft.ie UK: Land Registry
Bloom, B., Nobe, M., & Nobe, M. (2011). Valuing green home designs: A study of ENERGY STAR® homes. Journal of Sustainable Real Estate, 3(1), 109-126.	USA	Energy Star	Residential	cross section	1999-2005	300 properties; 150 Energy Star	Transaction data from the county assessor's records matched with Energy Star Colorado data
Bond, S.A. & Devine, A., 2016. Certification Matters: Is Green Talk Cheap Talk? Journal of Real Estate Finance and Economics, 52(2), pp.117–140.	USA	LEED	Residential	cross section	2001-2012	sample size: 1600	miscellanous
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.	Netherlands	EPC	Residential	cross section	2008-2009	31,993 observations	Sales transaction data from the database of the Dutch Association of Realtors. EPC database by Agentschap NL.
Cajias, M., & Piazolo, D. (2013). Green performs better: energy efficiency and financial return on buildings. Journal of Corporate Real Estate, 15(1), 53-72.	Germany	EPC	Residential	cross section	2008-2010	2630 buildings observations	German Investment Property Database (IPD), German statistical office
Cerin, P., Hassel, L.G. & Semenova, N., 2014. Energy Performance and Housing Prices. Sustainable Development, 22(6).	Sweden	EPC	Residential	cross section	2009-2010	67,559 observations	Boverket and Lanmäteriet
Chegut, A., Eichholtz, P. & Kok, N., 2014. Supply, Demand and the Value of Green Buildings. Urban Studies, 51(1), pp.22–43.	UK	BREEAM	Office	cross section	2000-09	1149 rents, 2103 transaction prices	BREEAM address files, CoStar FOCUS, Estates Gazette Interactive
Deng, Y., & Wu, J. (2014). Economic returns to residential green building investment: The developers' perspective. Regional Science and Urban Economics, 47, 35-44.	Singapore	Green Mark	Residential	panel data	2000-2010	13,224 dwellings in 62 Green Mark developments and 55,983 dwellings in 1,375 non-GM developments	Building and Construction Authority data on rated properties matched with the Urban Redevelopment Authority's Real Estate Information System
Deng, Y., Li, Z., & Quigley, J. M. (2012). Economic returns to energy-efficient investments in the housing market: evidence from Singapore. Regional Science and Urban Economics, 42(3), 506-515.	Singapore	Green Mark	Residential	cross section	2000-2010	62 projects (18 296 dwelling unit transactions)	Building and Construction Authority data on rated properties matched with the Urban Redevelopment Authority's Real Estate Information System

Reference	property listings / transaction prices	Premium found	Sales / Rents	Energy efficiency attributes besides the label	Comments
Addae-Dapaah, K. & Chieh, S., 2011. Green Mark certification: does the market understand? Journal of Sustainable Real Estate.	transaction prices	9.6-27.8% depending on rating	Sales	No	
Bio Intelligence Service, Lyons, R. & Ieep, 2013. Energy performance certificates in buildings and their impact on transaction prices and rents in selected EU countries	Austria: listings Belgium: listings France: transaction prices Ireland: listings UK: transaction prices	Location ; Transaction Premium ; Rental Premium (one-letter or equivalent improvement) Oxford, UK ; - 4% ; - Vienna, Austria; 8% ; 4.4% Flanders, Belgium; 4.3% ; 3.2% Wallonia, Belgium; 5.4%; 1.5% Brussels, Belgium; 2.9%; 2.2% Marseille, France; 4.3%; - Lille, France; 3.2%; - Ireland; 2.8% ; 1.4%	Both	No	Control as much as possible for location fixed effects and other attributes such as dwelling condition
Bloom, B., Nobe, M., & Nobe, M. (2011). Valuing green home designs: A study of ENERGY STAR homes. Journal of Sustainable Real Estate, 3(1), 109-126.	transaction prices	+8.66$/square foot	Sales	No	Several modelling biases (e.g. effective controls for area fixed effects) and a small sample of properties (only 300 properties) weaken the argument
Bond, S.A. & Devine, A., 2016. Certification Matters: Is Green Talk Cheap Talk? Journal of Real Estate Finance and Economics, 52(2), pp.117–140.	listings	+8.8% rental rate premium	Rents	No	Compares LEED appartments with apartments marketed as green (without certification) and find a premium.
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.	transaction prices	3.6% (A-C compared to D-G)	Sales	Yes	Control for insulaton quality and central heating
Cajias, M., & Piazolo, D. (2013). Green performs better: energy efficiency and financial return on buildings. Journal of Corporate Real Estate, 15(1), 53-72.	transaction prices	Energy-efficient buildings yield an up to 3.15% higher return and 0.76 €/m2 higher rent than inefficient buildings	Rents	No	
Cerin, P., Hassel, L.G. & Semenova, N., 2014. Energy Performance and Housing Prices. Sustainable Development, 22(6).	transaction prices	Price elasticity with respect to energy performance: 0.06	Sales	No	
Chegut, A., Eichholtz, P. & Kok, N., 2014. Supply, Demand and the Value of Green Buildings. Urban Studies, 51(1), pp.22–43.	both	19.7% for rents and 14.7% for sales transactions	Both	No	Control for: - Contract features - Market competition and gentrification (number of BREEAM - certified buildings within a 500 -metre radius) - Investor types - Location
Deng, Y., & Wu, J. (2014). Economic returns to residential green building investment: The developers' perspective. Regional Science and Urban Economics, 47, 35-44.	transaction prices	4-5%	Sales	No	Using a smaller sample of repeat transactions, DID approach estimates price appreciation premium for Green Mark dwellings of 2% to 3%. There were significant differences between presale and resale price premiums with premiums for re-sales found to be substantially higher. They infer from the results that developers are capturing a small part of the green premium.
Deng, Y., Li, Z., & Quigley, J. M. (2012). Economic returns to energy-efficient investments in the housing market: evidence from Singapore. Regional Science and Urban Economics, 42(3), 506-515.	transaction prices	4-6%	Sales	No	

Reference	Location	Label	Segment	Panel/Cross section	Period	Sample size	Name of database
DINAMIC. (2015). Valeur verte des logements d'après les bases Notariales BIEN et PERVAL.	France	EPC	Residential	cross section	2012-2013	115,000 transactions	bases notariales BIEN and PERVAL
Dinan, T. M., & Miranowski, J. A. (1989). Estimating the implicit price of energy efficiency improvements in the residential housing market: A hedonic approach. Journal of Urban Economics, 25(1), 52–67.	USA	None	Residential	cross section	1982	234	Greater Des Moines Board of Realtors; City and county assessor of Des Moines; 1980 census
Eichholtz, P., Kok, N. & Quigley, J., 2010. Doing well by doing good? Green office buildings. The American Economic Review, 100(December), pp.2494–2511.	USA	Energy Star, LEED	Office	cross section	2004-2007	8,000 rents / 1,813 transaction prices	CoStar database
Eichholtz, P., Kok, N., & Quigley, J. M. (2013). The economics of green building. Review of Economics and Statistics, 95(1), 50–53.	USA	Energy Star, LEED	Office	cross section	2004-2009	20,801 rents; 5,993 transaction prices	CoStar database
Feige, A., Mcallister, P., & Wallbaum, H. (2013). Rental price and sustainability ratings: which sustainability criteria are really paying back?. Construction Management and Economics, 31(4), 322-334.	Switzerland	36 sustainability indicators	Residential	cross section	2009	2453 residential apartments	several portfolios
Fregonara, E., Rolando, D., Semeraro, P., & Vella, M. (2014). The impact of Energy Performance Certificate level on house listing prices. First evidence from Italian real estate. Aestimum.	Italy	EPC	Residential	cross section	2012	500	Turin Real Estate Market Observatory
Fuerst, F. & McAllister, P., 2011. Green Noise or Green Value? Measuring the Effects of Environmental Certification on Office Values. Real Estate Economics, 39(1), pp.45–69.	USA	Energy Star, LEED	Office	cross section	2008 for rents/ 1999-2008 for transaction prices	10,970 observations for rent/ 6,157 for transaction prices	CoStar database
Fuerst, F. et al., 2015. Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England. Energy Economics, 48, pp.145–156.	England	EPC	Residential	panel data	1995-2012	335,095 dwellings	several sources

Reference	property listings / transaction prices	Premium found	Sales / Rents	Energy efficiency attributes besides the label	Comments
DINAMIC. (2015). Valeur verte des logements d'après les bases Notariales BIEN et PERVAL.	transaction prices	5%	Sales	No	
Dinan, T. M., & Miranowski, J. A. (1989). Estimating the implicit price of energy efficiency improvements in the residential housing market: A hedonic approach. Journal of Urban Economics, 25(1), 52–67.	transaction prices	$1 decrease in the level of expenditures necessary to maintain the house at 65'F (in the average heating season) will increase the expected selling price of the house by $11.63	Sales	N/A	Direct measure of energy efficiency on transaction prices. No label.
Eichholtz, P., Kok, N. & Quigley, J., 2010. Doing well by doing good? Green office buildings. The American Economic Review, 100(December), pp.2494–2511.	transaction prices	3% for rental rate, above 7% for effective rate, 16% for transaction prices. A 10 percent decrease in energy consumption leads to an increase in value of about 1 percent, over and above the rent and value premium for a labeled building.	Both	No	Investigates the determinants of the premium using per degree day cooling and heating which come from the details of the label. Energy savings are an important determinant, however there are other intangible factors.
Eichholtz, P., Kok, N., & Quigley, J. M. (2013). The economics of green building. Review of Economics and Statistics, 95(1), 50–53.	transaction prices	Certification: 3% for rents; 13% for market value. Besides, a one dollar saving in energy costs of a building is on average associated with a 3.5% higher rent and a one dollar saving in energy costs is associated with a 4.9% premium in market valuation.	Both	No	Investigates the determinants of the label using utility bill estimation which comes from the details of the label. Energy savings are an important determinant, however there are other intangible factors.
Feige, A., Mcallister, P., & Wallbaum, H. (2013). Rental price and sustainability ratings: which sustainability criteria are really paying back?. Construction Management and Economics, 31(4), 322-334.	transaction prices	Positive association between a number of sustainable features and (rental) prices	Rents	No	It is noteworthy that they found an unexpected negative relationship between energy efficiency and price. This was attributed to Swiss residential lease structures where landlords tend to recover the estimated cost of energy from tenants in advance. Hence, less energy efficient buildings may have appeared to have a higher rent since the energy cost is 'bundled' with rent.
Fregonara, E., Rolando, D., Semeraro, P., & Vella, M. (2014). The impact of Energy Performance Certificate level on house listing prices. First evidence from Italian real estate. Aestimum.	listings	No premium found	Sales	No	Control for apartment condition ("to be completely renovated", "to be partially renovated", "good" and "refurbished"
Fuerst, F. & McAllister, P., 2011. Green Noise or Green Value? Measuring the Effects of Environmental Certification on Office Values. Real Estate Economics, 39(1), pp.45–69.	transaction prices	Rental premium of 5% for LEED certification and 4% for Energy Star certification. For sales prices, price premia of 25% for LEED-certified buildings and 26% for Energy Star.	Both	No	
Fuerst, F. et al., 2015. Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England. Energy Economics, 48, pp.145–156.	transaction prices	A/B (5%) or C (1.8%) compared to dwellings rated D.For dwellings rated E (-0.7%) and F (-0.9%)	Sales	No	A concern with the results of this study is that there was no control for potential omitted variable bias due to the absence of information on improvements and other quality variables such as age.

Reference	Location	Label	Segment	Panel/Cross section	Period	Sample size	Name of database
Fuerst, F. et al., 2015. Variations in the Implicit Pricing of Energy Performance by Dwelling Type and Tenure: A Study of Wales. SSRN Electronic Journal.	Wales	EPC	Residential	(1) Cross-sectional famework(2) Repeat sales methodology	2003-2014	191,544 transactions. 47,158 (25%) of these included a second transaction	National Statistics Postcode Directory to account for inflation
Fuerst, F., & McAllister, P. (2011). Eco-labeling in commercial office markets: Do LEED and Energy Star offices obtain multiple premiums? Ecological Economics, 70(6), 1220–1230.	USA	Energy Star, LEED	Office	cross section	1999-2009 sales; 2009 rents	13,971 sales; 36,236 rents	CoStar database
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.	UK	EPC	Office	cross section	2011	708	Investment Property Databank UK Universe
Högberg, L., 2013. The impact of energy performance on single-family home selling prices in Sweden. Journal of European Real Estate Research.	Sweden	EPC	Residential	cross section	2009	1,073 observations	Varderingsdata for sales prices; National Board of Housing Building and Planning (NBHBP) for EPCs
Hyland, M., Lyons, R. C., & Lyons, S. (2013). The value of domestic building energy efficiency—evidence from Ireland. Energy Economics, 40, 943-952.	Ireland	BER	Residential	cross section	2008-2012	15,060 sales; 20,825 rents	daft.ie
Jaffee, D., Stanton, R., & Wallace, N. (2012). Energy Factors , Leasing Structure and the Market Price of Office Buildings in the U . S . Fisher Center Working Papers.	USA	Energy Star	Office	cross section	2001-2010	816	CoStar combined with US EPA Energy Star information

Reference	property listings / transaction prices	Premium found	Sales / Rents	Energy efficiency attributes besides the label	Comments
Fuerst, F. et al., 2015. Variations in the Implicit Pricing of Energy Performance by Dwelling Type and Tenure: A Study of Wales. SSRN Electronic Journal.	transaction prices	(1) Positive premiums for dwellings in bands A and B (11.3%) or C (2.1%) compared to dwellings in band D. For dwellings in EPC bands lower than D there are statistically significant discounts; -2.1% for band E dwellings, -4.7% for band F dwellings and -7.2% for dwellings in band G.(2) Compared to a band D dwelling, the estimated price premium for band A/B dwellings drops to 4.5%. The price premium for band C dwellings decreases to less than 1%.	Sales	No	It is unknown if upgrades have been made in the repeat sales analysis
Fuerst, F., & McAllister, P. (2011). Eco-labeling in commercial office markets: Do LEED and Energy Star offices obtain multiple premiums? Ecological Economics, 70(6), 1220–1230.	transaction prices	Sales: 18% and 25% for Energy Star and LEED rated office buildings respectively. Rents: 3%–5%	Both	No	
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.	appraisal values	No premium found	Both	No	
Högberg, L., 2013. The impact of energy performance on single-family home selling prices in Sweden. Journal of European Real Estate Research.	transaction prices	1% reduction in standard energy consumption leads to 0.04% increase in selling price	Sales	No	Also investigates the effect of the presence of cost-effective improvement recommendations on the housing price. Suprisingly, the paper finds a negative effect. Possible explanation: absence of recommendations is a proxy for dwelling care (omitted variable bias)
Hyland, M., Lyons, R. C., & Lyons, S. (2013). The value of domestic building energy efficiency—evidence from Ireland. Energy Economics, 40, 943-952.	listings	A/D:+9% sale price, +2% rental price;	Both	No	
Jaffee, D., Stanton, R., & Wallace, N. (2012). Energy Factors , Leasing Structure and the Market Price of Office Buildings in the U . S . Fisher Center Working Papers.	transaction prices	No premium found	Sales	No	Control for total expenses per square foot which also include energy expenditures. Besides, energy factor market prices, the shape of the energy price curves, and weather metrics are consistently shown to be statistically significant determinants of building transaction prices.

Reference	Location	Label	Segment	Panel/Cross section	Period	Sample size	Name of database
Jensen, O. M., Hansen, A. R., & Kragh, J. (2016). Market response to the public display of energy performance rating at property sales. Energy Policy, 93, 229–235.	Denmark	EPC	Residential	cross section	2007-2012	117,483 sales	Building Stock Register (BBR) (Danish Enterpise and Construction Authority)
Johnson, R.C. & Kaserman, D.L., 1983. Housing market capitalization of energy-saving durable good investments. Economic Inquiry, 21(3), pp.374–386.	USA	None	Residential	cross section	1978	1,317 observations	Multiple Listing Services of the board of Realtors of Knoxville, Tennesse; Knoxville Metropoltan Planning Commission; 1970 US Census of Population and Housing; Knoxville Utilities Board
Kahn, M. E., & Kok, N. (2014). The capitalization of green labels in the California housing market. Regional Science and Urban Economics, 47, 25-34.	USA	Energy Star, LEED, GreenPoint	Residential	cross section	2007-2012	1,609,976 observations, 5500 with green labels	USGBC, Build It Green
Kholodilin, K. A., & Michelsen, C. (2014). The Market Value of Energy Efficiency in Buildings and the Mode of Tenure.	Germany	EPC	Residential	cross section	2011-2013	11894 rents/31221 sales	data downloaded from rental and selling ads on internet
Kok, N., & Jennen, M. (2012). The impact of energy labels and accessibility on office rents. Energy Policy, 46, 489–497.	Netherlands	EPC	Office	cross section	2005-2010	1057 sales	Leasing transaction data from real estate agents CBRE, DTZ Zadelhoff and Jones Lang LaSalle G4
Laquatra, J., 1986. Housing market capitalization of thermal integrity. Energy Economics, 8(3), pp.134–138.	USA	None	Residential	cross section	1980	144 observations	Minnesota Housing Finance Agency
Miller, N., Spivey, J. & Florance, A., 2008. Does green pay off? Journal of Real Estate Portfolio.	USA	LEED, Energy Star	Office	cross section	2003-2007	927 total observations	CoStar database
Olaussen, J., Oust, A. & Solstad, J., 2015. Implementing Energy Performance Certificates–Informing the Informed?	Norway	EPC	Residential	(1) cross sectional framework(2) repeat sales model with panel data	2009-2014	sample size: 4000	Eiendomsverdi (The company develops and supplies information tools and systems to estimate market value (both on an individual unit level and on a portfolio level) for the Norwegian residential real estate market)
Pivo, G., & Fisher, J. (2010). Income, value, and returns in socially responsible office properties. Journal of Real Estate Research.	USA	Energy Star	Office	cross section	1999-2008	6,000-7,500 observations	Quarterly data from National Council of Real Estate Investment Fiduciaries. Transaction data for properties that had not been sold. US EPA data on Energy Star. Unclear whether rental value is all transaction data or also a mix of appraised and transaction value.
Ramos, A., Pérez-Alonso, A., & Silva, S. (2015). Valuing Energy Performance Certificates in the Portuguese Residential	Portugal	EPC	Residential	cross section	2015	21,170 observations	website remax.pt

Reference	property listings / transaction prices	Premium found	Sales / Rents	Energy efficiency attributes besides the label	Comments
Jensen, O. M., Hansen, A. R., & Kragh, J. (2016). Market response to the public display of energy performance rating at property sales. Energy Policy, 93, 229–235.	transaction prices	+10% ABC/DEFG	Sales	No	Increase of the premium after EPC mandatory in advertising.
Johnson, R.C. & Kaserman, D.L., 1983. Housing market capitalization of energy-saving durable good investments. Economic Inquiry, 21(3), pp.374–386.	transaction prices	+$20.73 per one-dollar reduction in the annual fuel bill	Sales	No	Major caveat: the quantity of energy consumed (independent variable) is not completely determined by thermal characteristics of the structure. The paper also looks for implicit housing market discount rates related to energy consumption and find results that do not suggest a discount rate substantially different from the social discount rate.
Kahn, M. E., & Kok, N. (2014). The capitalization of green labels in the California housing market. Regional Science and Urban Economics, 47, 25-34.	transaction prices	5%	Sales	No	
Kholodilin, K. A., & Michelsen, C. (2014). The Market Value of Energy Efficiency in Buildings and the Mode of Tenure.	listings	For each additional kWh/m2/year of energy needed, the price is reduced by €1.81.An additional kWh/m2 energy consumptionleads to a decrease of rent by roughly €0.2 per m2.	both	No	Another relevant finding for the present study is the significantly lower implicit prices of energy efficiency of rental dwellings compared to owner-occupied dwellings. The authors explain these differences as a sign of the market power of tenants or as a result of the split incentive problem.
Kok, N., & Jennen, M. (2012). The impact of energy labels and accessibility on office rents. Energy Policy, 46, 489–497.	transaction prices	6.5% (A-C compared to D-G)	Rents	No	
Laquatra, J., 1986. Housing market capitalization of thermal integrity. Energy Economics, 8(3), pp.134–138.	transaction prices	A unit decrease in Thermal Integrity Factor ->increase in house sale price by $2,510	Sales	No	Special case of an Energy Efficient Housing Demonstration Program. Thus, buyers can be considered as "early adopters" and therefore not representative of the general population.
Miller, N., Spivey, J. & Florance, A., 2008. Does green pay off? Journal of Real Estate Portfolio.	transaction prices	10% LEED; 5.8% Energy Star	Sales	No	
Olaussen, J., Oust, A. & Solstad, J., 2015. Implementing Energy Performance Certificates–Informing the Informed?	transaction prices	(1) premium found(2) no premium found	Sales	No	It is unknown if upgrades have been made in the repeat sales analysis.
Pivo, G., & Fisher, J. (2010). Income, value, and returns in socially responsible office properties. Journal of Real Estate Research.	transaction prices	8.5% sales; 5.2% rents	Both	No	
Ramos, A., Pérez-Alonso, A., & Silva, S. (2015). Valuing Energy Performance Certificates in the Portuguese Residential	listings	Dwellings with EPC equal to A, B or C are sold at a 5.9%higher price per square meter than those with an EPC equal to D. In contrast, dwellings with EPC equalto E, F or G are sold at 4% less	Sales	Yes	Control for a couple of energy characteristics of the dwelling such as the heating system and the presence of double-glazed windows

Reference	Location	Label	Segment	Panel/Cross section	Period	Sample size	Name of database
Reichardt, A., Fuerst, F., & Rottke, N. (2012). Sustainable building certification and the rent premium: a panel data approach. Journal of Real Estate.	USA	Energy Star, LEED	Office	panel data	2000-2010	8,197	CoStar
Soriano, F. (2008). Energy efficiency Rating and House Price in the ACT. Modelling the relationship of energy efficiency attributes to house price the case of detached houses sold in the Australian Capital Territory in 2005 and 2006.	Australia	ACTHER S	Residential	cross section	2006	2719	Land Information Centre transaction data; ACT-PLA energy ratings
Wahlström, M. H. (2016). Doing good but not that well? A dilemma for energy conserving homeowners. Energy Economics, 60, 197-205.	Sweden	EPC	Residential	cross section	2009-2010	77,000 observations	Boverket 2014
Wiley, J., Benefield, J. & Johnson, K., 2010. Green design and the market for commercial office space. The Journal of Real Estate Finance.	USA	Energy Star, LEED	Office	cross section	2008	rents: 7,308 observation-ssales: 1,151 observations	CoStar
Yoshida, J. & Sugiura, A., 2010. Which "greenness" is valued? Evidence from green condominiums in Tokyo. 46th Annual AREUEA Conference, pp.1–34.	Japan	Tokyo Green Labeling System for Condominiums	Office	cross section	2002-2009	38,680 observations	Transaction Price Information Service
Bruegge, C., Carrión-Flores, C. & Pope, J.C., 2016. Does the housing market value energy efficient homes? Evidence from the energy star program. Regional Science and Urban Economics, 57, pp.63–76.	USA	Energy Star	Residential	cross section	1998-2009	6,000 observations	Alachua County Property Appraiser's Office, Florida Solar Energy Center
Walls, M., Palmer, K. & Gerarden, T., 2013. Is energy efficiency capitalized into home prices? Evidence from three US cities. Evidence from Three US Cities.	USA	Energy Star	Residential	cross section	2005-2011	175,000 observations	multiple listing services
Das, P., Tidwell, A. & Ziobrowski, A., 2011. Dynamics of green rentals over market cycles: evidence from commercial office properties in San Francisco and Washington DC. Journal of Sustainable Real Estate.	USA	Energy Star, LEED	Office	panel data	2007-2010	1,256 observations	USGBC, CoStar

Reference	property listings / transaction prices	Premium found	Sales / Rents	Energy efficiency attributes besides the label	Comments
Reichardt, A., Fuerst, F., & Rottke, N. (2012). Sustainable building certification and the rent premium: a panel data approach. Journal of Real Estate.	transaction prices	2.9% (LEED), 2.5% (Energy Star)	Rents	No	
Soriano, F. (2008). Energy efficiency Rating and House Price in the ACT. Modelling the relationship of energy efficiency attributes to house price the case of detached houses sold in the Australian Capital Territory in 2005 and 2006.	transaction prices	2% per star level	Sales	Yes	Controls for the largest window facing north, double glazed windows, wall/ceiling insulation. Slightly smaller premium when control for insulation (1.9% to 1.7%).
Wahlström, M. H. (2016). Doing good but not that well? A dilemma for energy conserving homeowners. Energy Economics, 60, 197-205.	transaction prices	No premium found. Dwellings with higher estimated expected energy consumption are sold at a higher price.	Sales	Yes	Controls for an important number of energy-related attributs including type of energy systems for heating and cooling, type of ventilation, and number of frost days per year
Wiley, J., Benefield, J. & Johnson, K., 2010. Green design and the market for commercial office space. The Journal of Real Estate Finance.	both	Rents: 7.3% to 8.6% for Energy Star properties and 15.2% to 17.3% for LEEDSales: $30/ft2 for Energy Star and 129/ft2$ for LEED	Both	No	Estimated occupancy levels are higher by approximately 10% to 11% for Energy Star properties and 16% to 18% for LEED-certified properties
Yoshida, J. & Sugiura, A., 2010. Which "greenness" is valued? Evidence from green condominiums in Tokyo. 46th Annual AREUEA Conference, pp.1–34.	transaction prices	-5.6% when green evaluation	Sales	No	Explanation proposed: maitenance costs for green buildings are higher, omitted variable bias (e.g.: develop as a green building to mitigate some negative factors such as location or developer characteristics)
Bruegge, C., Carrión-Flores, C. & Pope, J.C., 2016. Does the housing market value energy efficient homes? Evidence from the energy star program. Regional Science and Urban Economics, 57, pp.63–76.	transaction prices	1.2%	Sales	No	Also uses a panel data analysis with repeat sales methodology to estimate the decrease of the premium. Both with cross section and panel data, they find a decrease of the premium over time. Potential explanations are presented in the paper
Walls, M., Palmer, K. & Gerarden, T., 2013. Is energy efficiency capitalized into home prices? Evidence from three US cities. Evidence from Three US Cities.	transaction prices	0-2%	Sales	No	Energy savings are found to roughly equal the premium when it exits (in Washington and in Portland, not in Austin). Besides, local labels receive a higher premium. It is explained by the fact that local labels certify more attributes than energy efficiency performance.
Das, P., Tidwell, A. & Ziobrowski, A., 2011. Dynamics of green rentals over market cycles: evidence from commercial office properties in San Francisco and Washington DC. Journal of Sustainable Real Estate.	transaction prices	0.1%- 2.4%	Rents	No	2.4% premium in down markets, 0.1% premium in up markets.

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Chapter 2

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

This chapter is a joint work with Pierre Fleckinger and Matthieu Glachant. We are grateful to participants of the economics doctoral seminar at MINES ParisTech, the FAERE 5th annual conference at University of Aix-Marseille, the 2016 YEEES seminar at University of Edinburgh, the 2018 Workshop on the Economics of Energy Efficiency Policies in the Residential Sector at University of Montpellier and the 11th Conference on the Economics of Energy and Climate at TSE.

Abstract

In the European Union, Energy Performance Certificates (EPCs) provide potential home buyers or tenants with information on a property's energy performance. By mitigating informational asymmetries on real estate markets, the conventional wisdom is that EPCs will reduce energy use and greenhouse gas emissions, and increase energy-efficiency investments.

We develop a dynamic model that partly contradicts these predictions. Although EPCs minimize total private costs, 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. Last, our model analyzes the interaction of EPCs with other policy instruments such as a carbon tax and subsidies, and studies conditions when these instruments are substitutes or complements.

Dans l'Union européenne, le diagnostic de performance énergétique (DPE) fournit aux acheteurs ou locataires potentiels des informations sur la performance énergétique d'une propriété. En atténuant les asymétries d'information sur les marchés immobiliers, il est généralement admis que le DPE réduira la consommation d'énergie et les émissions de gaz à effet de serre et augmentera les investissements en efficacité énergétique. Nous développons un modèle dynamique qui contredit en partie ces prédictions. Bien que le DPE minimise les coûts privés totaux, leur impact sur la consommation d'énergie et les investissements est ambigu et dépend à la fois de l'horizon temporel considéré et de l'hétérogénéité des besoins énergétiques dans la population. Enfin, notre modèle analyse l'interaction du DPE avec d'autres instruments de politique publique tels que la taxe carbone et les subventions, et étudie les conditions dans lesquelles ces instruments sont substituables ou complémentaires.

2.1 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 Union 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 30% target for 2030.

Energy taxation is the primary policy strategy to reduce energy use, but it is usually combined with sector-specific policies. This is particularly true for buildings, which are responsible for a sizable share of total energy use (e.g. 40% in the EU). Many countries grant tax credits and other subsidies to energy retrofits of existing buildings. Building codes also include energy performance

provisions for new buildings.

Another popular policy approach is to provide potential buyers or tenants with information on the energy performance. In the European Union, so-called Energy Performance Certificates (EPCs) give information on a property's typical energy use and energy cost, an energy efficiency rating from A (most efficient) to G (least efficient), practical advice on improving such performance. Their publication is compulsory in all advertisements for the sale or rental of buildings since 2007. Figure 2.1 shows an example of EPC. 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 performance 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 informational asymmetries, EPCs are primarily expected to improve the matching between properties with heterogeneous energy performance and households with heterogeneous energy needs on the real estate market. 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 lesser efficient properties. EPCs also raise the incentives to invest in energy efficiency as the price of energy-efficient properties is higher than that of inefficient ones. 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 total private costs 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 ingredients. First, homeowners[1] can make investments to upgrade their dwelling's energy performance. 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 retrofitting with and without energy certification, and the resulting impact on energy consumption.

[1] Although we cast the model in terms of residential homes, it equally applies to office buildings.

Energy Performance Certificate

SAP

17 Any Street, Any Town, County, YY3 5XX	Dwelling type: Date of assessment: Date of certificate: Reference number: Total floor area:	Detached house 02 February 2007 [dd mmmm yyyy] 0000-0000-0000-0000-0000 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.

Energy Efficiency Rating

	Current	Potential
Very energy efficient - lower running costs		
(92-100) A		
(81-91) B		
(69-80) C		73
(55-68) D		
(39-54) E		
(21-38) F	37	
(1-20) G		
Not energy efficient - higher running costs		

England & Wales EU Directive 2002/91/EC

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.

Environmental Impact (CO_2) Rating

	Current	Potential
Very environmentally friendly - lower CO_2 emissions		
(92-100) A		
(81-91) B		
(69-80) C		69
(55-68) D		
(39-54) E		
(21-38) F	31	
(1-20) G		
Not environmentally friendly - higher CO_2 emissions		

England & Wales EU Directive 2002/91/EC

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.

energy saving recommended

Certification mark

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**

Page 1 of 6

Figure 2.1: Example of an energy performance certificate

We find that the introduction of EPCs minimizes total private costs. However, the impact on the level of energy use and on the volume of energy efficiency investments is ambiguous. In the short term, EPCs reduce energy use and increase energy efficiency investments. In the long term, it is the opposite. Indeed, while information asymmetry could lead to mismatch where a high-energy use household would purchase and then retrofit an energy-inefficient dwelling, EPC ensures an optimal allocation efficiency which suppresses extra retrofitting. Finally, we study how certification interacts with other policy instruments: carbon tax, subsidy and standard. While EPCs and standards are substitutes in essence, certification and taxation or subsidies can be either substitutes or complements depending on the policy objective (and in particular depending on the time horizon of the policy objective).

The remainder of the paper is organized as follows: section 2.2 reviews the literature on building energy certification, section 2.3 presents the model, section 2.4 and 2.5 present the equilibrium with and without certification, section 2.6 provides examples of applications of the model with chosen parameters, section 2.7 studies how certification interacts with other policy instruments, and section 2.8 concludes.

2.2 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 total private costs. 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 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 reducing 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 a paper by Comerford et al. (2016) who examine the impact of EPC 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 want to 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: some sellers might over-invest to reach the letter D, some sellers might under-invest because their letter is already D or above.[2].

In this paper, we also model the heterogeneity of households in their energy demand. This is in line with Adan and Fuerst (2015) who find households' composition, income, age and employment status to be important drivers of gas used for space heating. Similarly, Bakaloglou and Charlier (2018) provide evidence that 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). In particular, 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 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 consumption (for instance, see Jessoe and Rapson (2012)). The underlying mechanisms are totally different since this information does not reduce informational asymmetries on real estate markets, but is expected to mitigate behavioral biases.

Last, our theoretical framework can be also interpreted with the behavioral concept of *inattention* which is often considered as a possible explanation for the energy efficiency gap. Indeed, one can argue that households are inattentive to the information that they do have on building energy performance (in the absence of EPCs, potential buyers visit the dwelling, can ask for its age, can require energy bills of previous residents; all these actions give them information

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

about building energy performance). Because EPCs are required to be present and salient in the dwelling listing, one can argue that it increases consumers' attention. However, empirical evidence of consumers' inattention are scarce. For instance, studying car purchases and providing fuel economy information to people shopping for new vehicles, Allcott and Knittel (2017) find zero statistical or economic effect of information on average fuel economy of vehicles purchased.

2.3 Model

2.3.1 Setting

We develop a dynamic model in discrete time, which describes the evolution of the building stock of a city. The stock includes dwellings with energy performance θ. Each dwelling can either be energy-efficient ($\theta = 1$) or inefficient ($\theta = 0$). The dwellings are owned and occupied by a continuum of households with heterogeneous energy needs.[3] More specifically, each household consumes a quantity of energy $(1-\theta)\cdot e$ per period[4] where e is distributed over $[0, +\infty)$ according to a cumulative distribution function F. F is continuous, strictly increasing[5], and the overall level of energy consumption is bounded: $\int_0^{+\infty} e \, \mathrm{d}F(e) < +\infty$.

Let q_t denote the share of efficient dwellings. We assume that all dwellings are inefficient at the beginning of the game: $q_0 = 0$. Any household can then invest in any period to upgrade its property if $\theta = 0$. The cost is I and $\theta = 1$ after investment, which is irreversible and which has an infinite lifetime (after investment, the energy performance is 1 over the entire time horizon). The share of efficient dwellings at time t is q_t.

In each period, m households exogenously and randomly move out and sell their dwelling to the same number of households who lived outside the city and who move in. Incoming and outgoing households are drawn from the same energy consumption distribution and every

[3]We extend the analysis to the rental case in section 2.9.2 in the appendix.

[4]We do not model the rebound effect in this paper. Gillingham et al. (2016) review the theory and (rare) empirical estimates of the rebound effect and find estimates of the short-to-medium-run elasticity of electricity demand between -0.09 and -0.12., which suggests a modest magnitude of the rebound effect.

[5]The continuity assumption is purely technical and helps us simplify the proofs. Relaxing it makes the proofs more tedious without changing the results. The monotonicity assumption has more importance: if relaxed, results derived in the paper do not necessarily hold any longer. What matters for the results to hold is that there is always a household which energy consumption is so high that it will invest in any circumstances. Thus, we can replace the monotonicity assumption by $F(I(1-\delta(1-m)) < 1$ with m which is defined later in this section. This latter assumption ensures that there are some households who are ready to invest in any circumstances.

household always 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. Also, we assume that moving costs are large compared to home energy performance costs[6] so that households have no incentives to move for home-energy-performance-related reasons. The real estate market is competitive.

When there is certification, energy performance is perfectly observable before the sale. Without certification, we assume that incoming households only observe it after moving in. The 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. Incoming households observe the energy performance of their home.
3. Each household who lives in an inefficient dwelling ($\theta = 0$) decides whether to invest I or not.
4. Payoffs are realized.

Last, we assume that all households form perfect expectations about future housing prices in all scenarios.

2.3.2 Policy objectives and evaluation

The classical approach to evaluate a policy is to define a welfare function or, equivalently, a social cost function. In climate change economics, doing so lead to several issues. In particular, it requires to define the social cost of carbon. Because this concept is questionable (Pottier, 2016), we prefer to revert to a cost-effectiveness analysis which, furthermore, is closer to what policymakers do in practice.

Policy objectives are formulated in terms of GHG emission and/or energy reduction targets. For instance, the EU wants to cut its GHG emissions by 20% in 2020 and by 40% in 2030 compared to 1990 levels. In our model, we assimilate energy consumption with energy emission[7];

[6] An equivalent setting is to allow moving decisions to be partially endogenous and to assume moving costs greater than I.

[7] This is equivalent to consider that emission reduction are proportional to energy use. This is true when energy fuel is fixed. Otherwise, it is an over-simplification.

therefore, we will use indifferently emission targets and energy use targets. In our model, total energy use at time t is given by:

$$E_t = \int_0^{+\infty} \mathbb{P}_t(\theta = 0|e) e \, \mathrm{d}F(e) \tag{2.1}$$

where $\mathbb{P}_t(\theta = 0|e)$ is the (endogenous) share of households with energy need e who live in inefficient dwellings at period t. A policy target is defined as follows:

Definition 1 (Policy target)**.** *A policy target is a couple $(\bar{E}, \tau)$ where $\bar{E}$ is the emission/energy use level and τ is the time of achievement. The target is reached if: $\forall t \geq \tau, E_t \leq \bar{E}$.*

Section 2.9.1 in the appendix elaborates on alternative policy targets based on cumulative emission or investment rate.

Policymakers are willing to minimize costs to attain their targets. The total cost function is the discounted sum of investments and energy expenditures over the entire time horizon and can be written (when energy consumption is expressed in monetary units):

$$C = \sum_{t=0}^{\infty} \delta^t \left(\int_0^{+\infty} \mathbb{P}_t(\theta = 0|e) e \, \mathrm{d}F(e) + (q_{t+1} - q_t) I \right) \tag{2.2}$$

where δ is the discount factor[8]. From this definition, we can compare the cost-effectiveness of two different policies:

Definition 2 (Cost-effectiveness)**.** *For a given policy target $(\bar{E}, \tau)$ and two policies $\mathcal{P}_1$ and $\mathcal{P}_2$ which reach this target, $\mathcal{P}_1$ is said to be more cost-effective than $\mathcal{P}_2$ if the total cost $C(\mathcal{P}_1)$ associated to $\mathcal{P}_1$ is lower than the total cost $C(\mathcal{P}_2)$ associated to $\mathcal{P}_2$.*

2.4 Equilibrium with an EPC

In this section, we examine the equilibrium investment path under perfect information on energy performance. From now on, let $u_t(e, \theta)$ denote the expected lifetime surplus of a household of type e living in a dwelling with performance θ at the beginning of period t. In the case where

[8] If r is the discount rate, then $\delta = \frac{1}{1+r}$

the dwelling is efficient ($\theta = 1$), this surplus is given by the recurrence relation:

$$u_t(e,1) = \delta[mp^1_{t+1} + (1-m)u_{t+1}(e,1)] \tag{2.3}$$

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 $u_{t+1}(e,1)$.

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:

$$u_t(e,0) = \max\{u^I_t(e), u^\emptyset_t(e)\} \tag{2.4}$$

where:

$$u^I_t(e) = -I + \delta mp^1_{t+1} + \delta(1-m)u_{t+1}(e,1) \tag{2.5}$$

$$u^\emptyset_t(e) = -e + \delta mp^0_{t+1} + \delta(1-m)u_{t+1}(e,0) \tag{2.6}$$

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 the sales is then given by p^0_t, p^1_t, and the allocation function $g_t : e \mapsto \theta$ which satisfies two conditions:

- Market clearing: $\int_0^{+\infty} g_t(e)\mathrm{d}F(e) = q_t$.
- Incentive compatibility: $g_t(e) = \underset{\theta}{\operatorname{argmax}}\ u_t(e,\theta) - p^\theta_t$.

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

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

Proof. See section 2.9.4 in the appendix. □

A direct implication is that the relative prices in equilibrium are those making the limit type $\tilde{e}_t$ indifferent between both dwelling types:

Corollary 1. *In the market equilibrium, we have* $p_t^1 - p_t^0 = u_t(\tilde{e}_t, 1) - u_t(\tilde{e}_t, 0)$.

In order to predict the investment decisions in this market environment, we now compare u_t^I with $u_t^\emptyset$. It is intuitive that investors are the households with the highest energy needs.

Lemma 2. *In period t, a household of type 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 section 2.9.4 in the appendix. □

So far, we have considered that investment decisions can vary with the period t. However, we show that a key feature of an EPC policy is that all investments are made during the initial period $t = 0$. Indeed, let us imagine that new investments are made at $t > 0$ by a household of type e. We can wonder why it did not carry out its investment in the previous period. A possible explanation is that the household just moved in. However, because of the perfect matching (lemma 1), it means that there is necessarily another household with type e who lived in an inefficient dwelling at period $t - 1$ (otherwise, it would have been able to purchase an efficient dwelling) so the question remains. On the cost side, investing in period t or $t - 1$ has the same cost I. Besides, there are two benefits in investing: energy savings and the price premium when selling the dwelling. Expected energy savings do not change from one period to another and only depends on the household type e. Price premium however can change if market conditions evolve. Because the supply of efficient dwellings is non decreasing, the price premium is non increasing. Thus, there are no additional benefits in investing later. We are now able to state the main proposition of this section.

Proposition 1 (EPC equilibrium)**.** *Under perfect information on energy performance, all investments in energy efficiency are made during the initial period $t = 0$ by households with type $e \geq \breve{e} = I(1 - \delta)$. In following periods, efficient dwellings are purchased by households with type $e \geq \tilde{e} = \breve{e} = I(1 - \delta)$. The time-invariant quantity of efficient dwellings in the*

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

Proof. See section 2.9.4 in the appendix. □

The intuition underlying this result is as follows. Lemma 1 implies that investing households anticipate that, if they move out in a next period, their home will be purchased by the highest 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 $e/(1-\delta)$.

Intuitively, the quantity of efficient dwellings increases when the discount rate decreases or when energy demand increases for the whole distribution[9], and it decreases when investment cost I increases.

Now that we have described the equilibrium path with an EPC policy, we can evaluate its policy relevance and cost-effectiveness.

Corollary 2 (EPC policy evaluation)**.** *A policy target* $(\bar{E}, \tau)$ *is reached by an EPC policy if and only if* $\bar{E} \geq E_{EPC} = \int_0^{I(1-\delta)} e \, \mathrm{d}F(e)$*. In this case, the EPC policy is optimal in terms of cost-effectiveness.*

Proof. See section 2.9.4 in the appendix. □

The first part of the result (reachable policy targets) is a straightforward consequence from proposition 1. Using equation (2.1) which gives the formula for per-period energy use, we obtain that $E_t = \int_0^{I(1-\delta)} e \, \mathrm{d}F(e)$ for all t with an EPC policy. It must be stressed that an important feature of an EPC policy is that the time horizon τ of a policy target becomes irrelevant because of the one-shot investment dynamic of the EPC equilibrium. The second part of the result (optimal cost-effectiveness) is due to the absence of market failure in our framework. EPC deals with information asymmetry and we don't take into account environmental externalities because we opted for a cost-effectiveness analysis.

[9] In more formal terms, for two distributions F_1 and F_2 of types 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*.

2.5 Equilibrium without EPC

The main difference with the certification case is that we now have a pooling equilibrium on the real estate market with $p_t^0 = p_t^1$. This greatly simplifies the analysis as the real estate market gives zero value to energy retrofit ($p_t^0 = p_t^1$) and incoming households are randomly assigned to the dwellings.

When making an investment decision, the households just need to compare the investment cost with the expected savings in their own energy consumption in the current and future periods . Household e will thus invest if:

$$I \leq e \times \sum_{k=1}^{\infty} (\delta(1-m))^k = \frac{e}{1-\delta(1-m)} \tag{2.7}$$

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 3. *When building energy performance is not certified, in any period, a household of type e living in an inefficient dwelling invests if $e \geq \hat{e}$ where $\hat{e} = I(1-\delta(1-m))$.*

Although individual investment incentives are lower than when there is certification at any period, 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 high types 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.
- Types higher 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 type 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 4. *When building energy performance is not certified, in period $t \geq 1$, the share of efficient dwellings is $q_t = 1 - F(\hat{e})[1 - m(1 - F(\hat{e}))]^{t-1}$. The overall level of energy investment flow is $I_t = mI(1 - F(\hat{e}))F(\hat{e})[1 - m(1 - F(\hat{e}))]^{t-1}$ and the overall level of energy consumption is $E_t = [1 - m(1 - F(\hat{e}))]^t \int_0^{\hat{e}} e \, \mathrm{d}F(e)$.*

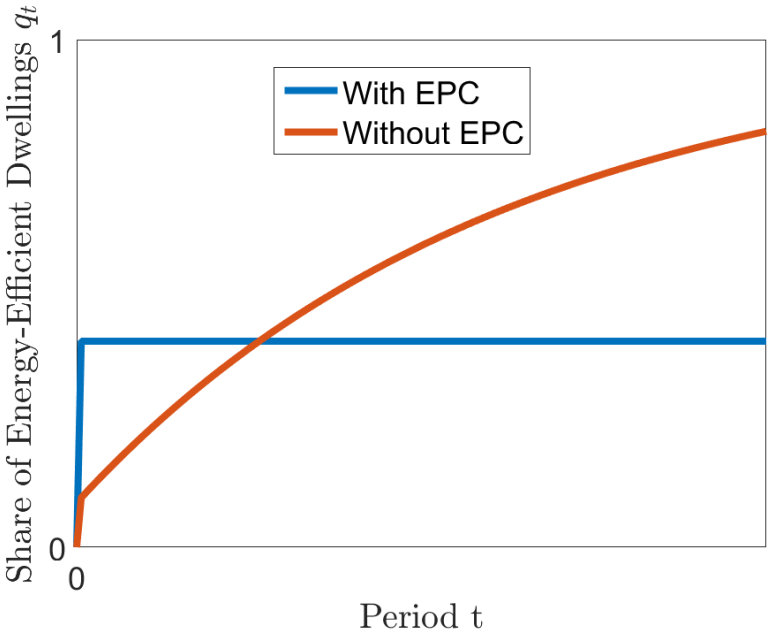
From lemma 4, we directly obtain the main proposition of this section.

Proposition 2 (Dynamic without certification)**.** *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: $q_t \to 1$. The levels of per-period investments and energy use converge to zero: $E_t \to 0$ and $I_t \to 0$.*

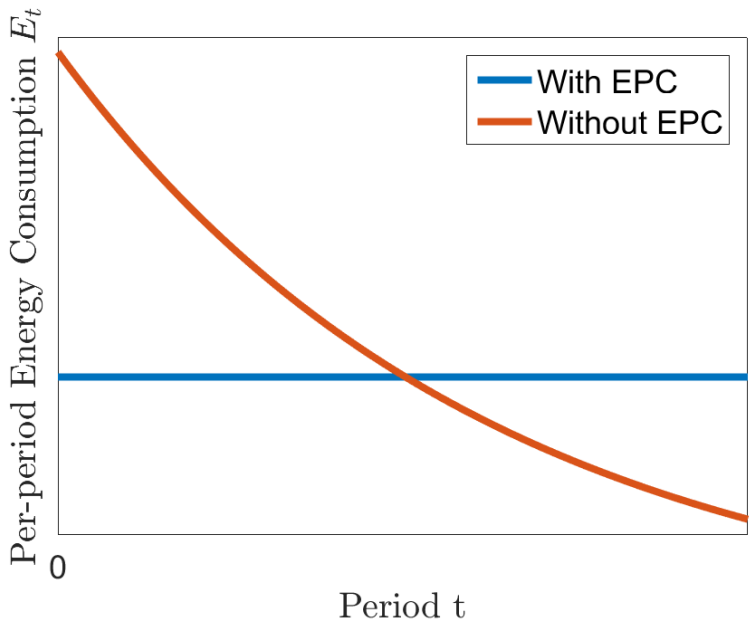
This dynamics is represented in Figure 2.2 which compares the evolution over time of the efficient building stock q_t and the per-period total energy use E_t with and without certification. Accounting for the dynamics of the building stock thus yields the counter-intuitive results that the absence of energy certification leads to more energy efficiency investments and less energy consumption in the long run. However, this achievement comes with two disadvantages. First, in the short run, the absence of certification always reduces less the energy consumption than with an EPC policy. Second, when a policy target $(\bar{E}, \tau)$ can be reached with and without certification, we showed with corollary 2 that the EPC policy is more cost-effective than in the absence of certification. The following corollary describes the policy targets that can be reached without certification.

Corollary 3 (Policy target without certification)**.** *A policy target $(\bar{E}, \tau)$ can be reached without certification if and only if: $[1 - m(1 - F(\hat{e}))]^\tau \int_0^{\hat{e}} e \, \mathrm{d}F(e) \leq \bar{E}$.*

Unlike with an EPC policy, the reachability of a policy target does depend on the time horizon τ when there is no certification. The further the time horizon is, the more likely the policy target will be reachable. The following result (straightforward from what precedes) gives more insights to analyze the policy relevance of introducing an EPC.



(a) Trajectories of efficient dwelling stock q_t



(b) Trajectories of per-period energy use E_t

Figure 2.2: Comparison of equilibrium dynamics with and without certification

Corollary 4. *Let us define*

$$\tau_{lim} = \frac{\ln\left(\frac{E_{EPC}}{\int_0^{\hat{e}} e \, \mathrm{d}F(e)}\right)}{\ln\left(1 - m(1 - F(\hat{e}))\right)}$$

For a policy target $(\bar{E}, \tau)$ such that $\tau \leq \tau_{lim}$, if it can be reached without certification, it can be reached with an EPC policy in a more cost-effective way. On the other hand, for any $\tau > \tau_{lim}$, we can find an energy consumption level $\bar{E}$ such that the policy target $(\bar{E}, \tau)$ can be reached without certification but not with an EPC policy.

Figure 2.3 compares the policy target that can be reached with and without certification and thus illustrates the previous result. The set of policy targets can be partitioned in four:

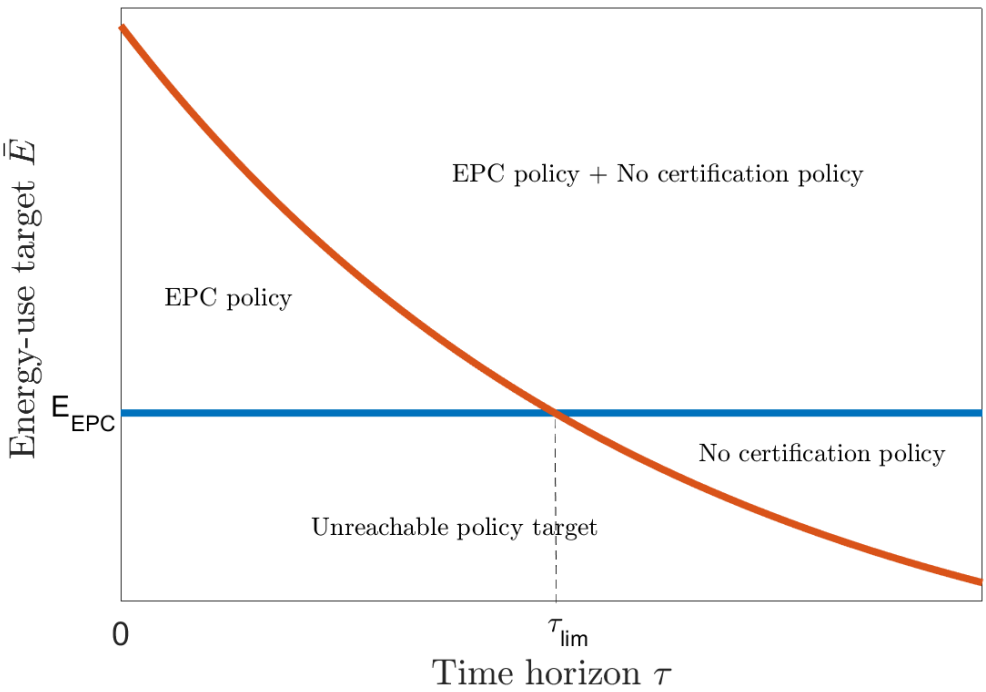


Figure 2.3: Reachable policy targets with and without certification

- policy targets only reached by an EPC policy. These are policy targets with a short time horizon and an energy consumption target greater that E_{EPC}.
- policy targets reached with and without certification. These are policy targets with a longer

time horizon and an energy consumption target greater than E_{EPC}. In this case, it is more relevant from a policy perspective to favor an EPC policy because it is more cost-effective.

- policy targets only reached without certification. These policy targets necessarily have both a long time horizon ($\tau > \tau_{lim}$) and a low energy consumption target ($\bar{E} < E_{EPC}$).
- policy targets that can't be reached in any case. These are policy targets with both a short time horizon and a low energy consumption target ($\bar{E} < E_{EPC}$).

Thus, τ_{lim} appears as a key indicator of the trade-off between a certification policy and a non-certification policy. A large τ_{lim} should lead policy-makers to favor certification whereas a small τ_{lim} should lead them to be cautious with certification.

We would like to know how τ_{lim} changes with the parameters of the model m, δ, I and F. However, the effect of each of these parameters taken separately is ambiguous. Thus, it is not possible to derive any general result for comparative statics on τ_{lim}.

2.6 Examples

2.6.1 Summer colony

Let us consider a town with two types of inhabitants: permanent residents who live there all year long and who have high energy needs $\bar{e} > I(1 - \delta(1 - m))$, and seasonal residents who only come during vacation and therefore have low energy needs $\underline{e} < I(1-\delta)$. This is typically the case of summer colonies such as Martha's Vineyard in the U.S.[10]. In this situation, whether there is certification or not, only permanent residents have incentives to invest in home energy retrofit. Thus, $\tau_{lim} = 0$ and the level of investments and energy consumption is the same at $t = 0$ with and without certification. As a result, it means that any policy objective that can be reached with certification can also be reached without certification, while the converse is not true. In the absence of other policy instruments, certification in this case has a detrimental effect on the level of investments in energy efficiency and on the energy consumption both in the short and the long term.

[10] According to a study of the Martha's Vineyard Commission in 2000, 56% of the Vineyard's 14,621 homes are seasonally occupied.

Nonetheless, if permanent residents have lower energy needs $\bar{e} \in [I(1-\delta), I(1-\delta(1-m))]$, the conclusion is reversed: there is no investment in the absence of certification, and only certification allows investments for dwellings occupied by permanent residents. In this case, we have $\tau_{lim} = +\infty$

2.6.2 Homogeneous residential community

Let us now examine a homogeneous residential community where the population is quite similar in its energy needs. As a matter of illustration, we can consider a retirement community with high energy needs $\bar{e} > I(1-\delta(1-m))$ because retired people spend a substantial amount of time at home, a commuter town with intermediaries energy needs $e \in [I(1-\delta), I(1-\delta(1-m))$ because inhabitants spend most of their daytime at work or at school for children, and a college town with low energy needs $\underline{e} < I(1-\delta)$ because students are more likely to trade a lower energy bill with a less cozy thermal comfort. In these three cases, certification has a positive or neutral impact on energy efficiency investments and energy consumption. The effect is neutral for the retirement community (all dwellings are retrofitted in any case) and for the college town (no investment made in any case), and is positive for the commuter town where certification triggers investments. In this latter case, we have $\tau_{lim} = +\infty$.

Examples considered in this section are obviously stylized examples and reality is far more complex. Nonetheless, they illustrate how important the dispersion of the distribution of energy needs is in our model. When energy needs are homogeneous, certification is always (weakly) better. When heterogeneity in energy needs is important and dispersion is high, this might no be the case and in the absence of other policy instruments, a policymaker might want to favor a no-certification policy.

2.7 Certification and other policy instruments

Policymakers have other instruments at hand that they can use concurrently to reach their policy target, among which carbon tax, subsidies and standards are the most popular.

2.7.1 Certification and carbon tax

Let us recall that we assume here a proportionality between energy use and carbon emission. Consequently, in our framework, a carbon tax is equivalent to a tax on energy. A household of type e in an dwelling of type θ has an energy bill of $(1-\theta)\cdot e$ per period. With a carbon tax λ, its energy bill becomes $(1-\theta)\cdot e\cdot(1+\lambda)$.

Let us consider a policy target $(\bar{E},\tau)$. Here again, the set of policy targets can be partitioned in four (figure 2.4 offers a graphical representation of this partition ; figures 2.3 and 2.4 are perfectly symmetric):

- Short-term ($\tau < \tau_{lim}$) modest policy target ($\bar{E} > E_{EPC}$) not reached without certification ($\bar{E} < 1-m(1-F(\hat{e}))]^{\tau}\int_0^{\hat{e}} e\,\mathrm{d}F(e)$). In this case, certification and carbon tax are *substitutes*: using certification exempts from using a carbon tax while in the absence of certification, the policy target cannot be reached without a carbon tax.

- Long-term ($\tau > \tau_{lim}$) ambitious ($\bar{E} < E_{EPC}$) policy target that can be reached without certification ($\bar{E} \geq 1-m(1-F(\hat{e}))]^{\tau}\int_0^{\hat{e}} e\,\mathrm{d}F(e)$). In this case, certification and carbon tax are *complements*: using certification forces to use a carbon tax while in the absence of certification, there is no need for a carbon tax.

- Very ambitious policy target ($\bar{E} < E_{EPC}$ and $\bar{E} < [1-m(1-F(\hat{e}))]^{\tau}\int_0^{\hat{e}} e\,\mathrm{d}F(e)$). In this case, carbon tax and certification might be complements or substitutes depending on the choice of parameters. In other words, depending on the choice of parameters, the carbon tax might be higher with or without certification.

- Very modest policy target ($\bar{E} > E_{EPC}$ and $\bar{E} > [1-m(1-F(\hat{e}))]^{\tau}\int_0^{\hat{e}} e\,\mathrm{d}F(e)$). In this case, a carbon tax is irrelevant whether there is certification or not.

Thus, depending on the policy target, certification and carbon tax can be substitutes or complements; they tend to be substitutes for short-term modest policy targets and complements for long-term ambitious policy targets.

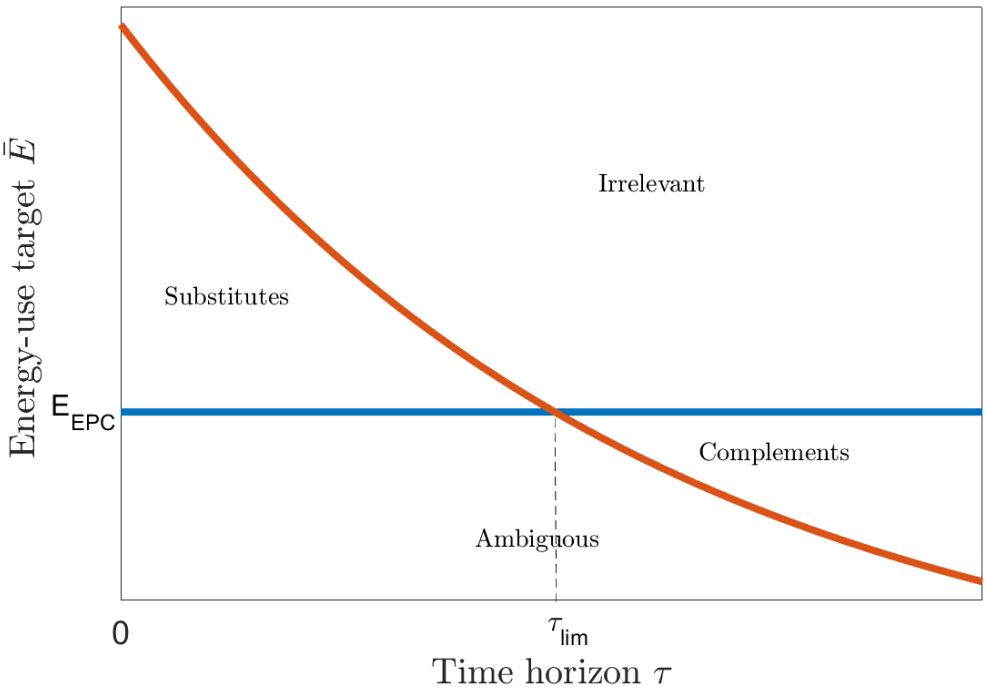


Figure 2.4: Complementary/substituability of a carbon tax/subsidy with certification

2.7.2 Certification and subsidy

Because energy consumption is inelastic in our framework, tax and subsidy are equivalent here[11]. Therefore, figure 2.4 also represents the policy targets for which certification and subsidy are complements and substitutes.

It is worth noting, that in the absence of certification, independently of any policy target, a second-best policy is to offer a subsidy on investment, or equivalently, to impose a tax on energy consumption. Indeed, in the absence of information an investment in home energy retrofit produces a positive externality on future households who will purchase the dwelling. That positive externality needs to be internalized via a subsidy $\mu = \frac{\delta m \int_0^{+\infty} e \, \mathrm{d}F(e)}{(1-\delta)(1-\delta(1-m))}$ or a non-linear energy consumption tax $\lambda(e) = \frac{\delta m \int_0^{+\infty} e \, \mathrm{d}F(e)}{(1-\delta)e}$.

2.7.3 Certification and Standards

In our framework, a standard policy is to impose an energy performance $\theta = 1$ for all buildings. Therefore, certification and standard are substitutes in essence: if a standard policy is used, certification becomes irrelevant. In practice, energy performance is not binary and therefore certification and standards can be used concomitantly on different segments of energy performance. A standard ensures a floor level of energy performance and certification is used for higher levels. In our theoretical framework, because of the cost-effectiveness of certification due to the allocation efficiency, it follows that it is not desirable to use standards more than necessary (i.e. to set the energy performance floor level higher than necessary) to reach a policy target.

2.8 Conclusion

We developed a theoretical framework which allows to analyze the dynamic consequences of building energy performance certification via EPCs on energy consumption, GHG emissions, and home energy efficiency investments. Within our framework, we showed that EPCs are effective in the short term, with a sharp increase in investments which is accompanied with a decrease in

[11] Even in our framework, this equivalence has nevertheless some limits. An obvious one is that tax and subsidy are different from a public finance perspective. A second difference which is more subtle concerns the dynamic incentives if the introduction of a tax/subsidy is delayed at a period $t > 0$. While a subsidy provides incentives to delay investments at time t to benefit from it, a tax does not.

energy consumption and GHG emissions. Also, EPCs ensure optimal cost-effectiveness. However, in the long term, allocation efficiency enabled by EPCs lead to a stop in investments and a stagnation in energy consumption and GHG emissions while investments and energy consumption decrease continue when there is no certification. Besides, depending on the ambition and the time horizon of policy targets, EPCs can be either a substitute or a complement to carbon tax and subsidies: substitute for short-term low-ambition target, complement for long-term high-ambition targets.

This first theoretical attempt to investigate the effects of the EPCs calls for empirical work to supplement and support our results. We see at least two directions for future research. The first one is to assess empirically the mechanisms which form the base of our model. In particular, how EPCs increase buyers' information and to which extent energy efficiency is a non factor in moving decisions. A second direction is to feed the parameters of our model with real-world data in order to compute and compare the equilibrium that we derive. In particular, it would be very useful from a policy perspective to compute a value for τ_{lim}.

Although our paper is purely theoretical and needs empirical work to provide robust and scientific insights, it encourages policy-maker to be cautious about what they can expect from information. Our theoretical development concludes that if information can improve cost-effectiveness, information alone is likely to be insufficient (and in some cases might even be detrimental) to reach ambitious environmental policy targets, and needs to be considered within a mix of other classical environmental policy instruments.

2.9 Appendix

2.9.1 Alternative policy objectives

Cumulative emissions

From a climatologist perspective, it might have more sense to set cumulative emission objectives because GHG emissions stay in the atmosphere from one year to another (Intergovernmental Panel on Climate Change, 2014). Let us recall that we assume here a proportionality between

energy use and carbon emission. Using an exponential decay[12] factor $\nu \in (0,1)$, cumulative emission in our model at time t is given by:

$$S_t = \sum_{k=0}^{t} \nu^{t-k} E_k = \sum_{k=0}^{t} \nu^{t-k} \int_0^{+\infty} \mathbb{P}_k(\theta = 0|e) e \, \mathrm{d}F(e)$$

A policy target becomes a couple $(\bar{S}, \tau)$ where $\bar{S}$ is the cumulative emission level and τ is the time of achievement. The target is reached if $S_\tau \leq \bar{S}$.

Equilibrium with an EPC The following result is a direct consequence from proposition 1 which describes the equilibrium with an EPC:

Corollary 5 (EPC equilibrium)**.** *Under perfect information on energy performance, the stock of emissions is given by:* $S_t = \frac{1-\nu^{t+1}}{1-\nu} E_{EPC} = \frac{1-\nu^{t+1}}{1-\nu} \int_0^{I(1-\delta)} e \, \mathrm{d}F(e)$.

Unlike per-period emission, cumulative emissions vary when buyers are informed about energy performance: they increase toward a finite limit $\frac{E_{EPC}}{1-\nu}$. As a result, whether the policy target is reached or not also depends on the deadline τ, which was not the case previously.

Equilibrium without EPC The following result is a direct consequence from lemma 4 which describes the equilibrium without EPC:

Corollary 6. *When building energy performance is not certified, the stock of emissions is* $S_t = \frac{\nu^{t+1} - A^{t+1}}{\nu - A} \int_0^{\hat{e}} e \, \mathrm{d}F(e)$ *where* $A = [1 - m(1 - F(\hat{e}))]$ *when* $A \neq \nu$*, and* $S_t = \nu^t (t+1) \int_0^{\hat{e}} e \, \mathrm{d}F(e)$ *when* $A = \nu$*. In particular,* S_t *converges to zero:* $S_t \to 0$.

$A = [1 - m(1 - F(\hat{e}))]$ is the exponential decay factor for per period emissions ($E_t = A^t \int_0^{\hat{e}} e \, \mathrm{d}F(e)$). From corollary 6, we can derive results which provide more insights on the dynamics of cumulative emissions S_t in the absence of certification.

Corollary 7. *When building energy performance is not certified, if* $A, \nu > \exp(-1)$*, then* S_t *is increasing on* $[0, t_1]$ *and decreasing on* $[t_1, +\infty)$ *with* $t_1 = \frac{\ln\left(\frac{\ln A}{\ln \nu}\right)}{\ln\left(\frac{\nu}{A}\right)} - 1$ *when* $A \neq \nu$*, and* $t_1 = -1 - \frac{1}{\ln \nu}$ *if* $A = \nu$*. In contrast, if* $A, \nu < \exp(-1)$*, then* S_t *is decreasing on* $[0, +\infty)$*. For other couples* (A, ν)*,* S_t *is either decreasing on* $[0, +\infty)$*, or increasing and then decreasing.*

[12] This is obviously a simplification as greenhouse gas dynamics in the atmosphere is very complex.

Proof. Differentiate S_t with respect to t and solve the inequality $\frac{\mathrm{d}S_t}{\mathrm{d}t} > 0$. □

Corollary 7 invites us to distinguish two situations. In the first case $(A, \nu > \exp(-1))$, per-period emissions decrease slowly $(A > \exp(-1))$ and GHG atmospheric lifetime is high $(\nu > \exp(-1))$. Thus, cumulative emissions increase and reach a maximum at t_1 before declining. The second case is the opposite: per-period emissions decrease rapidly $(A < \exp(-1))$ and GHG atmospheric lifetime is low $(\nu < \exp(-1))$. Thus, right from $t = 0$, additional emissions do not compensate the decay of the stock of emissions and S_t decreases from the beginning.

Comparison with and without EPC In corollary 4 was defined the time threshold τ_{lim} which allowed to analyze the temporal relevance of an EPC policy compared to a no certification policy. We can define a similar threshold for policy objectives based on cumulative emissions.

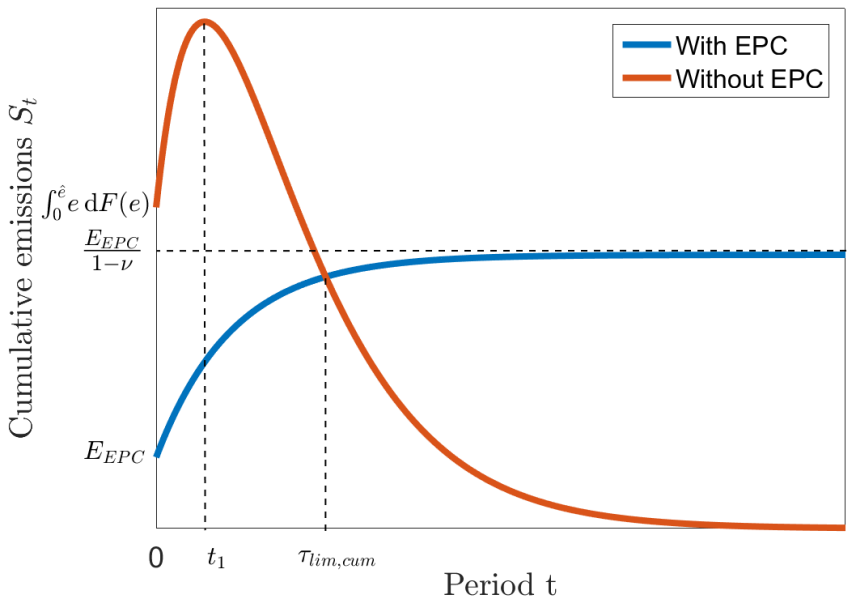
Corollary 8. *The equation:*

$$\frac{1-\nu^{t+1}}{1-\nu} E_{EPC} = \begin{cases} \frac{\nu^{t+1}-A^{t+1}}{\nu-A} \int_0^{\hat{e}} e \, \mathrm{d}F(e) \text{ if } A \neq \nu \\ \nu^t (t+1) \int_0^{\hat{e}} e \, \mathrm{d}F(e) \text{ if } A = \nu \end{cases}$$

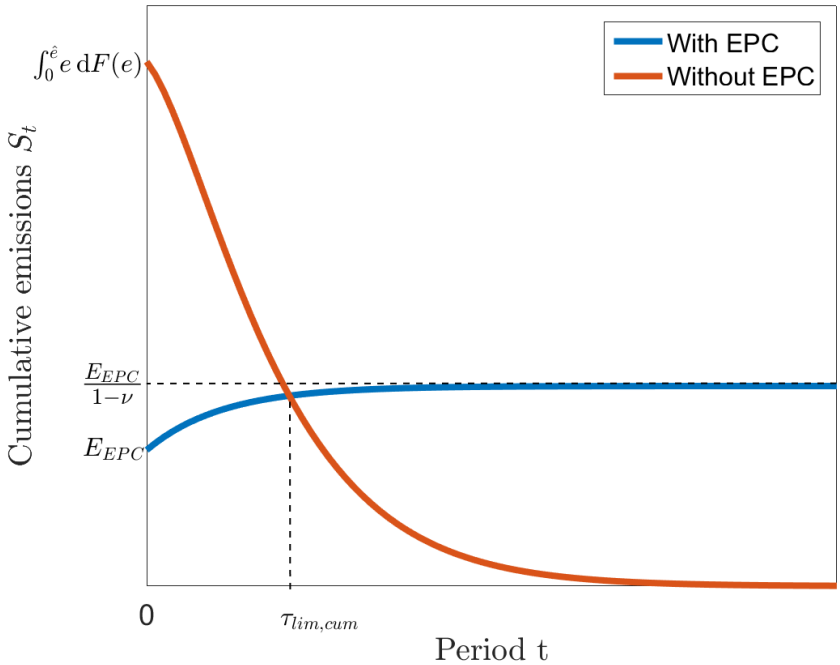
has a unique solution in t that we denote $\tau_{lim,cum}$. For a policy target $(\bar{S}, \tau)$ such that $\tau \leq \tau_{lim,cum}$, if it can be reached without certification, it can be reached with an EPC policy in a more cost-effective way. On the other hand, for any $\tau > \tau_{lim}$, we can find a cumulative emission level $\bar{S}$ such that the policy target $(\bar{S}, \tau)$ can be reached without certification but not with an EPC policy.

Proof. The proof relies on the study of the function $t \mapsto \frac{\nu^{t+1}-A^{t+1}}{\nu-A} \int_0^{\hat{e}} e \, \mathrm{d}F(e) - \frac{1-\nu^{t+1}}{1-\nu} E_{EPC}$ if $A \neq \nu$ and $t \mapsto \nu^t (t+1) \int_0^{\hat{e}} e \, \mathrm{d}F(e) - \frac{1-\nu^{t+1}}{1-\nu} E_{EPC}$ if $A = \nu$. It is continuous, strictly positive for $t = 0$, strictly negative when t goes to infinity, and it is either strictly decreasing on $[0, +\infty)$, or non-decreasing and then strictly decreasing depending on the value of the parameters. Consequently, it has a unique root. The cost-effectiveness is due to the absence of market failure in our framework when there is an EPC. □

Figure 2.5 represents the evolution of cumulative emissions with and without certification in the two situations identified in corollary 7. In both cases, we recognize the same four sectors as in figure 2.3 for the reachable policy targets.



(a) Cumulative emissions when $A, \nu > \exp(-1)$



(b) Cumulative emissions when $A, \nu < \exp(-1)$

Figure 2.5: Comparison of equilibrium dynamics with and without certification for cumulative emissions

Here again, $\tau_{lim,cum}$ appears as a key indicator of the trade-off between a certification policy and a non-certification policy. A large $\tau_{lim,cum}$ should lead policy-makers to favor certification whereas a small $\tau_{lim,cum}$ should lead them to be cautious with certification.

Like in section 2.5, we would like to know how $\tau_{lim,cum}$ changes with the parameters of the model m, δ, I, F and ν. However, exactly like in section 2.5, the effect of each of these parameters taken separately is ambiguous. Thus, it is not possible to derive any general result for comparative statics on $\tau_{lim,cum}$.

Investment intensity

Policymakers can also set targets for investments intensity. For instance, France has a renovation target of 500,000 dwellings per year from 2017 onward. From an environmental policy perspective, these targets can be considered as intermediary goals and not final goals[13]. As shown in propositions 1 and 2, investment intensity is very different with and without certification in our model. With certification, investments stop after the initial period while they are maintained at a decreasing rate when there is no certification. Thus, certification only goes against an investment intensity objective. One way to sustain investment while certifying building energy performance is to increase the carbon/energy tax at each period.

2.9.2 Rental case

Our results can be easily extended to the rental market where tenants rent their dwellings to landlords. The conditions for our results to hold in the rental case are:

- Tenants pay the energy bill
- Tenants are allowed to carry out energy retrofit in their dwelling or landlords and tenants can negotiate (no transaction cost) so that the landlord carry out energy retrofit in the dwelling in exchange for an increase in the rent.

In France, these conditions are commonplace: legislation encourages an individualized energy bill and allows both landlords and tenants to carry out energy retrofit work if they can find

[13] Although one can imagine that targeting an investment rate can have other purposes with non-environmental rationales such as a sustained economic activity and employment in the renovation sector

an arrangement. However, our framework is ill-suited for situations such as collective heating with no individualized energy bill where free riding and moral hazard can play a significant role. Besides, we expect parameters of our model to be substantially different in the rental case compared to the house-owner case. For instance, renters tend to move more frequently which corresponds to a higher m.

2.9.3 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 in previous periods. Before $t_{EPC} - 1 \geq 0$, their investment behavior is thus not influenced by future signals on the real estate market[14]. Second, at the beginning of period t_{EPC}, the share $q_{t_{EPC}}$ of energy-efficient buildings and the allocation correspond to those of the trajectories described in lemma 4. Under these assumptions, we derive the following result:

Proposition 3 (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 $E_{EPC} > E_\infty > 0$.*

Proof. Proof is in section 2.9.4 of the appendix. □

At the end of period t_{EPC}, there remains one inefficiency: low types who still live in efficient dwellings. This imperfect matching will progressively vanishes in the next periods when the 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 (or that moving costs are greater than I). That is, we rule out cases where low types living in efficient dwellings would all move

[14]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.

in inefficient dwellings in the city, thereby increasing their surplus by selling at a high price to high types.

Exactly like in corollary 4, we can define a time threshold τ_{lim} which allowed to analyze the temporal relevance of an EPC policy compared to a no certification policy.

Corollary 9. *There exists*[15] $\tau_{lim} \in (t_{EPC} - 1, +\infty)$ *which verifies the following properties:*

- *For a policy target* $(\bar{E}, \tau)$ *such that* $\tau \leq \tau_{lim,cum}$*, if it can be reached without certification, it can be reached with an EPC policy in a more cost-effective way.*
- *On the other hand, for any* $\tau > \tau_{lim}$*, we can find an energy consumption level* $\bar{E}$ *such that the policy target* $(\bar{E}, \tau)$ *can be reached without certification but not with an EPC policy.*

Proof. Proof is in section 2.9.4 of the appendix. □

Figure 2.6 represents the evolution of energy consumption with and without a delayed certification. We recognize the same four sectors as in figure 2.3 for the reachable policy targets.

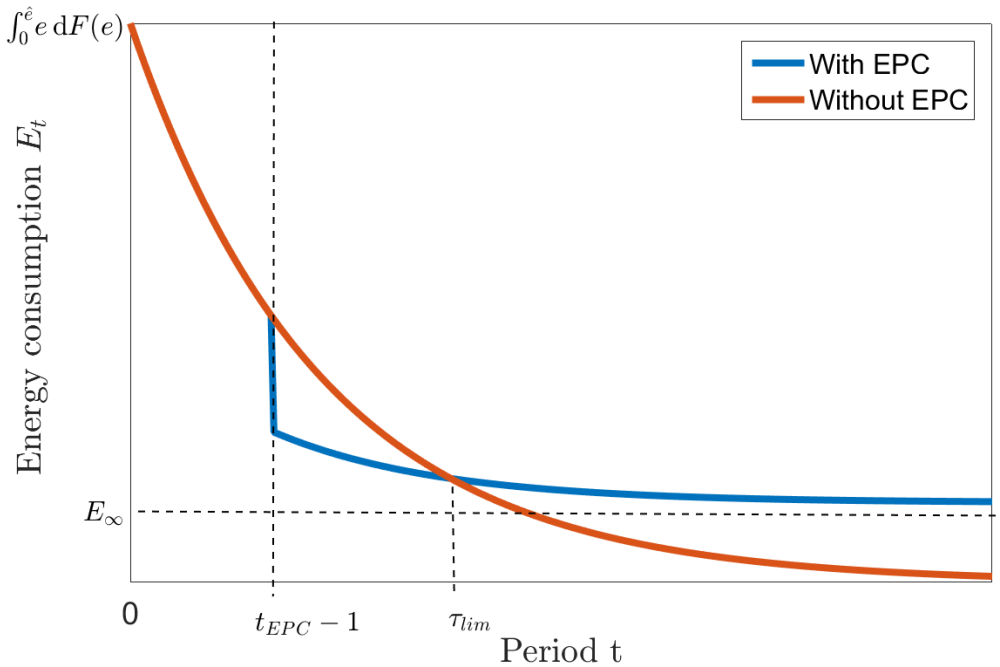


Figure 2.6: Trajectories of per-period energy use E_t with a delayed EPC introduction

[15] if we impose τ_{lim} to be an integer, it is unique.

$\tau_{lim} - t_{EPC}$ appears as a key indicator of the trade-off between a certification policy and a non-certification policy. A large $\tau_{lim} - t_{EPC}$ should lead policy-makers to favor certification whereas a small $\tau_{lim} - t_{EPC}$ should lead them to be cautious with certification. Like in section 2.5, we would like to know how τ_{lim} changes with the parameters of the model m, δ, I, F and t_{EPC}. However, exactly like in section 2.5, the effect of each of these parameters taken separately is ambiguous. Thus, it is not possible to derive any general result for comparative statics on τ_{lim}.

2.9.4 Proofs

Proof of lemma 1

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 (2.3). Last, from equation (2.4) 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 $\tilde{e}$.

Proof of lemma 2

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 1 then implies that $I < p_t^1 - p_t^0$,

which is absurd.

Proof of proposition 1

To prove proposition 1, we need to derive a couple of preliminary results. Before that, let us call $\Delta_t(e) = u_t^I(e) - u_t^{\emptyset}(e)$ the utility gain of investing at period t for a household of type e. By definition of $\breve{e}_t$ in lemma 2, we have $\Delta_t(\breve{e}_t) = 0$. Moreover:

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

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:

$$\Delta_t(e) = e - I(1-\delta) + \delta(1-m)\min(0, \Delta_{t+1}(e)) + \delta m \min(0, \Delta_{t+1}(\tilde{e}_{t+1})) \tag{2.8}$$

We are now ready to derive additional lemmas which will allow us to prove proposition 1.

Lemma 5. *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 1). 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 6. *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:

$$\forall x, y \in \mathbb{R}, \min(0, x) - \min(0, y) \leq \max(0, x - y) \tag{2.9}$$

Lets us arbitrarily pick $E \in [\tilde{e}_1, +\infty)$. Given $t \in \mathbb{N}$ and $e \in [0, E]$, it follows from equation 2.8 and the above property:

$$\begin{aligned}
\Delta_{t+1}(e) - \Delta_t(e) =& \delta(1-m)\left(\min(0, \Delta_{t+2}(e)) - \min(0, \Delta_{t+1}(e))\right) \\
&+ \delta m \left(\min(0, \Delta_{t+2}(\tilde{e}_{t+2})) - \min(0, \Delta_{t+1}(\tilde{e}_{t+1}))\right) \\
\leq& \delta(1-m) \max(0, \Delta_{t+2}(e) - \Delta_{t+1}(e)) \\
&+ \delta m \max(0, \Delta_{t+2}(\tilde{e}_{t+2}) - \Delta_{t+1}(\tilde{e}_{t+1}))
\end{aligned} \tag{2.10}$$

$\Delta_{t+2}(e)$ 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 1), it follows $\Delta_{t+2}(\tilde{e}_{t+2}) \leq \Delta_{t+2}(\tilde{e}_{t+1})$. Equation 2.10 becomes:

$$\begin{aligned}
\Delta_{t+1}(e) - \Delta_t(e) \leq& \delta(1-m) \max(0, \Delta_{t+2}(e) - \Delta_{t+1}(e)) \\
&+ \delta m \max(0, \Delta_{t+2}(\tilde{e}_{t+1}) - \Delta_{t+1}(\tilde{e}_{t+1}))
\end{aligned} \tag{2.11}$$

Let us define the sequence a_t by:

$$a_t := \sup_{e \in [0, E]} \{\max(0, \Delta_{t+2}(e) - \Delta_{t+1}(e)) : e \in [0, E]\} \tag{2.12}$$

Because for any $t \in \mathbb{N}$, $-I \leq \Delta_t(e) \leq e \leq E$ (straightforward from equation 2.8), a_t is real and $\forall t \in \mathbb{N}, 0 \leq a_t \leq E + I$. From equation 2.11, 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:

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

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

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

When q 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 10. *When incoming households are perfectly informed about dwellings' energy performance,, $\breve{e}_t$ is non decreasing.*

Proof. Straightforward from lemma 6, 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 4 (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 5, corollary 10 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 7. *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 6 shows that $\Delta_t(e)$ is non increasing. From proposition 4, 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 6 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 5 (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 4, it follows: $q_1 = 1 - F(\breve{e})$. From lemma 1, 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 2.8 yields:

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

□

Proof of corollary 1

The reachability of the policy target is a direct consequence of proposition 1. We will here only prove the optimal cost-effectiveness of an EPC policy. Let us recall the total cost function defined in equation 2.2:

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

Let us now consider the minimization problem

$$\begin{aligned} \underset{q_t, x_t(.)}{\text{minimize}} \quad & \sum_{t=0}^{\infty} \delta^t \left(\int_0^{+\infty} x_t(e) e \, \mathrm{d}F(e) + (q_{t+1} - q_t) I \right) \\ \text{subject to} \quad & 0 \leq x_t(e) \leq 1, \ e \in [0, +\infty) \text{ (probability weight)} \\ & \int_0^{+\infty} x_t(e) \, \mathrm{d}F(e) = 1 - q_{t+1} \text{ (stock conservation)} \\ & q_t \leq q_{t+1} \text{ (non decreasing stock)} \end{aligned} \tag{P}$$

Our model yields an output $(q_t, \mathbb{P}_t(\theta = 0|e))$ which is in the feasible set of the above problem. Our proof consists in showing that the perfect information solution $(1 - F(I(1-\delta)), \mathbb{1}_{e \leq I(1-\delta)})$ is a solution of this maximization problem.

First, let us show that the feasible set can be reduced to elements of the form $(q_t, \mathbb{1}_{e \leq e_t})$ where (e_t) is non increasing. Let us consider a feasible solution $(q_t, x_t(e))$. For any t, we can define the function $\varphi_t(y) := q_{t+1} - \int_0^{+\infty} \mathbb{1}_{e \geq y} \, \mathrm{d}F(e)$. φ_t is strictly increasing, $\varphi_t(0) = q_{t+1} - 1 \leq 0$ and

$\lim_{y\to+\infty}\varphi_t(y) = q_{t+1} \geq 0$. Therefore, the equation $\varphi_t(y) = 0$ has a unique solution denoted e_t, which might be $+\infty$, and $(q_t, \mathbb{1}_{e\leq e_t})$ is a feasible solution of problem P with $(e_t)_t$ non increasing. Assuming $e_t < +\infty$, let us now define the two functions $F_t^A(z) := \frac{1}{q_{t+1}}\int_0^z \mathbb{1}_{e\leq e_t}\,\mathrm{d}F(e)$ and $F_t^B(z) := \frac{1}{q_{t+1}}\int_0^z x_t(e)\,\mathrm{d}F(e)$. F_t^A and F_t^B are cumulative distribution functions and it is easy to see that the distribution associated to F_t^B has (weak) first-order stochastic dominance over the one associated to F_t^A. It follows: $\int_0^{+\infty} x_t(e)e\,\mathrm{d}F(e) \geq \int_0^{+\infty}\mathbb{1}_{e\leq e_t}e\,\mathrm{d}F(e)$. The previous inequality still holds when $e_t = +\infty$ (the two integrals are equal to zero). Thus, the feasible solution $(q_t, x_t(e))$ is (weakly) dominated by the feasible solution $(q_t, \mathbb{1}_{e\leq e_t})$ in the minimization problem P.

We can therefore restrict the feasible set to solutions of the form $(q_t, \mathbb{1}_{e\leq e_t})$ where (e_t) is non increasing. Moreover, we use the convention $e_{-1} = +\infty$. Let us rearrange the terms of the objective function in the following way:

$$
\begin{aligned}
&\sum_{t=0}^{\infty}\delta^t\left(\int_0^{+\infty} x_t(e)e\,\mathrm{d}F(e) + (q_{t+1}-q_t)I\right)\\
=&\sum_{t=0}^{\infty}\delta^t\left(\int_0^{+\infty} e\,\mathrm{d}F(e) - \int_{e_t}^{+\infty} e\,\mathrm{d}F(e)\right) + \sum_{t=0}^{\infty}\delta^t(q_{t+1}-q_t)I\\
=&\frac{1}{1-\delta}\int_0^{+\infty} e\,\mathrm{d}F(e) - \sum_{t=0}^{\infty}\delta^t\sum_{k=0}^{t}\int_{e_k}^{e_{k-1}} e\,\mathrm{d}F(e) + \sum_{t=0}^{\infty}\delta^t\left(\int_{e_t}^{+\infty} 1\,\mathrm{d}F(e) - \int_{e_{t-1}}^{+\infty} 1\,\mathrm{d}F(e)\right)I\\
=&\frac{1}{1-\delta}\int_0^{+\infty} e\,\mathrm{d}F(e) - \sum_{t=0}^{\infty}\sum_{k=t}^{\infty}\delta^k\int_{e_t}^{e_{t-1}} e\,\mathrm{d}F(e) + \sum_{t=0}^{\infty}\delta^t I\int_{e_t}^{e_{t-1}} 1\,\mathrm{d}F(e) \text{ (by reorderring the summation)}\\
=&\frac{1}{1-\delta}\int_0^{+\infty} e\,\mathrm{d}F(e) - \sum_{t=0}^{\infty}\int_{e_t}^{e_{t-1}} e\,\mathrm{d}F(e)\sum_{k=t}^{\infty}\delta^k + \sum_{t=0}^{\infty}\delta^t\int_{e_t}^{e_{t-1}} I\,\mathrm{d}F(e)\\
=&\frac{1}{1-\delta}\int_0^{+\infty} e\,\mathrm{d}F(e) + \sum_{t=0}^{\infty}\delta^t\left(\int_{e_t}^{e_{t-1}}\left[-\frac{e}{1-\delta}+I\right]\mathrm{d}F(e)\right)
\end{aligned}
$$

Written this way, it is now clear that the non increasing sequence (e_t) which minimizes the cost function is the constant sequence (e^*) where $\frac{e^*}{1-\delta} = I$, that is the EPC equilibrium.[16]

[16]For a feasible solution $(q_t, \mathbb{1}_{e\leq e_t})$, q_{t+1} is given by e_t and the stock conservation constraint in problem P. Consequently, it is sufficient to denote a feasible solution by a sequence (e_t).

Proof of proposition 3 and corollary 9

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 2.4, 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 2.4, 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 1). 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:

$$\frac{e}{1 - \delta(1 - m)} + \frac{\delta m}{1 - \delta(1 - m)} \frac{F^{-1}(1 - q_{t_{EPC}})}{1 - \delta} \tag{2.13}$$

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 4), 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:

$$q_{t_{EPC}} = 1 - F(\breve{e})(1 - m(1 - F(\hat{e})))^{t_{EPC}-1} \tag{2.14}$$

Inserting equation 2.14 in the expression 2.13 and subtracting the cost of investment I, we obtain a net gain of investing for a household of type e equal to:

$$-I + \frac{e}{1 - \delta(1 - m)} + \frac{\delta m}{(1 - \delta(1 - m))(1 - \delta)} F^{-1}\left(F(\breve{e})(1 - m(1 - F(\hat{e})))^{t_{EPC}-1}\right) \tag{2.15}$$

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:

$$I = \frac{\breve{e}}{1-\delta(1-m)} + \frac{\delta m}{(1-\delta(1-m))(1-\delta)} F^{-1}\left(F(\breve{e})(1-m(1-F(\hat{e})))^{t_{EPC}-1}\right) \tag{2.16}$$

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

$$\tilde{e} = F^{-1}(1-q_{t_{EPC}}) = F^{-1}(F(\breve{e})(1-m(1-F(\hat{e})))^{t_{EPC}-1}) \tag{2.17}$$

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 2.13 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 2.14, 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 $t \in [t_{EPC}-1, +\infty)$:

$$E_t = \int_0^{\tilde{e}} e \,\mathrm{d}F(e) + (1-m)^{t+1-t_{EPC}} \left(A^{t_{EPC}-1} \int_0^{\breve{e}} e \,\mathrm{d}F(e) - \int_0^{\tilde{e}} e \,\mathrm{d}F(e) \right) \tag{2.18}$$

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:

$$E_t = A^t \int_0^{\hat{e}} e \,\mathrm{d}F(e) \tag{2.19}$$

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):

$$\int_0^{\tilde{e}} e \,\mathrm{d}F(e) + (1-m)^{t+1-t_{EPC}} \left(A^{t_{EPC}-1} \int_0^{\breve{e}} e \,\mathrm{d}F(e) - \int_0^{\tilde{e}} e \,\mathrm{d}F(e) \right) = A^t \int_0^{\hat{e}} e \,\mathrm{d}F(e) \tag{2.20}$$

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:

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

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.

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Chapter 3

Energy Performance Certificates and Investments in Building Energy Efficiency: a Simulation-Based Analysis

This chapter is a joint work with Pierre Fleckinger and Matthieu Glachant.

Abstract

In the European Union, Energy Performance Certificates (EPCs) provide potential home buyers or tenants with information on a property's energy performance. By mitigating informational asymmetries on real estate markets, EPCs are expected to increase incentives to invest in energy retrofit and improve the matching between households energy profiles and building energy performance, thus reducing energy consumption. We perform the first simulation-based analysis which focuses on the evaluation of the effects of an EPC policy on the energy performance of the building stock and on the residential energy consumption in the short and long term in the French context. We find that an EPC policy requires moderate investment cost, moderate to high energy savings, and a low discount rate to be effective. Besides, the more heterogeneous is individual energy demand, the lower energy

consumption is under EPC. Our simulations also suggest that the scenario with energy reduction under EPC is very much more likely. These findings support the idea that EPC needs to be supplemented by other policy instruments including carbon taxes, energy retrofit subsidies, and low-interest energy retrofit loans.

Dans l'Union européenne, le diagnostic de performance énergétique (DPE) fournit aux acheteurs ou locataires potentiels des informations sur la performance énergétique d'une propriété. En atténuant les asymétries d'information sur les marchés immobiliers, le DPE devrait inciter davantage les ménages à investir dans l'amélioration de l'efficacité énergétique et améliorer l'adéquation entre les profils énergétiques des ménages et la performance énergétique des bâtiments, réduisant ainsi la consommation d'énergie. Nous réalisons la première analyse par simulation qui porte sur l'évaluation des effets d'une politique de DPE sur la performance énergétique du parc immobilier et sur la consommation énergétique résidentielle à court et long terme dans le contexte français. Nous constatons qu'une politique de DPE exige des coûts d'investissement modérés, des économies d'énergie modérées à élevées et un faible taux d'actualisation pour être efficace. En outre, plus la demande d'énergie est dispersée entre les ménages, moins une politique de DPE est efficace. Nos simulations apaisent également les craintes que le DPE puisse être préjudiciable à la réduction de la consommation d'énergie à long terme. Ces résultats appuient l'idée qu'une politique de DPE est pertinente dans le cadre d'un ensemble complémentaire d'instruments de politique publique, notamment la taxe carbone, les subventions à la rénovation énergétique et les prêts à taux subventionné.

3.1 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 Union 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 30% target for 2030.

Energy taxation is the primary policy strategy to reduce energy use, but it is usually combined with sector-specific policies. This is particularly true for buildings, which are responsible for a sizable share of total energy use (e.g. 40% in the EU). Many countries grant tax credits and other subsidies to energy retrofits of existing buildings. Building codes also include energy performance provisions for new buildings.

Another popular policy approach is to provide potential buyers or tenants with information on the energy performance. In the European Union, so-called Energy Performance Certificates (EPCs) give information on a property's typical energy use and energy cost, an energy efficiency rating from A (most efficient) to G (least efficient), practical advice on improving such performance. Their publication is compulsory in all advertisements for the sale or rental of buildings since 2007. Figure 3.1 shows an example of EPC. 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 performance 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 informational asymmetries, EPCs are primarily expected to improve the matching between properties with heterogeneous energy performance and households with heterogeneous energy needs on the real estate market. 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 lesser efficient properties. EPCs also raise the incentives to invest in energy efficiency as the price of energy-efficient properties is higher than that of inefficient ones. These two mechanisms are expected to reduce energy use and GHG emissions in a cost-effective way.

Fleckinger et al. (2018) developed a theoretical model which examines the impact of EPCs on the level of energy use and investments in energy retrofit. The model describes how the building stock of a city evolves over time. They find that the implementation of an EPC policy leads to a surge in retrofit investments in the short term followed by a termination in retrofitting due

Energy Performance Certificate

SAP

17 Any Street, Any Town, County, YY3 5XX	Dwelling type: Date of assessment: Date of certificate: Reference number: Total floor area:	Detached house 02 February 2007 [dd mmmm yyyy] 0000-0000-0000-0000-0000 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.

Energy Efficiency Rating

	Current	Potential
Very energy efficient - lower running costs		
(92-100) A		
(81-91) B		
(69-80) C		73
(55-68) D		
(39-54) E		
(21-38) F	37	
(1-20) G		
Not energy efficient - higher running costs		

England & Wales EU Directive 2002/91/EC

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.

Environmental Impact (CO_2) Rating

	Current	Potential
Very environmentally friendly - lower CO_2 emissions		
(92-100) A		
(81-91) B		
(69-80) C		69
(55-68) D		
(39-54) E		
(21-38) F	31	
(1-20) G		
Not environmentally friendly - higher CO_2 emissions		

England & Wales EU Directive 2002/91/EC

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.

energy saving recommended

Certification mark

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**

Page 1 of 6

Figure 3.1: Example of an energy performance certificate

to matching efficiency between households energy profiles and building energy performance. In the long term, they find that there is a time after which energy consumption becomes lower in a scenario where an EPC policy is not implemented because investment in retrofitting continues in this case due to matching inefficiency between household energy profile and building energy performance.

We calibrate the input parameters of the model developed in Fleckinger et al. (2018) with data mostly from the French context. We then perform simulations and sensitivity analysis to assess the effects of the different input parameters of the model on the effectiveness of an EPC policy. We find that an EPC policy requires moderate investment cost, moderate to high energy savings, and a low discount rate to be effective. Besides, the more dispersion there is in energy demand among households, the less effective is an EPC policy. Last, our simulations quiet down worries that EPC could be detrimental to decrease energy consumption and stimulate energy efficiency investments in the long term.

The remainder of the paper is organized as follows: section 3.2 recalls the setting and the main results of the model developed by Fleckinger et al. (2018), section 3.3 presents the calibration of the input parameters of the model, section 3.4 discusses the results of the simulations , and section 3.5 concludes.

Literature Review We contribute to the economic literature on energy labeling of buildings with the first simulation-based study which focuses on building energy performance labeling's impact on retrofit investments and energy consumption in the short and long term. There is a large body of empirical literature which focuses on the impact of building energy performance and energy label 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 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. However, they do not study if this price premium has an impact on energy retrofit investments and building energy performance. Comerford et al. (2016) is an exception: they examine the impact of energy labeling on building 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 want to game the system when information is disclosed.

There is also a substantial literature on the modeling of the residential building stock and its energy consumption. For instance, Lechtenböhmer and Schüring (2011) develop a bottom-up modeling of the energetic characteristics of the building shells of the EU residential buildings. They perform a simulation-based analysis of the thermal quality and costs of the components of the building shell for new buildings as well as the refurbishment of the existing building stock. However, there is no detailed description of how information about building energy performance play a role in investment decisions. Similarly, Giraudet et al. (2012) introduce a hybrid framework named Res-IRF developed to assess future household energy demand in France. This a bottom–up module of energy consumption for space heating. Among its features, there is the inclusion of barriers to energy efficiency in the form of intangible costs, consumer heterogeneity parameters and an endogenous determination of retrofitting. Here again, the issue of information asymmetry is reduced to intangible cost, unlike our paper where the modeling of information asymmetry is significantly more detailed. Branger et al. (2015) extend the work of Giraudet et al. (2012) and present results of a sensitivity analysis of Res-IRF. They find that the Res-IRF model is most sensitive to energy prices and that inputs mimicking barriers to energy efficiency have little influence. We reconsider this analysis by modeling the interaction between energy prices (and other parameters such as the investment cost, the discount rate or the housing market turnover) with the information asymmetry barrier.

3.2 Model

3.2.1 Setting

Fleckinger et al. (2018) develop a dynamic model in discrete time, which describes the evolution of the building stock of a city. The stock includes dwellings with energy performance θ. Each dwelling can either be energy-efficient ($\theta = 1$) or inefficient ($\theta = 0$). The dwellings are owned

and occupied by a continuum of households with heterogeneous energy needs. More specifically, each household consumes a quantity of energy $(1-\theta)\cdot e$ per period where e is distributed over $[0,+\infty)$ according to a cumulative distribution function F. F is continuous, strictly increasing, and the overall level of energy consumption is bounded: $\int_0^{+\infty} e\,\mathrm{d}F(e) < +\infty$.

q_t denotes the share of efficient dwellings. It is assumed that all dwellings are inefficient at the beginning of the game: $q_0 = 0$. Any household can then invest in any period to upgrade its property if $\theta = 0$. The cost is I and $\theta = 1$ after investment, which is irreversible and which has an infinite lifetime (after investment, the energy performance is 1 over the entire time horizon). The share of efficient dwellings at time t is q_t.

In each period, m households exogenously and randomly move out and sell their dwelling to the same number of households who lived outside the city and who move in. Incoming and outgoing households are drawn from the same energy consumption distribution and every household always has the same probability m of moving out at each period. The real estate market is competitive.

When there is certification, energy performance is perfectly observable before the sale. Without certification, it is assumed that incoming households only observe it after moving in. The timing of events within each period t is as follows:

1. m households move out and sell their dwellings to m households move in. When there is certification, the latter can observe the building energy performance before the sale.

2. Without certification, incoming households observe the energy performance of their home.

3. Each household who lives in an inefficient dwelling ($\theta = 0$) decides whether to invest I or not.

4. Payoffs are realized.

Certification is introduced at period t_{EPC} and is not anticipated before period $t_{EPC}-1$. Once certification is introduced, households form perfect expectations about future housing prices.

3.2.2 Equilibrium

When making an investment decision in the absence of EPC, households simply need to compare the investment cost with the expected savings in their own energy consumption in the current and future periods. Household of type e will thus invest iff:

$$I \leq e \times \sum_{k=1}^{\infty} (\delta(1-m))^k = \frac{e}{1-\delta(1-m)} \tag{3.1}$$

Consequently, there is an energy consumption threshold $\hat{e} = I(1-\delta(1-m))$ above which households are willing to invest without EPC (that is when only taking into account their own energy savings).

Proposition 6. *When building energy performance is not certified, the share of efficient dwellings in period $t \geq 1$ is $q_t = 1 - F(\hat{e})[1 - m(1 - F(\hat{e}))]^{t-1}$ where $\hat{e} = I(1-\delta(1-m))$. The overall level of energy consumption is $E_t = [1 - m(1 - F(\hat{e}))]^t \int_0^{\hat{e}} e \, \mathrm{d}F(e)$.*

The sustained investment dynamic when there is no certification is a consequence of the allocation inefficiency in the housing market due to the lack of information among buyers. Indeed, high-energy-use households have a positive probability to purchase energy-inefficient dwellings that they will then retrofit. As a result, energy consumption tends to zero when the time period t goes to infinity.

We deduce from proposition 6 that the upgrade rate of the building stock when there is no certification, that is the share of energy-inefficient building which is retrofitted at each period, is constant and equal to $m(1 - F(\hat{e}))$. It is maximum and equal to m when $F(\hat{e}) = 0$, that is when all households are willing to invest in energy retrofit when only taking into account their own energy savings.

When EPC is introduced, households can sell their energy-efficient dwelling with a price premium because buyers are able to distinguish energy building performance. Besides, high energy-use households are now able to purchase energy-efficient dwellings instead of having to retrofit an energy-inefficient dwelling. As a result, both incentives to invest in energy retrofit and allocation efficiency increase.

Proposition 7 (EPC equilibrium)**.** *When EPC is introduced at period t_{EPC}, all remaining*

investments are made at once. There is an investment surge: the quantity of energy-efficient dwellings in the market q_{EPC} when EPC is introduced is greater than the quantity of energy-efficient dwellings that would be in the market without EPC $q_{t_{EPC}}^{noEPC} = 1 - F(\hat{e})[1 - m(1 - F(\hat{e}))]^{t_{EPC}-1}$. After t_{EPC}, per-period energy consumption E_t decreases towards a value E_{EPC} which verifies $E_{EPC} > 0$.

In the particular case when certification exists since initial period $t = 0$, households act as if they were to stay forever in their dwelling. As a result, Household of type e will invest iff:

$$I \leq e \times \sum_{k=1}^{\infty} \delta^k = \frac{e}{1-\delta} \tag{3.2}$$

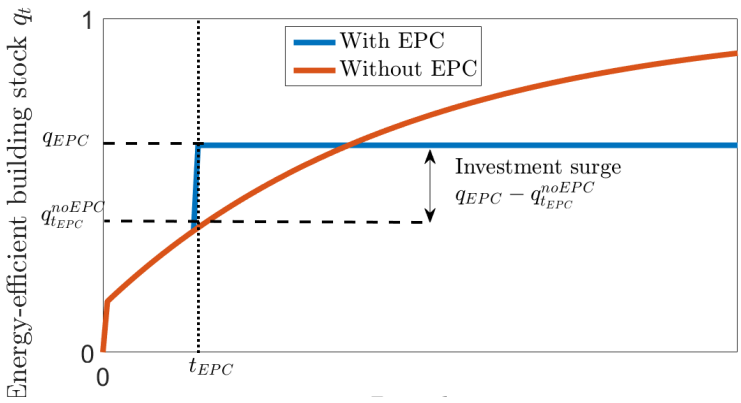
Similarly to the type threshold $\hat{e}$ defined when there is no EPC, there is a type threshold $e_{EPC} = I(1-\delta)$ above which households decide to invest when there is an EPC since initial period.

After the investment surge when EPC is introduced, energy retrofitting stops. This is different from a situation without EPC where investment dynamic is sustained until the building stock is fully retrofitted. Consequently, there is a period $\tau_{lim} \geq t_{PEC}$ after which the energy consumption would have been lower if the EPC hadn't been introduced. $\tau_{lim} - t_{EPC}$ is the break-even time, that is the time after the introduction of the EPC where the energy consumption is identical to a scenario in which the EPC is not introduced. A large break-even time $\tau_{lim} - t_{EPC}$ means that EPC is effective at reducing energy consumption even in the long term. On the contrary, a small break-even time means that EPC is detrimental to reduce energy consumption in the long term. The investment surge $q_{EPC} - q_{t_{EPC}}^{noEPC}$ is an indicator of the effectiveness of the EPC in the short term while the break-even time $\tau_{lim} - t_{EPC}$ is an indicator of the effectiveness of the EPC in the long term.

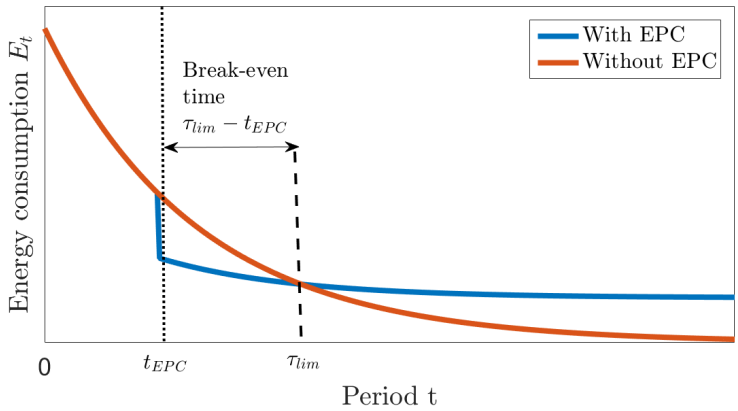
Figure 3.2 shows the evolution over time of the energy-efficient building stock q_t and the per-period total energy use E_t with and without the introduction of an EPC.

3.3 Parameters calibration

We mostly use inputs from Branger et al. (2015) for our baseline calibrations as the RES-IRF model is a reference in the French context. However, we use other sources to discuss admissible



(a) Trajectories of efficient dwelling stock q_t



(b) Trajectories of per-period energy use E_t

Figure 3.2: Comparison of equilibrium dynamics with and without the introduction of an EPC at period t_{EPC}

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

range of parameters.

3.3.1 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 3.1 as an input of their model. This matrix has been established with the help of experts insights.

There are several other studies which deal with investment costs. We report ADEME figures on average investment costs in France from 2006 to 2013 in table 3.2. In the U.S., Leinartas et al. (2015) establish a typology of 10 kinds of homes in Chicago area and estimate average upfront cost of retrofits to be around $14,400, resulting in average annual site energy savings of about 54%. Also in the U.S. context, Fowlie et al. (2015b) find lower figures (closer to ADEME figures), with average projected investment cost of $5,306 and average reported investment cost of $5,151. Also, Lechtenböhmer and Schüring (2011) is a good source for a detailed description of the technology costs for the improvement of the building shells (facade, roofs, floor, windows, with labor and material costs).

Monetary investment costs appear to be an underestimation of total costs of energy retrofit expenditures as it is argued in Fowlie et al. (2015a). In this paper is described a program where participants receive a substantial home "weatherization" retrofit; all installation and equipment costs are covered by the program. Less than one percent of presumptively eligible households take

year	Amount (€)
2006	5,370
2008	6,870
2010	6,410
2011	5,330
2013	5,210

Table 3.2: Average amount spent per energy retrofit in France. Source: ADEME

up the program in the control group. This rate increased only modestly after researchers took extraordinary efforts to inform households - via multiple channels - about the sizeable benefits and zero monetary costs. These findings are consistent with high non-monetary costs (including time) associated with program participation and/or energy efficiency investments. These findings tend to substantially increase the value of I.

On the other hand, subsidies are commonplace in Western countries for energy retrofit. In France, households have access to tax credits, reduced VAT, zero-interest loans and additional financial public support from national and local authorities. This tends to reduce the amount I.

This brief analysis of the energy retrofit investment cost encourages us to take a wide range for I in our simulations with substantial variation around a baseline based on table 3.1.

3.3.2 Distribution of energy-saving benefits F

By essence, we are forced to make non-verifiable assumptions on the nature of the distribution F. However, we can rely on the literature to get more insights on some features of the distribution F. The two most obvious properties on F are its mean and its standard deviation. While there exists several papers on the average benefits due to energy retrofit, literature on the dispersion of these benefits is scarcer. Besides, similarly to investment cost, energy-saving benefits vary with local conditions (including energy prices), building characteristics (including energy fuel) and weather conditions. Thus, comparisons are difficult and average estimate need to be taken with caution.

Table 3.3 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.

We distinguish two approaches to estimate energy savings due to energy retrofits: ex ante

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

Table 3.3: 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.

estimates generated via engineering modeling and ex post estimates obtained via an econometric analysis. Because the buildings considered are rarely comparable, it is rarely possible to compare ex ante and ex post estimates. However, Fowlie et al. (2015b) manage to do exactly this in their paper which reports on the results of an experimental evaluation of the U.S. largest residential energy efficiency program conducted on a sample of more than 30,000 households. They find that the upfront investment costs, $5,151 on average, are about twice the actual energy savings ($2,304 at most). Furthermore, the model-projected savings based on a computer-based audit tool[1] are roughly 2.5 times the actual savings. They are able to exclude a substantial rebound effect because they do not observe a change of indoor temperature of dwellings. This suggests that engineering estimates need to be taken with cautious when evaluating energy savings.

Adan and Fuerst (2016) computes econometric estimates for energy savings due to energy efficiency measures. They find that the single most effective energy efficiency measure when installed alone is cavity wall insulation, reducing annual gas consumption by 10.5 % and annual total energy consumption by 8.0 % in the year following installation. Comparing bundles of different energy efficiency measures, they find that dwellings retrofitted with both cavity wall insulation and a new efficient boiler experience the largest reductions in annual gas and total energy consumptions of 13.3 % and 13.5 %, respectively. Notice that these decrease figures are quite smaller than the energy-savings decrease due to a one-letter improvement in table 3.3

[1]The computer-based audit tool used in Fowlie et al. (2015b) is the National Energy Audit Tool (NEAT). This tool uses engineering algorithms to model the energy use of single-family and small multi-family residential units. NEAT is the most widely used tool for weatherization audits in the U.S.

(29%-47% energy consumption reduction for a one-letter improvement).

Personal benefits from energy retrofits are not only monetary. Better building energy performance brings improved thermal energy comfort (it can even lead to increased energy demand with the rebound effect), acoustic comfort (double-glazed windows) and environmental satisfaction among other co-benefits.[2] Besides, monetary benefits also include reduced exposition to energy price volatilty. In this respect, there is an insurance dimension to investment in energy retrofit. The importance of these co-benefits is what suggests Van Eeckhout (2018) in her story about energy retrofits in Villers-lès-Nancy, a town in Easter France. Inhabitants paid between €100,000 and €150,000 for their home renovation and obtained €1,700 in energy savings. The internal return rate of the investment is therefore between 1.1 % and 1.7% if we only consider monetary savings, which is quite low. Besides, in their paper with data from Sweden, Mandell and Wilhelmsson (2011) find that there is a positive willingness to pay for environmental attributes and it is higher for households who state that they are environmentally aware. However, in the Irish contex, Aravena et al. (2016) find that the decision to ultimately apply and invest in energy efficiency measures is mainly driven by monetary or economic factors such as gains in energy savings and the private cost of the measures. Comfort gains are found to be a secondary factor and environmental benefits of energy efficiency measures are found to be of little concern when making investment decisions. The magnitude of co-benefits of investing in energy retrofit is not clear, but preliminary results suggest that they can play at least a marginal role in the decision to invest.

The literature on the dispersion of energy consumption and energy-saving benefits among households is very scarce. Risch and Salmon (2017) show that the intensity of energy used per m^2 is almost completely determined by the technical properties of the dwelling and by the climate. The role of socio- demographic variables is particularly weak, which suggests a small dispersion of energy benefits due to energy efficiency investments. On the other hand, Bakaloglou and Charlier (2018) provide evidence that preferences for comfort over energy savings do have significant direct and indirect impacts on energy consumption, especially for high-income

[2] Ürge-Vorsatz (2009) makes a comprehensive review of co-benefits energy efficiency in buildings. While parts of them are externalities (not only GHG emissions, but also outdoor pollution, improved energy security, potential job creation), others are personal benefits (thermal comfort, better indoor air quality, pride due to environmental achievement).

households. Preferring comfort over economy or one additional degree of heating implies an average energy over-consumption of 10% and 7.8% respectively.

This brief analysis of the benefits from energy retrofit investments encourages us to take a wide range for F mean and standard deviation in our simulations with substantial variation around a baseline based on table 3.3 for the mean benefits and 10% of the mean for the standard deviation (based on the average energy extra consumption of 10% found by Bakaloglou and Charlier (2018) for households who prefer comfort over economy).

3.3.3 Discount factor δ

Let us first discard the risks associated to investments in energy efficiency and assume perfect access to credit. With these assumptions, households use the risk-free interest rate as their discount rate and would use a framework similar to the one used in the public sector by governments in their public investments projects. In the U.S., the Office of management and budget (OMB) recommends to use two discount rates: 3 % and 7%. The former is the average yield of 10-year federal obligations and is is supposed to represent the social rate of time preferences. The latter is the average yield before taxes of the private capital and is used as a proxy for the opportunity cost of capital. In the U.K., Ramsey rule is used and leads to a discount rate of 3.5 %. In France, Lebègue (2005) also uses the Ramsey rule with a calibration specific to the French context and recommends a 4% risk-free discount rate. Last report on the topic for the French government is Quinet (2013) which actualizes the analysis made by Lebègue (2005) and proposes a risk-free 2.5% discount rate to which must be added a systemic risk premium of 2 % weighted by a coefficient which depends on the sensibility of each project's profitability to economic growth. Besides, countries like France offer zero-interest-rate loans to encourage energy retrofits.

Because of the access to credit, the discount rate used by housholds might be different from a personal disoount rate which would reflect individual time preferences. Also, it does not take into account the potential risks associated to investments in energy efficiency (such as the uncertainties about the quality of energy retrofit and the energy savings). Stadelmann (2017) makes a short survey about empirical estimates of personal discount rates and finds relatively high rates of time preferences with average discount rates of 19% or more. For instance, Newell

and Siikamäki (2015) elicited individual discount rates using a hypothetical choice between a \$1,000 payment available in one month and a higher payment available in 12 months. They find substantial heterogeneity in individual discount rates, with a mean rate of 19%, a median of 11%, and a standard deviation of 23%. Not mentioned in Stadelmann (2017) is the work of Warner and Pleeter (2001). In their paper, they take advantage of a US military drawdown program in the early 1990's which offered over 65,000 separatees the choice between an annuity and a lump-sum payment. Their estimates of discount rates range from 0 to over 30 percent and vary with education, age, race, sex, number of dependents, ability test score, and the size of payment. Moreover, they find that the vast majority of personnel had discount rates of at least 18 percent.

It is worth noting that the personal discount rate values used in the RES-IRF model in Branger et al. (2015) are: 8% in owner-occupied single-family dwelling, 15% in owner-occupied multi-family dwellings, 45% in rented single-family dwellings, and 55% in rented multi-family dwellings. They end up with a weighted average discount rate of 20%.[3]

This brief analysis of the personal discount rate encourages us to take a wide range of discount rate $\frac{1}{\delta}-1$ for our simulations, with a lower bound at 0%, a baseline at 4% which reflects a risk-free discount rate when households have access to credit, and an upper bound above 30%.

3.3.4 Housing market turnover m

The rate at which households move in and out can be very different from one location to another, from one segment of dwellings to the other, from one year to the other. In France, according to INSEE, 7.3% of the households have changed their dwelling between 2011 and 2013. This average number hides substantial disparities: households who own their dwellings are only 3% to have changed their dwelling during this period while tenants in the private housing sector have a 17.8% turnover rate. Figure 3.3 shows the turnover rate during this period by ownership status and households' age. It is maximum (33.1%) for young households (18-29 years old) who are tenants in private housing and it is minimum (1.7%) for old households (50-plus years old) who own their dwellings.

We also have access to UK data on housing transactions that show how the turnover rate can

[3]This weighted average discount rate also takes into account social housing where the discount rate picked, 4%, is meant to reflect public decision making.

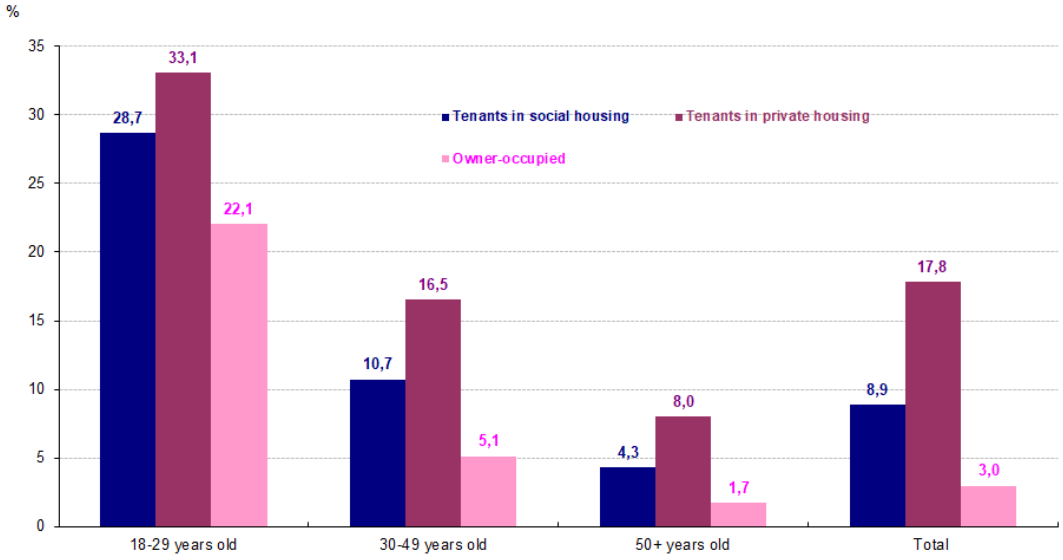


Figure 3.3: Housing turnover rate in France between 2011 and 2013 by ownership status and households' age. Source: INSEE

strongly vary over time. In figure 3.4, we observe that this turnover rate peaks at 14% in the late 80s and reaches a low at 10% in the late 2000s.

This brief analysis of the housing turnover encourages us to take a wide range of turnover rate m for our simulations, with a lower bound under 1% (50-plus-year-old owners in France), a baseline at 3.7% (average in France), and an upper bound above 17 % (18-29 year old tenants in private housing in France).

3.3.5 Start time of EPC t_{EPC}

In our model, the start time t_{EPC} is the time between the introduction of the EPC (following the EPB directive in 2002) and the age of the housing stock. This age can be very different from one place to another. In France for instance, some towns like Serris in Paris area have a building stock mostly built after 2000 while buildings built during Hausman's renovation of Paris are more than one century old. Figure 3.5 shows this heterogeneity. According to INSEE, more than one third of the dwellings in France in 2013 were built before 1949. Also the median age of a French dwelling is between 1949 and 1974. In the UK, according to a 2014 survey of the Department for Communities and Local Government (DCLG), 20% of the housing stock were

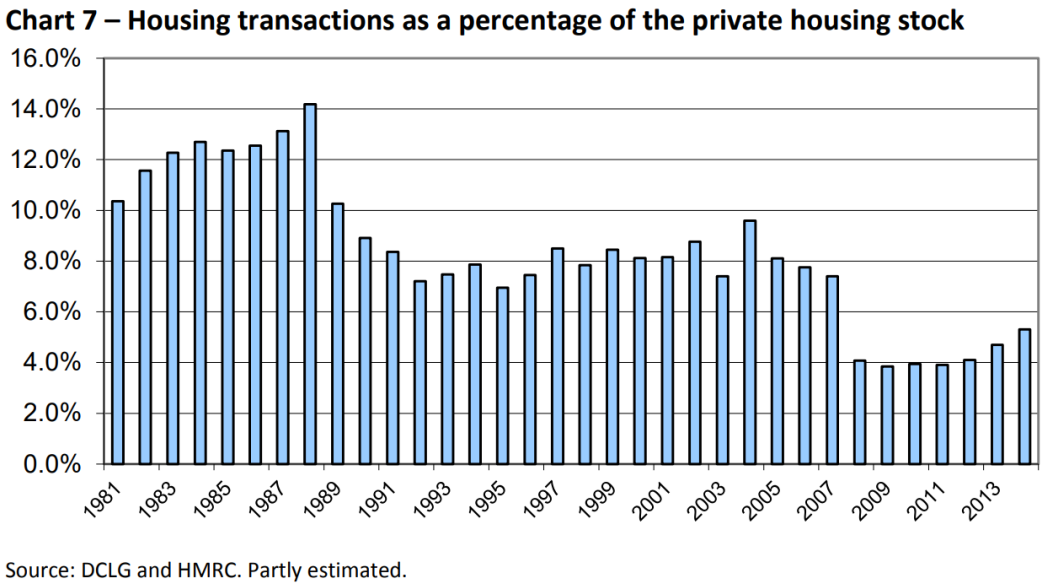


Figure 3.4: Housing turnover rate in the UK for private housing from 1981 to 2015. Source: Intermediary Mortgage Lenders Association

built before 1919 and 24% were built after 1980. The share of the housing built before 1850 is around 3%.

This brief analysis of the housing stock age encourages us to take a wide range of start time t_{EPC} for our simulations, with a lower bound at 0 (new housing project), a baseline at 45 years (median dwelling in France) and an upper bound above 150 years (historical districts). However, we must recognize the limitations of our model in which parameters such as the discount rate, the turnover rate or the energy benefits, are not allowed to vary over time. Consequently, the higher the start time t_{EPC} is, the less realistic our model is to describe the period between the construction of the building and the introduction of the EPC.

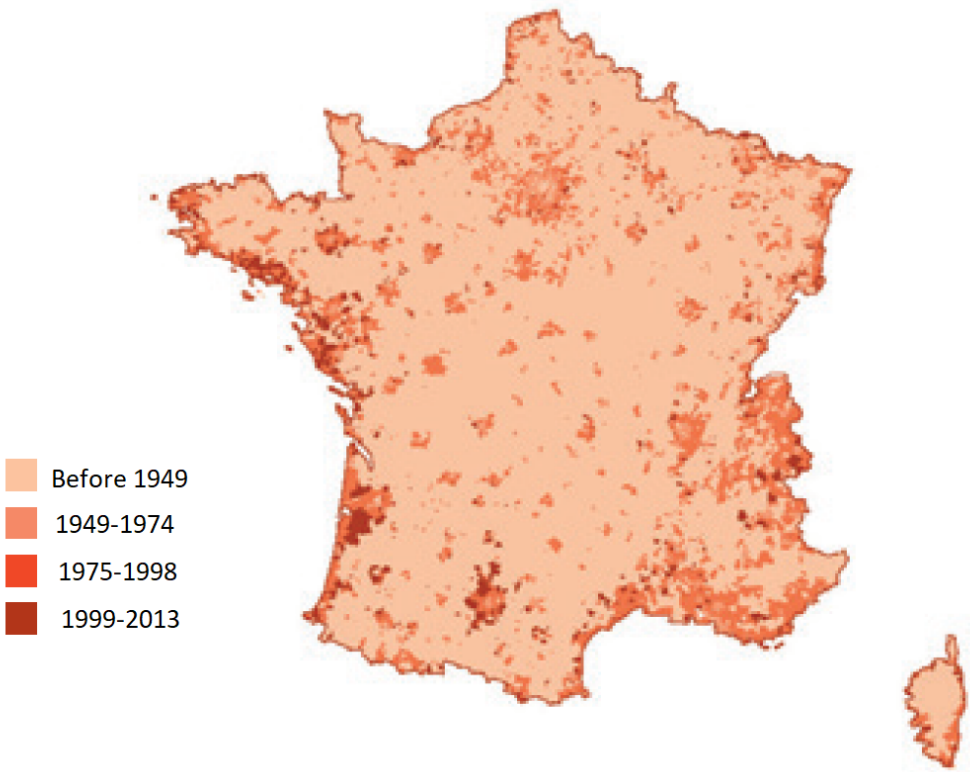


Figure 3.5: Age of the housing stock in France. Source: INSEE

Parameter	Baseline Value	Minimum Value	Maximum Value
Investment cost I	€204.67/m^2	10% Baseline	200 % Baseline
Average annual energy savings $\int_0^{+\infty} e \, \mathrm{d}F(e)$	€8.43/m^2	10% Baseline	200 % Baseline
F Standard deviation-mean ratio	10 %	1%	100%
Housing market turnover m	3.7 %	0%	30 %
EPC introduction time t_{EPC}	45 years	0 year	150 years
discount rate $\frac{1}{\delta} - 1$	4 %	0%	30 %

Table 3.4: Baseline input parameters

3.4 Results and discussion

3.4.1 Baseline

Based on the results of the PHEBUS survey[4] , we consider the case of a building which has an initial EPC grade D-E and a final EPC grade A-B-C[5]. We then use tables 3.2 and 3.3 to compute the average investment costs and energy savings when coming from an EPC grade D-E to an EPC grade A-B-C. To compute monetary energy savings, we use natural gas price as a reference as it is the most used heating energy fuel in France. The average marginal price over the period 2010-2016 according to the Pegase database[6] is €0.0543/kWh[7]. Input parameters values used for our baseline simulation are gathered in table 3.4 along with lower bounds and upper bounds for the sensitivity analysis.

Our model requires F to be continuous, have a finite mean and be supported on the interval $[0; +\infty)$ (which excludes the traditional normal distribution which is supported on the whole real line). To the best of our knowledge, there is no study on the functional form of the energy use and energy savings in the population. We test several functional specifications for F: Log-normal distribution, Gamma distribution, Inverse Gaussian distribution. We find almost identical results (for instance, for our baseline specification, the final share of energy-efficient dwellings

[4]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.

[5]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.

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

[7]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 3.3. 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.

when an EPC policy is implemented is 73.60% for the Inverse Gaussian distribution, 73.85% for the Gamma distribution, and 73.63% for the Log normal distribution). We use the log-normal distribution as the functional specification for F in the rest of the paper.

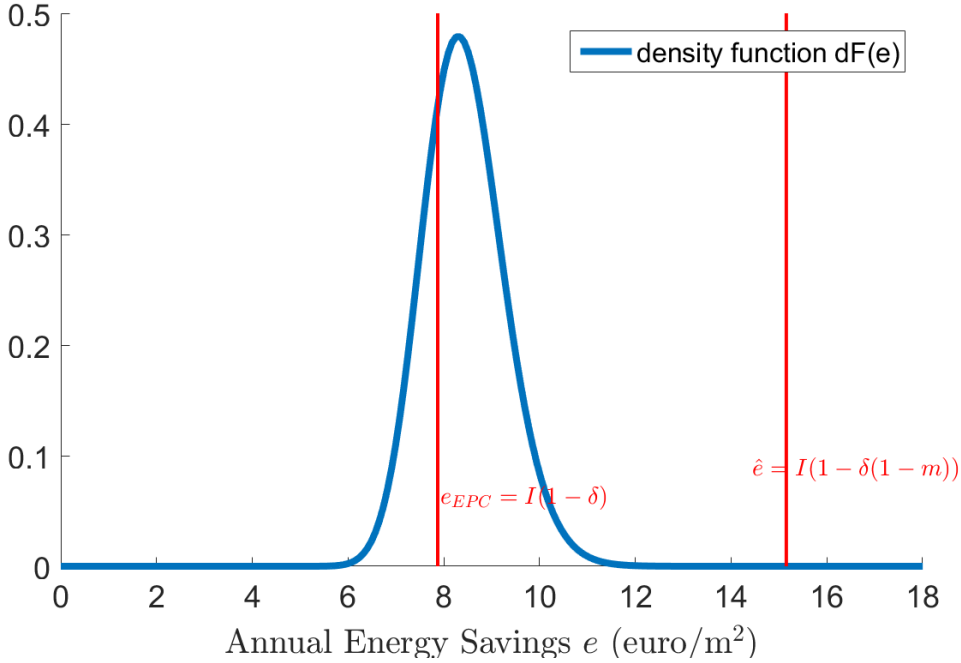
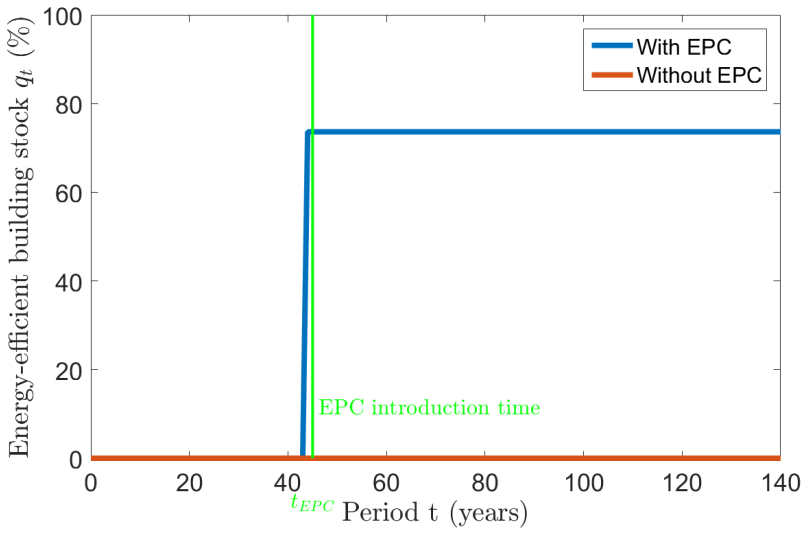


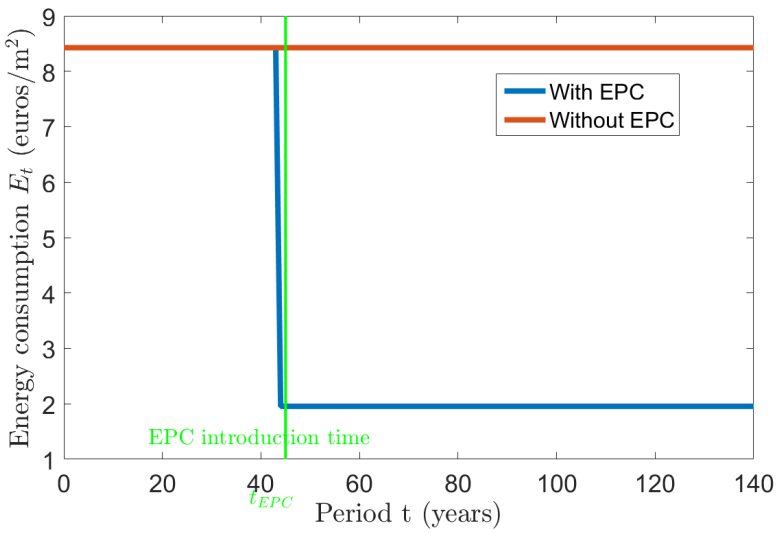
Figure 3.6: Distribution F - Baseline specification

Figure 3.6 shows the distribution F used in our baseline simulation. We add two thresholds in the figures: $e_{EPC} = I(1-\delta)$ for type above which households invest when there is an EPC from day one and $\hat{e} = I(1-\delta(1-m))$ for type above which households invest even without EPC (they only account for their personal energy savings). While e_{EPC} is not far from the mean of the distribution (€8.43/m^2), $\hat{e}$ is very much above and $F(\hat{e})$ is close to one. Thus, the share of households who are willing to retrofit their dwelling without an EPC is negligible in our baseline specification.

Figure 3.7a shows the evolution of the energy-efficient building stock q_t with and without EPC. Without EPC, the building stock remains almost completely energy-inefficient as the share of households who are willing to invest is close to zero. On the other hand, when EPC is introduced, there is a spike in investments and q_t jumps to 73.6% in our simulation. Figure 3.7b shows the



(a) Evolution of the energy-efficient building stock q_t with and without EPC



(b) Evolution of energy consumption E_t with and without EPC

Figure 3.7: Dynamics of energy consumption and energy-efficient building stock with and without EPC - Baseline specification

evolution of energy consumption E_t and is very much in line with figure 3.7a. Without EPC, energy consumption is almost constant and stays close to its maximum value €8.43/m^2 as there is almost no investment made. It decreases sharply to €1.96/m^2 following the investment spike due to EPC introduction. Subsequent decrease of energy consumption is negligible because the mismatch before the investment spike was negligible because there was almost no investment. We understand easily with figure 3.7b that the break even time $\tau_{lim} - t_{EPC}$ after which energy consumption is lower without EPC is extraordinarily large. Actually, because of computational limitations, we don't compute $\tau_{lim} - t_{EPC}$ when it is greater than 500 years. In our baseline specification, $\tau_{lim} - t_{EPC}$ is far greater than 500 years.

In our baseline specification, an EPC policy should be favored as it unambiguously leads to a decrease in energy consumption in the short and long term (and it does so in a cost-effective way). However, because of the uncertainties about the calibration of the parameters as seen in the previous section, it is difficult to have a robust interpretation of the results for the baseline specification. This is why we now perform a sensitivity analysis around this baseline specification.

3.4.2 Mono-variate sensitivity analysis around the baseline

We make vary sequentially each of the input parameters of table 3.4 around its baseline value. The output variables of interest that we consider are the investment surge $q_{EPC} - q_{t_{EPC}}^{noEPC}$ when the EPC is introduced, the final energy-efficient stock after the introduction of EPC q_{EPC}, the upgrade rate when there is no EPC $m(1 - F(\hat{e}))$, and the break even time $\tau_{lim} - t_{EPC}$ when we can compute it[8]. Note that the upgrade rate $m(1 - F(\hat{e}))$ is upper-bounded by the housing market turnover m which is 3.7% in the baseline. When $m(1 - F(\hat{e}))$ is equal to m, that is when $F(\hat{e})$ is equal to zero, all households are willing to invest in energy retrofit even without EPC.

[8]There are two reasons why we cannot compute $\tau_{lim} - t_{EPC}$. First reason is when $\tau_{lim} - t_{EPC}$ is too large like it is the case in the baseline scenario. We choose a cut-off of 500 years above which we stop computing the break-even time. Second reason is when q_{EPC} and $1 - F(\hat{e})$ (the share of high-energy-use households who would invest even without EPC) are both very close to zero, or when $q_{t_{EPC}}^{noEPC}$ and q_{EPC} are close to one. Indeed, in these latter cases, it is computationally hard to distinguish the two energy consumption trajectories which are either both very close to their maximum value $\int_0^{+\infty} e \, \mathrm{d}F(e)$ or to 0. From an economic point of view, all these cases where $\tau_{lim} - t_{EPC}$ cannot be computed do not have any relevance. Indeed, when $\tau_{lim} - t_{EPC}$ is too large to be computed, it means that a no EPC policy is always irrelevant. Thus, getting a precise value for $\tau_{lim} - t_{EPC}$ is unnecessary. When q_{EPC} and $(1 - F(\hat{e}))$ are both very close to zero, it means that energy retrofit will not happen in any case so getting a precise value for $\tau_{lim} - t_{EPC}$ is again unnecessary. When $(1 - F(\hat{e}))$ and $q_{t_{EPC}}^{noEPC}$ are close to one, the additional energy savings of a no-EPC policy for periods $t > \tau_{lim}$ are small so an EPC policy should be favored and therefore getting a precise value for $\tau_{lim} - t_{EPC}$ is still unnecessary.

Sensitivity to investment cost I

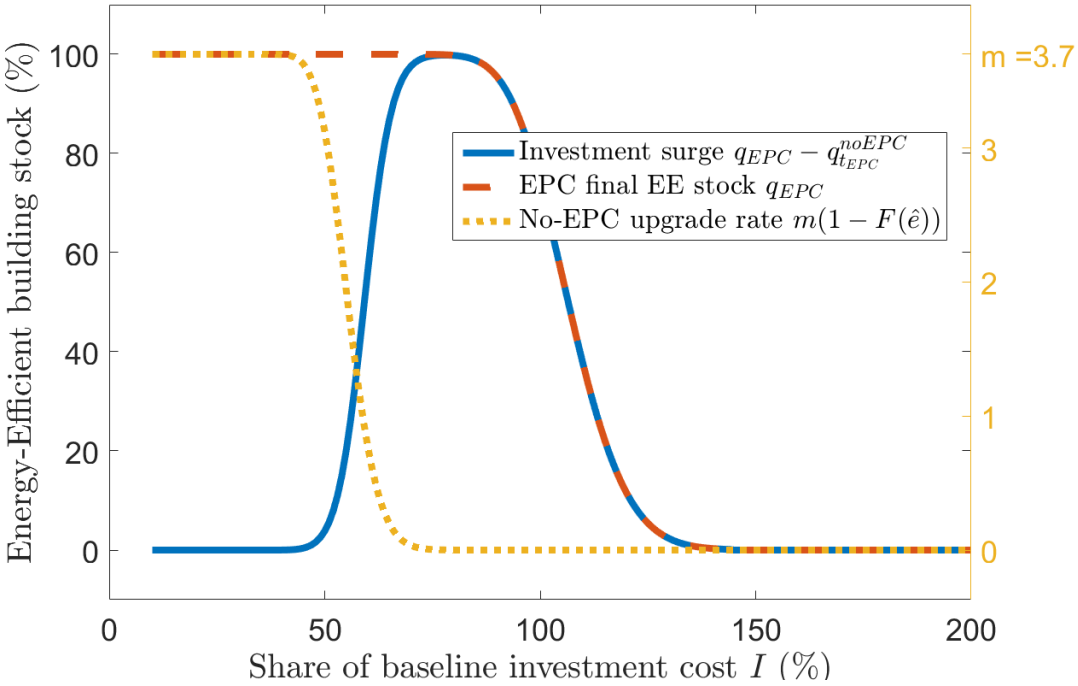


Figure 3.8: Sensitivity of baseline simulation to investment cost I

Figure 3.8 shows how the investment surge $q_{EPC} - q_{t_{EPC}}^{noEPC}$, the energy-efficient building stock with EPC q_{EPC} and the upgrade rate without EPC $m(1 - F(\hat{e}))$ vary when investment cost I varies between 10% and 200% of its baseline value. We distinguish four zones:

- Investment cost is less than 45% of the baseline cost. All households invest in energy efficiency even if there is no EPC. Thus, with or without EPC, the building stock is fully retrofitted.

- Investment cost is between 45% and 75% of the baseline. The upgrade rate when there is no EPC is both not maximum and not negligible while the energy-efficient building stock with EPC q_{EPC} is maximum and equal to one. Thus, an EPC policy guarantees a full retrofit of the building stock with a substantial investment surge when the EPC is implemented while a no EPC policy will be slower to reach this target. The break-even time $\tau_{lim} - t_{EPC}$ is large (greater than 500 years).

- Investment cost is between 75% and 140% of the baseline. The upgrade rate without EPC is negligible while the energy-efficient building stock with EPC q_{EPC} is substantial. Thus, only an EPC policy can trigger investments in energy efficiency and reduce energy consumption. The break-even time $\tau_{lim} - t_{EPC}$ is large (greater than 500 years).

- Investment cost is greater than 140%. Both the upgrade rate without EPC and the energy-efficient building stock with EPC are negligible. In both cases, retrofitting is therefore almost absent at all time because it is too costly to invest in energy efficiency.

Thus, our simulations suggest that an EPC policy is effective in the short and (foreseeable) long term for intermediary values of investment cost I (between 45% and 140% of the baseline). Outside this range, that is for relatively costly or inexpensive energy retrofit, our simulations suggest that an EPC policy has no effect compared to a no EPC policy.

Sensitivity to energy savings

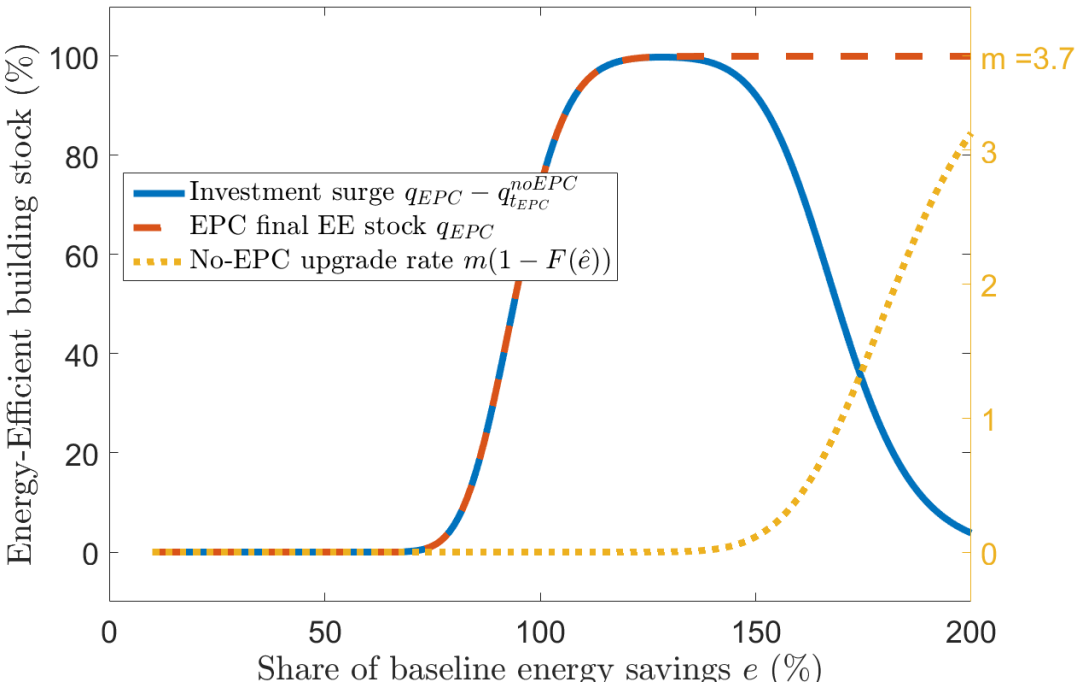


Figure 3.9: Sensitivity of baseline simulation to energy savings e

Figure 3.9 shows how the investment surge $q_{EPC} - q_{t_{EPC}}^{noEPC}$, the energy-efficient building stock with EPC q_{EPC} and the upgrade rate without EPC $m(1 - F(\hat{e}))$ vary when energy savings vary between 10% and 200% of their baseline value. Note that while the standard-deviation-mean ratio does not change (it stays at its baseline value 10 %), the absolute value of the standard deviation of the distribution F is multiplied by the same factor as the energy savings. We distinguish three zones:

- Energy savings are less than 70% of their baseline. Both the upgrade rate without EPC and the energy-efficient building stock with EPC are negligible. In both cases, retrofitting is therefore almost absent at all time because benefits of investing are too small.
- Energy savings are between 70% and 140% of their baseline. The upgrade rate without EPC is negligible while the energy-efficient building stock with EPC q_{EPC} is substantial. Thus, only an EPC policy can trigger investments in energy efficiency and reduce energy consumption. The break-even time $\tau_{lim} - t_{EPC}$ is large (greater than 500 years).
- Energy savings are between 140% and 200%. The upgrade rate when there is no EPC is both not maximum and not negligible while the energy-efficient building stock with EPC q_{EPC} is maximum and equal to one. Thus, an EPC policy guarantees a full retrofit of the building stock with a substantial investment surge when the EPC is implemented while a no EPC policy will be slower to reach this target. The break-even time $\tau_{lim} - t_{EPC}$ is large (greater than 500 years).

Results are symmetric to those of the sensitivity analysis with respect to the investment cost I: an increase in energy savings e have the same effect as a decrease in investment cost I for our output variables of interest. Not surprisingly, if we were to go over 200% of the baseline value for energy savings, we would see arise a fourth zone in figure 3.9 such as the first zone of figure 3.8 where the building stock is fully retrofitted with and without EPC because energy savings are large enough. Thus, we obtain a similar conclusion: our simulations suggest that an EPC policy is effective in the short and (foreseeable) long term for intermediary to high values of average energy savings e (between 70% and 200% of the baseline). Outside this range, that is for relatively low average energy savings or very high average energy savings, our simulations suggest that an EPC policy has no effect compared to a no EPC policy.

Sensitivity to the dispersion of energy savings

Figure 3.10a shows how the investment surge $q_{EPC} - q_{t_{EPC}}^{noEPC}$, the energy-efficient building stock with EPC q_{EPC} and the upgrade rate without EPC $m(1 - F(\hat{e}))$ vary when the energy savings standard deviation-mean ratio varies between 1% and 100% (recall that baseline value is 10%).

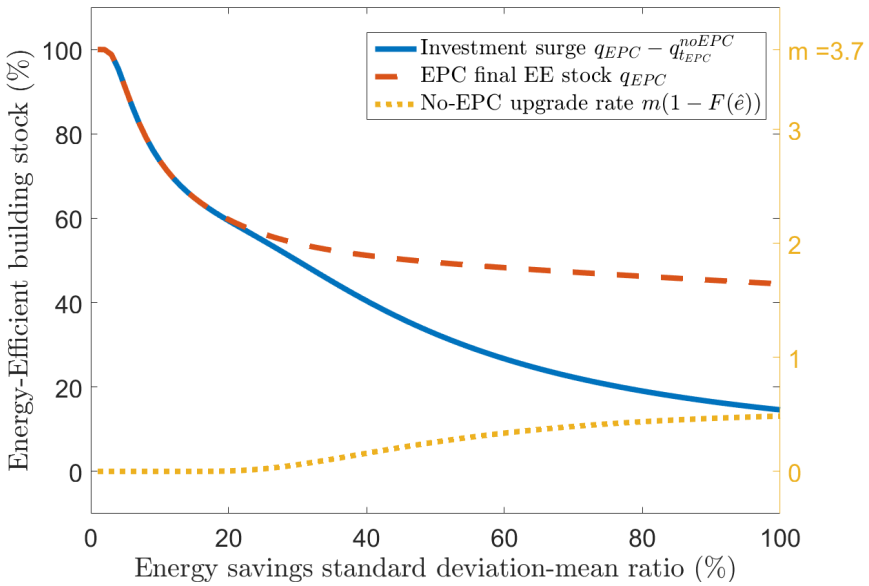
$q_{EPC} - q_{t_{EPC}}^{noEPC}$ and q_{EPC} on the one hand, and $m(1 - F(\hat{e}))$ on the other hand vary in opposite directions when the standard deviation-mean ratio changes. When dispersion increases, the energy-efficient building stock with EPC and the level of the investment surge decrease while the upgrade rate without EPC increases. Indeed, there are more high-energy users ready to invest even without EPC, which induces an increase in the upgrade rate. There are also less medium-energy-use households who would need an EPC to invest, which induces a decrease in the the energy-efficient building stock with EPC. Both effects lead to a decrease in the level of the investment surge.

Figure 3.10b shows how these results impact the break-even time $\tau_{lim} - t_{EPC}$. Above an energy-savings standard deviation-mean ratio of 42%, the break-even time $\tau_{lim} - t_{EPC}$ becomes lower than 500 years and keeps decreasing when the standard deviation-mean ratio increases. However, even with a standard deviation-mean ratio of 100%, the break even time is still very large: 144 years. In conclusion, an increase in energy savings dispersion tends to decrease the relative benefits of the introduction of an EPC. However, in our range of parameters for dispersion, this decrease is not sufficient to challenge the introduction of an EPC. Indeed, the horizon for which the introduction of an EPC would lead to higher emissions is still very distant even for our maximum value of dispersion.

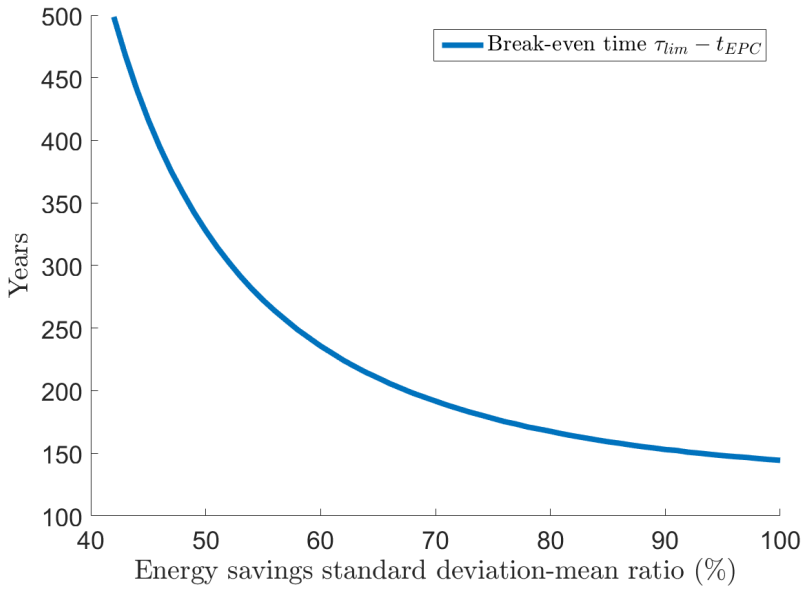
Sensitivity to discount rate

Figure 3.11 shows how the investment surge $q_{EPC} - q_{t_{EPC}}^{noEPC}$, the energy-efficient building stock with EPC q_{EPC} and the upgrade rate without EPC $m(1 - F(\hat{e}))$ vary when the discount rate varies between 0% and 8% (the maximum value for the discount rate in table 3.4 is 30%; however, all output variables of interest become negligible for discount rates above 5.5%). We distinguish three zones:

- Discount rate is less than 2%. The upgrade rate when there is no EPC is both not maximum



(a) Sensitivity of investment surge, final energy-efficient building stock with EPC and upgrade rate without EPC



(b) Sensitivity of the break even time $\tau_{lim} - t_{EPC}$

Figure 3.10: Sensitivity of the baseline simulation to the dispersion of energy savings

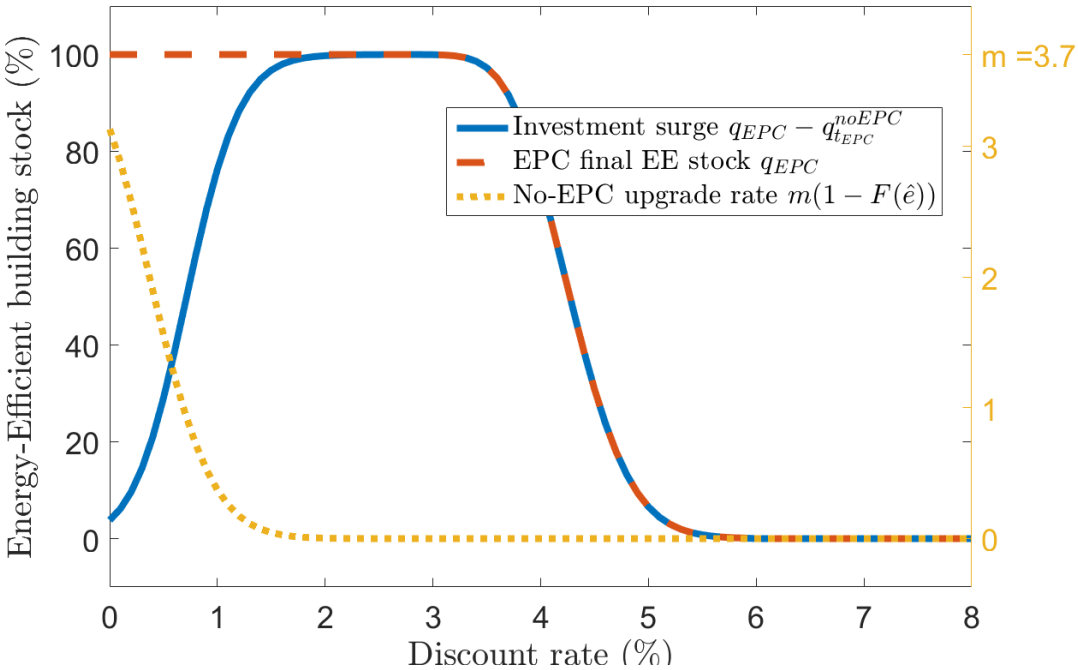


Figure 3.11: Sensitivity of the baseline simulation to the discount rate $\frac{1}{\delta} - 1$

and not negligible while the energy-efficient building stock with EPC q_{EPC} is maximum and equal to one. Thus, an EPC policy guarantees a full retrofit of the building stock with a substantial investment surge when the EPC is implemented while a no EPC policy will be slower to reach this target. The break-even time $\tau_{lim} - t_{EPC}$ is large (greater than 500 years).

- Discount rate is between 1.5% and 5.5%. The upgrade rate without EPC is negligible while the energy-efficient building stock with EPC q_{EPC} is not negligible. Thus, only an EPC policy can trigger investments in energy efficiency and reduces energy consumption (it even ensures full retrofitting if discount rate is 3% or less). The break-even time $\tau_{lim} - t_{EPC}$ is large (greater than 500 years).

- Discount rate is greater than 5.5 %. Both the upgrade rate without EPC and the energy-efficient building stock with EPC are negligible. Both the upgrade rate without EPC and the energy-efficient building stock with EPC are negligible. In both cases, retrofitting is

therefore almost absent at all time because future energy savings and sale premium due to building energy performance are discounted too heavily.

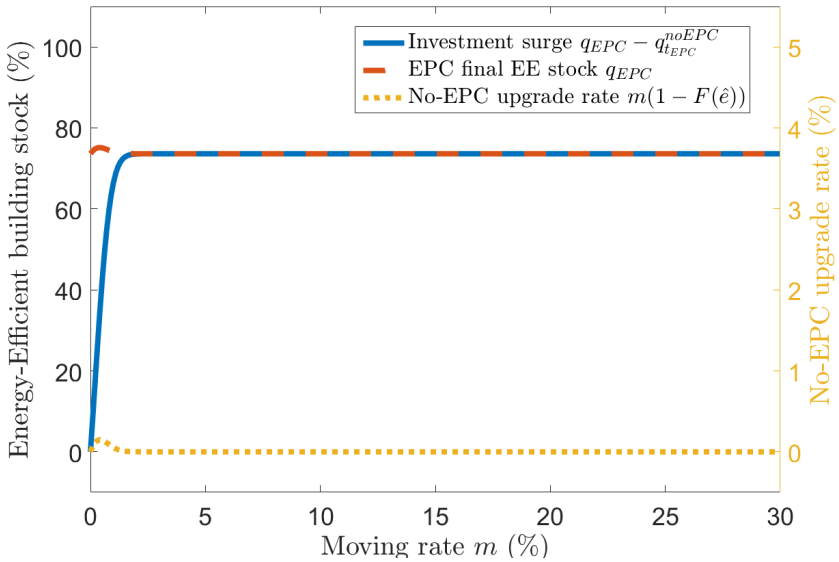
Thus, our simulations suggest that an EPC policy is effective in the short and (foreseeable) long term for low values of the discount rate (less than 5.5%). For higher discount rates, our simulations suggest that an EPC policy has no effect compared to a no EPC policy because future energy savings are discounted too heavily in both cases.

Sensitivity to housing market turnover m

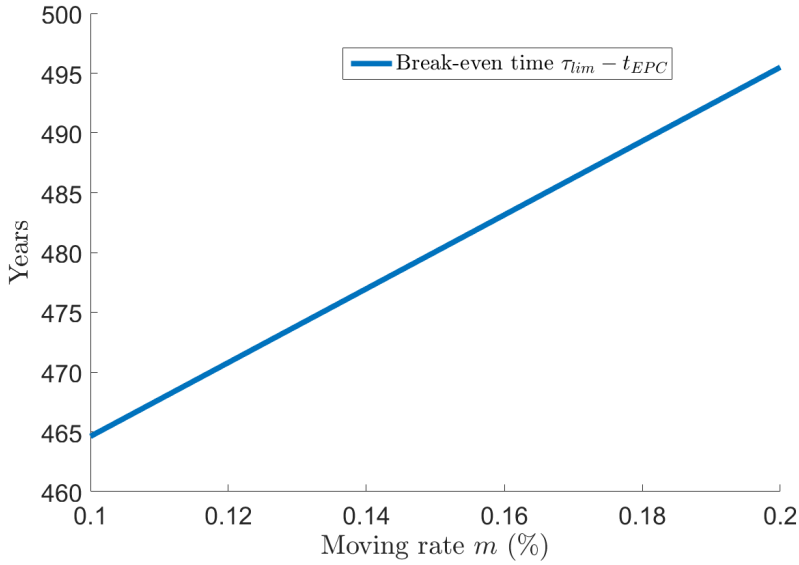
Figure 3.12a shows how the investment surge $q_{EPC} - q_{t_{EPC}}^{noEPC}$, the energy-efficient building stock with EPC q_{EPC} and the upgrade rate without EPC $m(1 - F(\hat{e}))$ vary when the housing market turnover m varies between 0% and 30% (recall that baseline value is 3.7%). We can distinguish two zones:

- Housing market turnover is less than 1.5%. When the housing market turnover is zero, that is when households never move out, there is no difference between an EPC scenario and a no EPC scenario because households internalize total energy savings in both cases. Then, when the housing market turnover m increases, the investment surge at the introduction of EPC quickly increases from 0% to reach the value of the baseline specification for $m = 1.5\%$. Over this range of housing market turnover rate, the upgrade rate without EPC is not negligible (although quite small; it peak at 0.15% for a housing market turnover rate of 0.5%) and the energy-efficient building stock with EPC is susbtantial (around 75%) but not maximum. Thus, we can challenge the effectiveness of an EPC policy in the long term because it is possible that the continuous upgrade of the building stock ends up being more effective than an EPC policy in the long term. Figure 3.12b answers this concern by showing the break-even time for small values of the housing market turnover. For a housing market turnover of 0.1%, the break-even time $\tau_{lim} - t_{EPC}$ is already 465 years. It becomes greater than 500 years when the housing market turnover exceeds .2%. Therefore, an EPC policy remains effective in the (foreseeable) long term compared to a situation without EPC.

- Housing market turnover is above 1.5%. The upgrade rate without EPC is negligible while



(a) Sensitivity of investment surge, final energy-efficient building stock with EPC and upgrade rate without EPC



(b) Sensitivity of the break even time $\tau_{lim} - t_{EPC}$

Figure 3.12: Sensitivity of the baseline simulation to the housing market turnover m

the energy-efficient building stock with EPC q_{EPC} is constant equal to 73.6%, that is its value for the baseline specification. In this range of housing market turnover, only an EPC policy can trigger investments in energy efficiency and reduces energy consumption. Indeed, expected energy savings during the stay in the dwelling are too small to encourage households to invest. The break-even time $\tau_{lim} - t_{EPC}$ is large (greater than 500 years).

Thus, our simulations suggest that an EPC policy is effective at reducing energy consumption and improving building energy performance in the short and (foreseeable) long term for all levels of housing market turnover compared to a situation without EPC. Furthermore, from low levels of housing market turnover (from $m = 1.5\%$), there is no investment in energy efficiency without EPC as expected energy savings over the stay in the dwelling are too small.

Sensitivity to EPC introduction time t_{EPC}

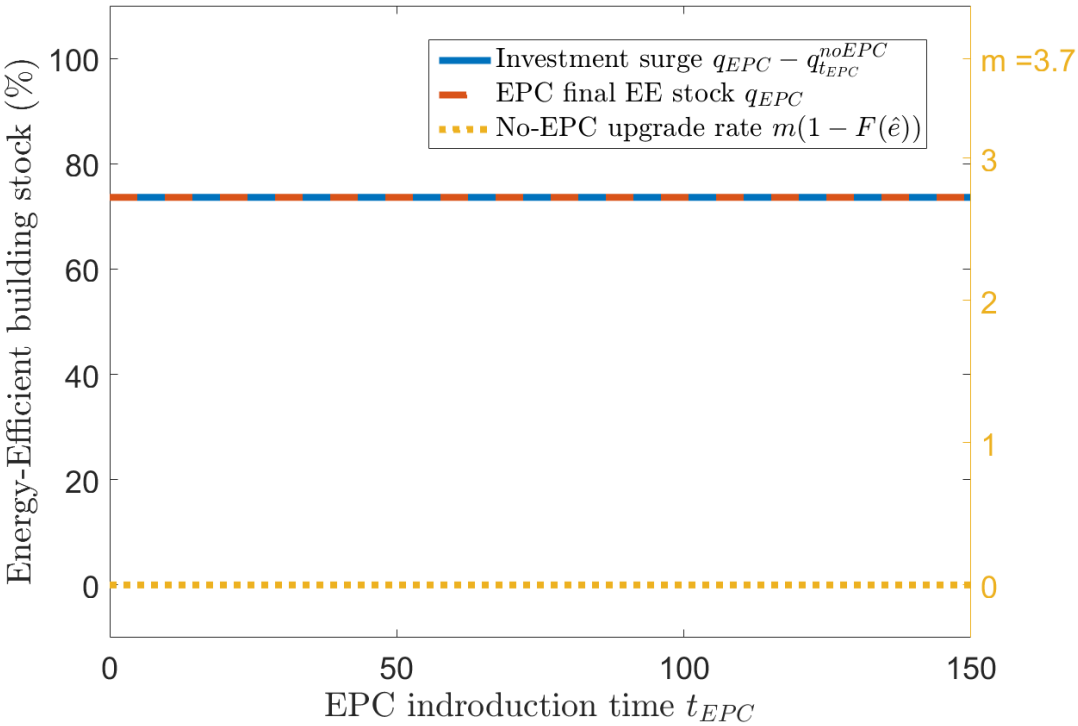


Figure 3.13: Sensitivity of baseline simulation to EPC introduction time t_{EPC}

As it is shown in figure 3.13, the introduction time of the EPC has no impact on the results

of our baseline simulation. Indeed, the introduction time has no effect on the incentives of households to invest when there is no EPC, and there is no retrofit before the introduction of the EPC whatever the introduction time is. Thus, the sensitivity analysis to the EPC introduction time t_{EPC} does not change the baseline specification conclusions where an EPC policy is more effective in the short and (foreseeable) long term.

3.4.3 Limitations

A major limitation of our model is the binary treatment of information. Either households are fully informed about energy performance or they are fully ignorant. Reality is likely more complex. On the one hand, as it is suggested by Olaussen et al. (2017), households have presumably some information about building energy performance even without EPC. Indeed, they know the age of the building, they can observe the presence of double-glazed windows, they can see if some insulation work has been done recently. On the other hand, information provided by the EPC is noisy (De Wilde, 2014). Therefore, even with an EPC, households can be upset by their building energy performance. Consequently, our model overestimates investment incentives induced by the introduction of the EPC and underestimates investment incentives in the absence of an EPC. This means that our simulations tend to overstate the effectiveness of the EPC, especially in the short term with the magnitude of the investment surge.

Obviously, our model has other numerous limitations made for tractability reasons. Input parameters are static: price, investment cost, housing market turnover, energy savings and discount rate are constant over time. Energy retrofit investment has an infinite lifetime. Building energy performance is binary. Population is homogeneous except for energy savings. While these assumptions are not realistic, we believe that our model is still able to capture relevant features of the dynamic of investment in building energy efficiency. And while absolute results produced by our simulations need to be taken with great caution, we believe that sensitivity analysis offers some useful policy insights.

3.5 Conclusion

We develop a simulation-based analysis of the impact of the introduction of the EPC on the energy performance building of the building stock in the French context. We find that an EPC policy requires moderate investment cost and moderate to high energy savings to be effective. Otherwise, it is either unnecessary compared to a scenario without EPC when energy savings are very high or investment costs are low, or insufficient when energy savings are low or investment costs are high. Besides, the more dispersion there is in energy consumption and energy savings among households, the less effective is an EPC policy because high-energy-use households who would invest even without EPC become more numerous. However, even for relatively high dispersion, we find that an EPC policy remains relevant. We also find that the effectiveness of an EPC policy is very dependent on the discount rate used by households. We find that a relatively low discount rate (less than 6%) is necessary for the EPC to be effective. Otherwise, future energy savings and price premium linked to high energy efficiency are discounted too heavily. Moreover, we find that an EPC policy is effective compared to a scenario without EPC even for small housing market turnover, and it becomes even more relevant when turnover is substantial. On the other hand, the timing at which an EPC policy is introduced (which can also be interpreted as the age of the building stock) does not seem to play a substantial role in the effectiveness of the EPC. Last but not least, our simulations quiet down worries that EPC could be detrimental to decrease energy consumption in the long term.

Our findings call for policymakers to use EPCs in interaction with other policy instruments: energy/carbon taxes to increase energy savings or subsidies to decrease investment costs. Also, they support the idea that credit access is a key factor in energy retrofit, not only because of the budget constraint (not considered in our model), but also because of households discounting which could be too high if credit access is limited.

With the modeling of the impact of an EPC policy, our paper offers a new brick for simulation-based research that could be added into more holistic simulation models such as Branger et al. (2015). Moreover, our paper lays the groundwork for future empirical research on the effects of the EPC. We hope that future research will allow to confront our simulation-based results with empirical results.

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Chapter 4

Effects of a Tax Credit Rate Increase on Residential Building Energy Efficiency Investments: Evidence from France

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Abstract

We study the impact of a tax credit scheme named "Crédit d'Impôt pour le Développement Durable" which is implemented in France since 2005 and which aims at encouraging households to invest in building energy efficiency equipments. We perform an econometric analysis of the effect of a 15-point tax credit rate increase implemented for a subgroup of the population using a difference in difference approach. We find that the 15-point tax credit

rate increase induces additional expenditures of €1,650 (+ 49%) on average for investments targeted by the rate increase. We also find preliminary evidence that there is substitution between eligible and non-eligible investments. As a result, we find that expenditures on non-eligible equipments are reduced by €420-650 on average. Our findings support the effectiveness of the CIDD to increase the amount spent by households in building energy efficiency investments and suggest that policymakers could use successfully differences in tax credit rates to target particular home energy efficiency investments.

Les bâtiments sont responsables d'environ 40% de la consommation d'énergie et 36% des émissions de CO2 dans l'UE. Une rénovation plus poussée des bâtiments existants pourrait permettre de réaliser d'importantes économies d'énergie et de réduire les émissions de CO2. Aux côtés d'autres instruments de politique publique, la France a mis en place depuis 2005 un système de crédit d'impôt nommé CIDD pour encourager les ménages à investir dans les équipements d'efficacité énergétique des bâtiments. Nous effectuons une analyse économétrique de l'effet d'une augmentation de 15 points du taux du crédit d'impôt sur les investissements des ménages français dans l'efficacité énergétique des bâtiments selon une approche par différence de différence. Nous constatons que l'augmentation du taux du crédit d'impôt induit des dépenses supplémentaires de €1,650 (+ 49%) en moyenne pour les équipements visés par la hausse du taux. Nous trouvons également des preuves préliminaires qu'il existe un effet de substitution entre les équipements visés par la hausse du taux et les autres équipements d'efficacité énergétique. En conséquence, nous constatons que les dépenses en équipements non éligibles sont réduites de €420-650 en moyenne. Nos constatations appuient l'efficacité du CIDD pour ce qui est d'accroître le montant dépensé par les ménages pour investir dans l'efficacité énergétique des bâtiments et suggèrent que les décideurs pourraient utiliser avec succès les différences de taux de crédit d'impôt pour cibler certains équipements d'efficacité énergétique dans le secteur résidentiel.

4.1 Introduction

Buildings are responsible for approximately 40% of energy consumption and 36% of CO2 emissions in the EU. Currently, about 35% of the EU's buildings are over 50 years old and almost

75% of the building stock is energy inefficient, while only 0.4-1.2% (depending on the country) of the building stock is renovated each year. Therefore, more renovation of existing buildings has the potential to lead to significant energy savings – potentially reducing the EU's total energy consumption by 5-6% and lowering CO2 emissions by about 5% (European Commission, 2018).

Along with other policy instruments, France has put in place since 2005 a tax credit scheme named "Crédit d'impôt pour le développement durable" (CIDD; in english: tax credit for sustainable development). Households who undertake home energy efficiency investments get partially reimbursed their investments via an income tax reduction, or a direct payment when households do not pay an income tax. The tax credit rate varies between 15% and 50% according to the year and equipment. Over the period 2005-2009, the public budget cost for home energy efficiency investments in the CIDD scheme was between 645 and 1,172 million euros annually (Administration, 2011). In 2018, the CIDD scheme still existed under the name "Crédit d'impôt pour la transition énergétique" (CITE; in english: tax credit for energy transition) for a total budget cost of 1,954 million euros (Honoré, 2018).

Analyzing and evaluating the impact of the CIDD is an important matter because of the substantial public expenditures that it represents and because of the ambitious GHG reduction goals in France and Europe (a cut of at least 40% compared to 1990 levels). This evaluation effort has been undertaken in Nauleau (2014), Mauroux (2014), Daussin-Benichou and Mauroux (2014) and Risch (2018). These papers evaluate the effect of the CIDD on the *intensive margin*, that is the number of households who decide to invest in building energy efficiency, and the *extensive margin*, that is the amount spent by households in building energy efficiency. They find a positive and significant effect of the CIDD in both cases, with various estimated values according to the year considered, the tax credit rate and the type of equipments.

Our paper continues this evaluation effort. The contribution of our paper is to apply the credible quasi-experiment framework used in Mauroux (2014) and Daussin-Benichou and Mauroux (2014) on a different dataset which has at least two advantages compared to the fiscal data used in the aforementioned papers: it does not suffer from the declaration bias[1] and it has substantially more control variables (including energy used in the dwellings and political prefer-

[1] An increase in the CIDD rate can encourage households to declare building energy efficiency investments that they would have done anyway.

ences). The quasi-experiment considered is a non-anticipated 15-point increase in the tax credit rate (the tax credit rate went from 25% to 40%) over the period 2006-2008 for households who live in a dwelling built before 1977 and who purchased it within 2 years. It allows us to define a treatment group and develop a difference in difference econometric analyis. We use a panel dataset provided by the French agency for environment and energy management ADEME[2] which contains detailed information on households energy use and home energy efficiency investments, socio-economic characteristics, and attributes of their dwellings. This is the same dataset used in Nauleau (2014) and Risch (2018), but with an identification strategy which is arguably less credible.

We do not find any statistically significant effect of the tax credit rate increase on the extensive margin. This is likely due to our limited number of observations which does not allow us to have a precise estimate of the effect of the tax credit rate increase on the extensive margin. On the other hand, we find evidence that the tax credit rate increase has a significant and substantial effect on the intensive margin. More precisely, We find that the tax credit rate increase induces additional expenditures of €1,650 (+ 49%) on average for equipments targeted by the rate increase. We also find preliminary evidence that there is a substitution effect between equipments targeted by the rate increase and other building energy efficiency equipments. As a result, we find that expenditures on non-eligible equipments are reduced by €420-650 on average. Our findings support the effectiveness of the CIDD to increase the amount spent by households in building energy efficiency investments and suggest that policymakers could use successfully differences in tax credit rate to target particular building energy efficiency equipments.

The remainder of the paper is structured as follows: section 4.2 reviews the literature on tax credit for building energy efficiency equipments, section 4.3 describes the CIDD scheme, section 4.4 presents the date used in the econometric analysis, section 4.5 presents the identification strategy, section 4.6 presents the results and section 4.7 concludes.

[2]In french: Agence de l'Environnement et de la Maîtrise de l'Energie

4.2 Literature Review

The French tax credit scheme CIDD has already been the subject of several papers. Nauleau (2014) focuses on insulation measures that are concerned by the CIDD. She estimates a logit model with random individual effects and finds that the tax credit had no significant effect during the first two years, suggesting a latency period related to inertia in households' investment decisions, possibly due to the complexity of the tax credit scheme. Then, she finds that the tax credit had an increasing, significant positive effect from 2007 to 2010, before slightly decreasing in 2011. She estimates the average proportion of free-riders to vary between 40% and 85% after 2006. Our paper uses the same database as Nauleau (2014), but includes measures concerning the heating system (change in boiler for instance). Also, we do not only look at the extensive margin (additional households who carry out energy efficiency measures in response to the tax credit scheme), but also at the intensive margin (additional expenditures made in energy efficiency measures in response to the tax credit scheme). Moreover, our identification strategy differs from Nauleau (2014). Nauleau (2014) does not use any time dummies and therefore do not control for time-varying effects such as more favorable macroeconomics situation, changes on the supply side, etc. Her estimates are therefore likely to be biased. With our identification strategy (presented in section 4.5), we are able to include time dummies and therefore control for all time-varying effects that impact homogeneously households.

Mauroux (2014) estimates on exhaustive fiscal data the impact of a marginal increase of the tax credit rate on the declaration rate of eligible households using a matching method combined with triple differences. She finds that if the tax credit rate had not been raised, in 2006 one eligible household in fifteen among the declarants living for less than three years in a dwelling completed between 1969 and 1976 would not have used this tax credit, one in eight in 2007 and in 2008. Daussin-Benichou and Mauroux (2014) complement the previous work by estimating the adjustment of households average expenditures after an unexpected increase in the tax credit rate (intensive margin). A difference-in-differences approach combined with a Tobit model and censored quantile regressions are estimated on exhaustive fiscal data. They find that households increased their housing improvement expenditures following the tax credit increase. Our paper uses an identification strategy that takes advantage of the same change in the tax credit scheme

as in Mauroux (2014) and Daussin-Benichou and Mauroux (2014). However, we carry out our analysis on a different dataset. French fiscal data have many advantages, among which they are exhaustive and reliable. However, the dataset that we use in this paper also has two important comparative advantages. First, in contrast with our database, fiscal data do not take into account households who make energy efficiency investments without declaring them (one reason for under declaration is the administrative burden). A second advantage is the relatively large number of control variables available in our dataset (including some variables about political preferences) compared to what is present in fiscal data.

Risch (2018) also evaluates the effect of the introduction of the CIDD in 2005 in a frawemork which is somewhat similar to Nauleau (2014). She finds that the effect on renovation rate is low, with an increase by 1.09% of the number of renovations (extensive margin). However, she finds an impact on renovation expenditures which is much higher with an increase of expenditures of 21.76%. Similarly to Nauleau (2014), the absence of time dummies prevents from disentangling the effects of the CIDD from the effects of other events that change over time: macroeconomic situation, energy prices, other policy instruments (informational instruments for instance), technology innovation on the supply side, etc.

There are also several empirical analysis of tax credits and similar financial incentives for home energy efficiency investments in EU countries and they often aim at measuring the free riding rate of the policy program considered, i.e. the share of households who would have invested in energy efficiency even in the absence of the program. Olsthoorn et al. (2017) perform a multi-country (EU states) contingent valuation experiment to evaluate a rebate program that promote the adoption of energy-efficient heating systems. They estimate that the share of free riders exceed 50% for most countries. Hecher et al. (2017) deal with Austrian data that was collected in an online survey carried out in 2015, from private homeowners of existing and newly built single and double-family houses in Austria who had invested in a new heating system within the last ten years. Subsidies for heating system investments and infrastructural adjustments reveal to be most effective for homeowners in problem situations to foster alternative heating systems. Collins and Curtis (2016) study the Irish case and find that free-riding varies by retrofit measure, with solar collector retrofits possessing close to zero free-riders, while free-riders comprised over 33% of heating controls retrofits. Compared to the rest of the literature, they find very low

free riding rates. Last, Alberini and Bigano (2015) evaluate incentives for residential energy upgrades in Italy using data from an original survey of Italian homeowners. they find that each $100 increase in the incentive amount raises the likelihood of replacing the heating system by 3 percentage points.

Financial incentives for home energy efficiency investments are also present in North America and have also been studied. For instance, Das et al. (2018) investigate demographic determinants of Canada's households' adoption of energy efficiency measures. They find that financial incentives offered via government grants are a substantial contributing factor for decisions regarding dwelling changes. Also, Rivers and Shiell (2016) look at subsidies for forced-air natural gas and furnaces and find that 50 percent of expenditures under the Canadian subsidy and tax credit programs represented free riding.

4.3 Description of the tax credit scheme CIDD

This section is essentially a synthesis of the description of the CIDD made in Nauleau (2014), Mauroux (2014) and Daussin-Benichou and Mauroux (2014).

4.3.1 Principles

Households can deduct from their income taxes 15 to 50 percent of their expenditures on energy conservation or renewable energy equipments in their primary home. If the tax credit exceeds the tax liability of the household, then the household is refunded the difference. This in particular the case for households who are not required to pay an income tax. The difference between the CIDD and a direct subsidy are a one year-delay in the reimbursements and the obligation to fill up an income tax form. The tax credit is capped at €8,000 for a single-person household and €16,000 for a two-person household, with an additional allowance of €400 per additional dependent person (usually children). These caps are applicable for a period of five consecutive years.

Until 2009, the tax credit was calculated on the prices of equipments and material costs (net of taxes), labor costs not included. Its rate depends on the installed item, the building construction date and the equipment installation year. Because it is calculated on the price excluding taxes,

it can be claimed in addition to the 5.5% VAT rate on housing repair services and products. Besides, if the household receives local or national subsidies for the equipment purchased, the tax credit is calculated on the total expenditures net of the other public subsidies. Eligible items are selected according to energy efficiency criteria which are regularly updated. They fall into three main categories:

- insulation and conservation investments: thermal insulation material such as fiberglass or mineral wool, double-glazed windows, shutters and doors
- heating system improvements: programmable thermostats, high efficiency boiler (low temperature and geothermal energy)
- equipments using a renewable source of energy: solar panels, solar water heat, geothermal energy

In our paper we mostly deal with the first two categories which are related to energy efficiency.

4.3.2 Evolution of the CIDD

Before the introduction of the CIDD in 2005, households could already benefit from a tax credit for their main residence for the installation of large heating equipments such as a collective boiler or a gas tank. However, it did not specifically target energy efficiency expenditures. Since 2001, renewable energy production equipments for new buildings were also eligible for the tax credit.

From 2005, the former tax credit for large equipments is replaced by the CIDD in 2005. Rates at the time are: 15% for a low-temperature boiler, 25% for a condensing boiler and thermal insulation materials, and 40% for renewable energy production equipments. The scheme has been modified several times with changes in the rates, list of eligible equipments and households, and performance criteria (table 4.1).

In 2006, the tax credit rate has been increased for energy efficiency improvements (excluding low-temperature boilers) when investment is made within two years following the acquisition of the dwelling which is required to be built before 1977. It becomes 40% instead of 25%. This rate increase has been removed in 2010. In 2009, many changes were made in the CIDD scheme: it was extended to landlords who rent their dwellings, the list of eligible expenditures has been revised

Type	Residence Eligibility	Tax credit rate (%)				
		2005	2006-2008	2009	2010	2011-2012
Boiler						
- low-temperature	Building age > 2 years	15	15			
- condensating	Building age > 2 years	25	25	25	15	13
	Built before 1977 and purchased within 2 years	25	40	40	15	13
Thermal insulation material						
- thermal insulation of opaque walls	Building age > 2 years	25	25	25(1)	25(1)	22(1)
	Built before 1977 and purchased within 2 years	25	40	40(1)	25(1)	22
- thermal insulation of glazed walls and shutters	Building age > 2 years	25	25	25	15	13
	Built before 1977 and purchased within 2 years	25	25	25	15	13
- thermal insulation of pipes	Building age > 2 years	25	25	25	25	22
	Built before 1977 and purchased within 2 years	25	40	40	25	22
- front door	Building age > 2 years				15	13
Heating control appliances	Building age > 2 years	25	25	25	25	22
	Built before 1977 and purchased within 2 years	25	40	40	25	22
Energy generation equipment from a renewable energy source						
- general case	all (including new-built)	40	50	50	50	45
- solar panel	all (including new-built)	40	50	50	50-25(2)	22
- boiler and heating system with a biomass fuel	all (including new-built)	40	50	40	25(6)	22(6)
Heat pump for heat generation						
- general case	all (including new-built)	40	50	40	25	22,5
- air/air	all (including new-built)		50			
- geothermal	all (including new-built)	40	50	40	40	36
- thermodynamic for domestic hot water	all (including new-built)				40	36
Connection equipment to a district heating network mostly powered by renewable energy or a cogeneration installation	all (including new-built)		25	25	25	22
Equipment to collect and treat rainwater	Building age > 2 years		25	25	25	22
Energy performance certificate	Building age > 2 years			50	50	45

(1) Workforce expenditures included
(2) 50% until September 28th, 2010, 25% from September 29th, 2010

Table 4.1: Rates for the tax credit scheme CIDD according to year, type of equipment, households and dwellings characteristics - Source: Mauroux (2014)

(low temperature boilers and air-air heat pumps have been excluded, workforce expenditures for thermal insulation work have been included along with equipments to collect and treat rainwater and building energy performance assessments), tax credit rate was decreased from 50% to 40% for heat pumps (excluding air-air) and wood heating equipments.

Besides, in 2009 was introduced a zero-interest loan for home energy efficiency investments: the "éco-prêt à taux zéro" (Eco-PTZ). This loan is capped at €30,000 and should be reimbursed within 10 years. To be obtained, it is required to achieve at least two different types of deep renovation in a main residence built before 1990. The goal is to reduce credit constraints to finance energy efficiency investments. It can be combined with the CIDD.

The tax credit scheme CIDD was still active in 2018 under the name CITE (Crédit d'impôt pour la transition énergétique).

4.4 Data

4.4.1 Dataset

The dataset used in this paper is the same as in Nauleau (2014) and Risch (2018). It comes from the annual Energy Management (EM) survey carried out by ADEME[3] and TNS-Sofres[4]. This survey provides detailed information on French households dwellings, energy information, and their decision to insulate their dwelling or improve their heating system. A first questionnaire provides data on socio-economic variables, housing information (including heating energy source), and information about dweller's situation (occupation status, move-in date) and stated political preferences. Those who have invested in home insulation or heating system improvement during the last year (11–16% each year) answer a second questionnaire to provide additional information including investment type and costs.

We only take into account house-owners who live in a detached dwelling. Indeed, they have a strong control on the decision to investments and therefore they are the most susceptible to be reactive to an increase in the tax credit rate. In contrast, tenants depend on their landlords for their energy retrofit decisions and households in apartments usually need the agreement of the

[3]French public agency for environment and energy management (in french: Agence de l'environnement et de maitrise de l'énergie)

[4]Currently named Kantar TNS. French company which carries out surveys.

	(1) all		(2) control		(3) treatment	
	mean	sd	mean	sd	mean	sd
Eligible energy efficiency investment	0.11	0.31	0.098	0.30	0.32	0.47
Expenditures for eligible energy efficiency equipments	3,532.4	4,247.6	3,350.8	3,662.0	4,817.4	7,015.7
Total expenditures	4,557.9	4,863.2	4,411.5	4,499.5	5,856.0	7,230.0
Observations	13,029		12,479		550	

Table 4.2: Dependent variables - descriptive statistics

building council to act. Note that these different situations are addressed by additional policy instruments (for instance, since a law voted in 2014[5], building councils are required to put at least 5% of their annual budget in a fund dedicated to renovation work[6]).

The dataset initially covers the period 2000-2013 but we only use the period 2005-2008 in our paper. It has an unbalanced panel structure with a couple (household,dwelling) which represents an individual. It contains 13,573 observations corresponding to 6,463 couples (household, dwelling). Because of missing values in our different variables, the number 13,573 is an upper bound of the observations used in our analysis. On average, a couple (household, dwelling) stay 2.1 years in the panel.

For our dataset, we only keep energy efficiency investments that are eligible to a tax credit for dwellings built before 1977 and purchased within 2 years, that is thermal insulation materials and heating control appliances (see table 4.1).[7]

4.4.2 Descriptive statistics

Table 4.2 shows the means and standard deviations for the dependent variables. Home energy efficiency investments for eligible equipment represent 11% of the observations. The average expenditure is €3,532 on these equipments. However, there is a substantial gap between the treatment and the control group. Indeed, in the treatment group, almost one third (32%) of the

[5]Bill 2014-366 of March 24th, 2014 for housing access and renovated urbanism, also known as ALUR bill or Duflot II bill

[6]It only concerns buildings which are more than five years old

[7]Condensating boilers are also eligible for a rate increase. However, our database does not allow us to distinguish between the different types of boilers.

	(1) all mean	(2) control mean	(3) treatment mean
Moved in within two years	0.08	0.04	1.00
Dwelling built before 1977	0.65	0.63	1.00
Observations	13,573	12,962	611

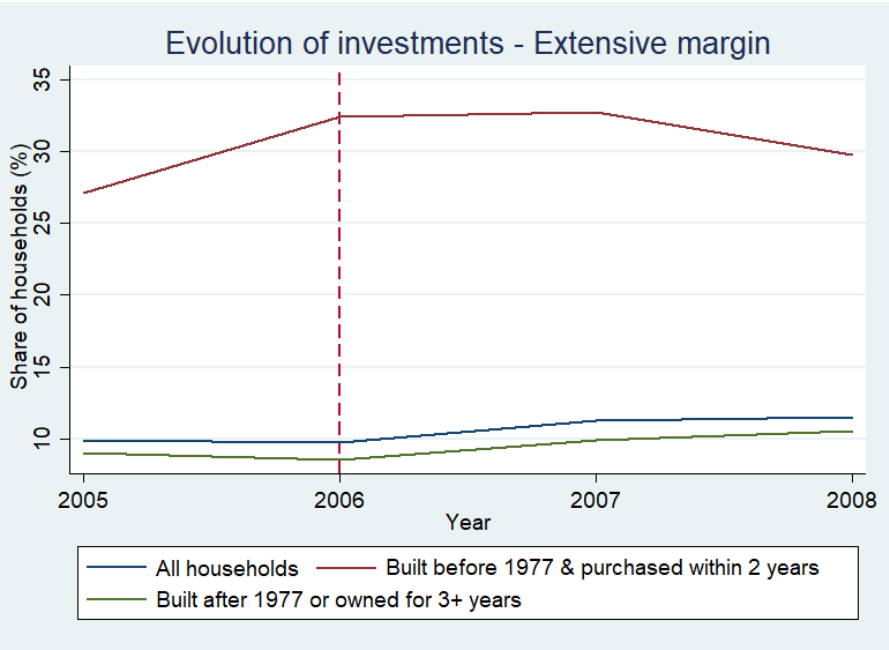
Table 4.3: Eligibility criteria - descriptive statistics

observations are concerned by a home energy efficiency investment while this represents only 9.8% of the observations in the control group. Moreover, the average expenditure among households who invest in eligible equipments is €4,817 in the treatment group in contrast to €3,351 in the control group. We find a similar difference when taking into account expenditures for all equipments (including non-eligible): average amount spent in the treatment group is €5,856 versus only €4,412 in the control group.

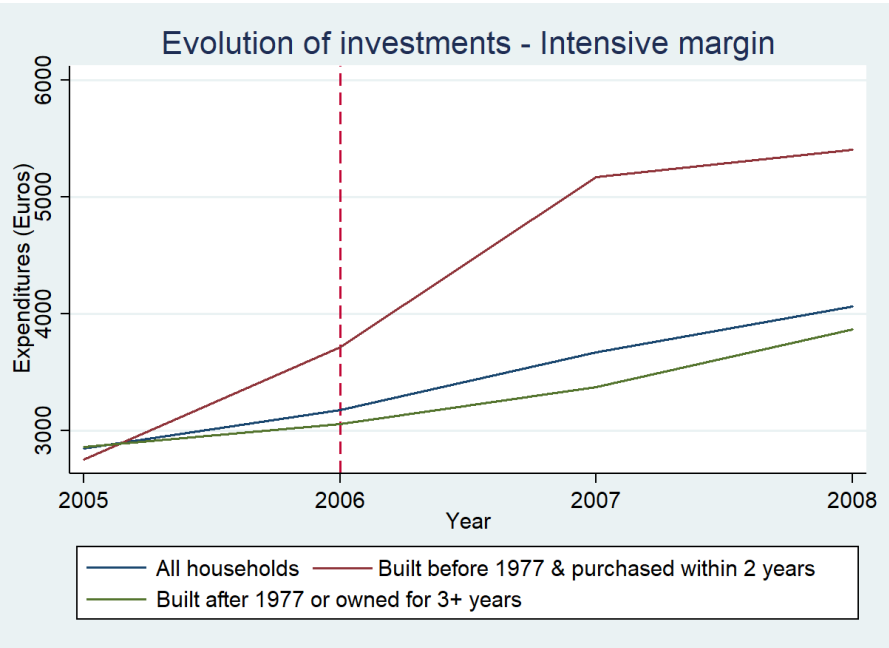
Figure 4.1a presents a less contrasted picture of the differences between the treatment group and the control group. Indeed, eligible households for the tax credit rate increase, that is households who have purchased within two years a dwelling built before 1977, already invested more than the other households before the rate increase: 27.1% of eligible households invested in home energy efficiency in 2005 when there was no tax credit rate increase versus 9.0% for the households not eligible to the tax credit rate increase. However, the share of households increase by 4 points right after the tax credit rate increase in 2006 for eligible households, at 32.5%, while it decreases by 0.5 point for non-eligible households, at 8.5%. Concerning the amount invested, presented in figure 4.1b, differences between eligible and non-eligible households are small before the tax rate increase: €2,752 spent on average by eligible households in 2005 versus €2,860 for non-eligible households. Over the period of the tax credit rate increase 2006-2008, expenditures increase in both cases, but substantially more for the eligible households. Thus, in 2007, eligible households spent on average €5,170 in home energy efficiency investments for featured equipments versus only €3,372 spent by non-eligible households.

Tables 4.3 to 4.9 show descriptive statistics for control variables used in our econometric analysis. Treatment group has slightly more revenues than the control group: average income of €28,596 in the control group and €29,987 in the treatment group [8]. Concerning political

[8]The difference is significant at a 5% level using the t test on the equality of means, but not at a 1% level



(a) Extensive margin (share of households who invest)



(b) Intensive margin (average expenditures in eligible home energy efficiency investments)

Figure 4.1: Evolution of investments in building energy efficiency

	(1) all mean	sd	(2) control mean	sd	(3) treatment mean	sd
Income - amount	28,658.4	15,047.3	28,596.0	15,041.3	29,987.2	15,125.7
Observations	13,306		12,709		597	

Table 4.4: Continuous control variables - descriptive statistics

	(1) all mean	(2) control mean	(3) treatment mean
Importance: pollution	0.58	0.58	0.64
Importance: unemployment	0.61	0.61	0.58
Importance: immigration	0.16	0.16	0.12
Importance: inequalities	0.38	0.38	0.42
Importance: scandals	0.06	0.06	0.05
Importance: crimes	0.33	0.33	0.28
Importance: education	0.17	0.17	0.25
Importance: pensions and retirement	0.30	0.30	0.29
Importance: Europe	0.06	0.06	0.05
Importance: terrorism	0.17	0.17	0.13
Importance: sovereignty	0.04	0.04	0.01
Importance: taxes	0.11	0.11	0.17
Observations	13,551	12,943	608

Table 4.5: Political preferences - Descriptive statistics

	(1) all mean	(2) control mean	(3) treatment mean
Fuel used in the dwelling: electricity	1.00	1.00	1.00
Fuel used in the dwelling: oil	0.25	0.25	0.23
Fuel used in the dwelling: natural gas	0.38	0.38	0.45
Fuel used in the dwelling: bottled gas	0.28	0.28	0.25
Fuel used in the dwelling: tank gas	0.04	0.04	0.03
Fuel used in the dwelling: petrol	0.05	0.05	0.06
Fuel used in the dwelling: coal	0.01	0.01	0.01
Fuel used in the dwelling: wood	0.43	0.44	0.39
Observations	13,571	12,961	610

Table 4.6: Energy fuel used in the dwelling - Descriptive statistics

	(1) all obs	pct	(2) control obs	pct	(3) treatment obs	pct
Size of the dwelling						
less than 50 m2	120	0.89	113	0.88	7	1.15
50-74 m2	975	7.22	909	7.05	66	10.87
75-99 m2	3,460	25.62	3,315	25.70	145	23.89
100-149 m2	6,106	45.22	5,861	45.44	245	40.36
150+ m2	2,843	21.05	2,699	20.93	144	23.72
Total	13,504	100.00	12,897	100.00	607	100.00
Past investments while enrolled in the panel						
0	11,792	87.41	11,283	87.57	509	83.99
1	1,489	11.04	1,400	10.87	89	14.69
2	191	1.42	183	1.42	8	1.32
3	19	0.14	19	0.15		
Total	13,491	100.00	12,885	100.00	606	100.00

Table 4.7: Dwelling characteristics - Descriptive statistics

preferences, treatment group is more concerned than the control group by pollution, education and taxes. It is less concerned than the control group by immigration, crimes, terrorism and sovereignty.[9] Concerning energy fuel used in the dwelling, treatment group uses more natural gas[10]. Treatment group tends to have more persons in the household, to invest in home energy efficiency for more occurrences during their stay in the panel, to live less in middle-size dwellings (75-149 m^2), to be more active (12.6% inactive household heads in the treatment group versus 50.1% in the control group) and younger (14.4% households are more than 55 years old in the treatment group versus 56.2% in the control group), and to have less rooms in their dwellings.[11]

4.5 Identification strategy

Our identification strategy is based on Mauroux (2014) and Daussin-Benichou and Mauroux (2014). We use the tax credit rate increase for eligible households as a quasi-experiment and a difference in difference approach to identify the effect of the tax credit rate increase. The tax credit rate increase was decided late in the year 2005 and was very unlikely to be anticipated by

[9]Differences are significant at a 1% level using the t test on the equality of means
[10]The difference is significant at a 1% level using the t test on the equality of means
[11]Differences are significant at a 5% level using the Pearson's chi-squared test

	(1) all obs	pct	(2) control obs	pct	(3) treatment obs	pct
Socio-professional category						
Farmer	206	1.52	196	1.51	10	1.64
Commercial, Artisan, Business Owner	346	2.55	332	2.56	14	2.30
Liberal Profession/Manager	1,267	9.34	1,146	8.84	121	19.84
Intermediary Profession	1,775	13.08	1,641	12.66	134	21.97
Clerk	1,019	7.51	929	7.17	90	14.75
Worker	2,384	17.57	2,220	17.13	164	26.89
Inactive	6,573	48.44	6,496	50.12	77	12.62
Total	13,570	100.00	12,960	100.00	610	100.00
Household head age						
less than 25 y.o.	19	0.14	9	0.07	10	1.64
25-34 y.o.	1,085	8.00	840	6.48	245	40.16
35-44 y.o.	2,611	19.24	2,411	18.60	200	32.79
45-54 y.o.	2,488	18.33	2,421	18.68	67	10.98
55-64 y.o.	2,480	18.28	2,431	18.76	49	8.03
65+ y.o.	4,887	36.01	4,848	37.41	39	6.39
Total	13,570	100.00	12,960	100.00	610	100.00
Household size						
1	2,278	16.82	2,201	17.02	77	12.64
2	5,736	42.35	5,539	42.83	197	32.35
3	1,940	14.32	1,796	13.89	144	23.65
4	2,527	18.66	2,384	18.43	143	23.48
5+	1,062	7.84	1,014	7.84	48	7.88
Total	13,543	100.00	12,934	100.00	609	100.00

Table 4.8: Household characteristics - Descriptive statistics

	(1) all		(2) control		(3) treatment	
	obs	pct	obs	pct	obs	pct
City category						
Paris area	1,001	7.38	965	7.45	36	5.90
> 100 000 inhabitants	2,975	21.92	2,840	21.91	135	22.13
20 000 - 100 000 inhabitants	1,909	14.07	1,838	14.18	71	11.64
2 000 - 20 000 inhabitants	2,882	21.24	2,747	21.20	135	22.13
Rural	4,803	35.39	4,570	35.26	233	38.20
Total	13,570	100.00	12,960	100.00	610	100.00
Region						
Ile de France	1,408	10.38	1,346	10.39	62	10.16
Nord	1,224	9.02	1,165	8.99	59	9.67
Lorraine	740	5.45	694	5.35	46	7.54
Alsace	364	2.68	349	2.69	15	2.46
Franche Comté	298	2.20	288	2.22	10	1.64
Champagne Ardennes	359	2.65	342	2.64	17	2.79
Picardie	503	3.71	470	3.63	33	5.41
Bourgogne	505	3.72	484	3.73	21	3.44
Haute Normandie	406	2.99	387	2.99	19	3.11
Basse Normandie	353	2.60	341	2.63	12	1.97
Centre	733	5.40	697	5.38	36	5.90
Loire	1,046	7.71	1,009	7.79	37	6.07
Bretagne	675	4.97	642	4.95	33	5.41
Poitou Charentes	551	4.06	533	4.11	18	2.95
Aquitaine	680	5.01	654	5.05	26	4.26
Midi Pyrénées	672	4.95	650	5.02	22	3.61
Limousin	183	1.35	170	1.31	13	2.13
Rhone Alpes	1,095	8.07	1,036	7.99	59	9.67
Auvergne	359	2.65	338	2.61	21	3.44
Languedoc	684	5.04	653	5.04	31	5.08
Provence Cote Azur	717	5.28	697	5.38	20	3.28
Corse	15	0.11	15	0.12	0	0.00
Total	13,570	100.00	12,960	100.00	610	100.0

Table 4.9: Local characteristics - Descriptive statistics

eligible households. As a result, we should not be worried about an overestimation of the effect of the treatment caused by households delaying their purchase.

Let us define the following events:

- P = Dwelling purchased within two years.
- B = Building built before 1977
- Y = year $\in [2006, 2008]$

We can now define the event treatment: $T = P \cap B \cap Y$.

4.5.1 Extensive margin

We use a logit framework in our econometric analysis of the extensive margin. Our main specification is a logit random-effect model that can be written:

$$\mathbb{P}(Invest_{it} = 1) = f(\alpha + \beta_T \mathbf{1}_T + \beta_1 \mathbf{1}_P + \beta_2 \mathbf{1}_B + \beta X_{it} + year_t + \mu_i + u_{it}) \tag{4.1}$$

where:

- $Invest_{it}$ is a dummy which denotes investment at time t for a couple (household, dwelling) i
- f is the function $x \mapsto \frac{\exp^x}{1+\exp^x}$
- X_{it} is the vector of time-variant control variables: annual income, household size, number of previous investments made when i was in the panel
- $year_t$ represents time dummies
- μ_i is the (household, dwelling)-specific random effect
- u_{it} is the error term

Because of the limited number of years in our panel (4 years) and because our panel is strongly unbalanced (on average, a couple (household, dwelling) stay 2.1 years in the panel), a fixed-effect model would discard too many observations to provide useful estimates. Because of the diverse

and relevant control variables that we have in our dataset, we can argue that we are able to control for (household, dwelling)-specific characteristics that are correlated with the treatment variable so that we can assume that the individual specific random effect is uncorrelated with the other independent variables.[12] We also use the same logit model without random effects as an alternative specification.

4.5.2 Intensive margin

For the intensive margin, we use a Tobit model similarly to Daussin-Benichou and Mauroux (2014). This can be written:

$$Expenditures_i = \begin{cases} Expenditures_i^* & \text{if } Expenditures_i^* > 0, \\ 0 & \text{if } Expenditures_i^* \leq 0. \end{cases} \tag{4.2}$$

where:

$$Expenditures_i^* = \alpha + \beta_T \mathbf{1}_T + \beta_1 \mathbf{1}_P + \beta_2 \mathbf{1}_B + \beta X_{it} + year_t + \mu_i + u_{it} \tag{4.3}$$

where X_{it} is the control variables vector and μ_i is an (household, dwelling)-specific random effect. We also use a simple tobit model without random effects as an alternative specification. As a robustness test, we use a linear regression model with results presented in the appendix.

4.6 Results

4.6.1 Extensive margin

Table 4.10 shows the results for the effects of the tax increase on the extensive margin, that is on the decision to invest in home energy efficiency for eligible equipements. We find a positive but not statistically significant effect of the tax credit rate increase for all specifications tested. Unlike the treatment, the variables "recent move-in" and "built before 1977" are positive and statistically significant. This is line with figure 4.1a where households who recently moved in a a building built before 1977 where far more likely to invest in home energy efficiency investments

[12] Nauleau (2014) also uses a random effects logit model but with a different identification strategy.

Investment in eligible equipments	logit RE (1)	logit RE (2)	logit RE (3)	logit (1)	logit (2)	logit (3)
Treatment variable	0.252	0.254	0.275	0.139	0.141	0.162
	(1.16)	(1.17)	(1.26)	(0.82)	(0.82)	(0.94)
Moved in within two years	0.958***	0.953***	0.932***	0.871***	0.866***	0.849***
	(5.39)	(5.36)	(5.21)	(6.09)	(6.05)	(5.88)
Dwelling built before 1977	1.131***	1.129***	1.119***	0.887***	0.883***	0.876***
	(9.93)	(9.90)	(9.78)	(10.60)	(10.55)	(10.39)
log(annual income)	0.122	0.115	0.117	0.0908	0.0859	0.0863
	(1.47)	(1.38)	(1.40)	(1.43)	(1.35)	(1.35)
Time dummies (ref: 2005)						
Year=2006	-0.0566	-0.0634	-0.0718	-0.107	-0.113	-0.122
	(-0.53)	(-0.59)	(-0.67)	(-1.13)	(-1.19)	(-1.27)
Year=2007	0.0326	0.0229	0.0146	-0.0952	-0.102	-0.109
	(0.31)	(0.21)	(0.14)	(-1.05)	(-1.12)	(-1.19)
Year=2008	0.0990	0.0774	0.0738	-0.106	-0.123	-0.127
	(0.87)	(0.67)	(0.64)	(-1.16)	(-1.33)	(-1.37)
Importance: pollution	0.0708	-0.102	-0.0972	0.0732	-0.0607	-0.0554
	(0.95)	(-0.57)	(-0.54)	(1.19)	(-0.40)	(-0.37)
Energy fuel	YES	YES	YES	YES	YES	YES
Dwelling characteristics	YES	YES	YES	YES	YES	YES
Household characteristics	YES	YES	YES	YES	YES	YES
City category	YES	YES	YES	YES	YES	YES
Additional political preferences	NO	YES	YES	NO	YES	YES
Region	NO	NO	YES	NO	NO	YES
Constant	-6.564***	-6.000***	-5.978***	-5.206***	-4.768***	-4.725***
	(-4.67)	(-4.00)	(-4.01)	(-4.56)	(-3.86)	(-3.84)
Constant	0.581***	0.583***	0.574***			
	(3.13)	(3.15)	(3.07)			
Observations	12,693	12,693	12,678	12,693	12,693	12,678

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors

Table 4.10: Logit regressions results - extensive margin for eligible equipments

even before the tax credit rate increase. We believe that the smaller number of observations and the higher number of control variables compared to Nauleau (2014), Mauroux (2014) and Risch (2018) mainly explain the relatively large standard deviations that we find for our treatment variable.

4.6.2 Intensive margin

Table 4.11 shows the results for the effects of the tax increase on the intensive margin, that is the amount spent for eligible home energy efficiency equipements. We find a statistically significant coefficient for our treatment variable with an estimated value around €1,650 depending on the specification. An interpretation is that households who would have invested without the tax credit rate increase would on average spend an additional amount of about €1,650 on eligible equipments if they can benefit from a tax credit rate increase. In relative term, this estimated additional expenditure for the treatment group represents 49% of what the control group spends on average on eligible equipments (€3,350).

We investigate the size of the substitution effects between energy efficiency equipments following a tax credit increase for a susbet of equipements. Households might spend more on eligible equipments and less on non-eligible equipments. Tables 4.12 and 4.13 try to answer this question. Table 4.12 shows the results for the effects of the tax increase on the total amount spent on home energy efficiency equipments, eligible and non-eligible to the tax credit rate increase. We find positive but not statistically coefficients with estimated values between €1,200 and €1,350 (versus €1,650 when taking into account only non-eligible equipments). With table 4.13, we try to see if this difference is statistically significant and we find limited evidence. For all specifications tested, we find a negative effect of an increase of the tax credit rate on expenditures on non-eligible equipments with estimated values between €-420 and €-650. However, this effect is statistically significant from zero only for the simple tobit specifications and not for the random effect tobit specifications. In relative term, the estimated net additional expenditure for the treatment group represents between 27% and 31% of what the control group spends on average on all building energy efficiency equipments (€4,412). This figure is consistent with what is found by Mauroux (2014): between 7% and 34% depending on the specifications and the year

Eligible expenditures	tobit RE (1)	tobit RE (2)	tobit RE (3)	tobit (1)	tobit (2)	tobit (3)
Treatment variable	1589.5**	1614.8**	1688.6**	1552.5***	1580.7***	1654.7***
	(2.03)	(2.07)	(2.17)	(11.68)	(11.86)	(12.42)
Moved in within two years	3061.7***	3039.5***	2958.7***	3156.7***	3128.6***	3047.4***
	(4.77)	(4.74)	(4.62)	(25.48)	(25.09)	(24.43)
Dwelling built before 1977	3651.1***	3622.4***	3596.7***	3489.3***	3456.7***	3436.7***
	(9.86)	(9.79)	(9.67)	(37.99)	(36.83)	(36.42)
log(annual income)	672.3**	664.9**	648.2**	677.5***	670.8***	653.1***
	(2.27)	(2.24)	(2.18)	(64.68)	(62.25)	(60.31)
Time dummies (ref: 2005)						
Year=2006	-412.3	-445.4	-473.6	-518.4***	-550.4***	-579.8***
	(-1.03)	(-1.11)	(-1.18)	(-7.45)	(-7.78)	(-8.15)
Year=2007	163.0	104.5	62.18	-38.65	-94.47	-137.9*
	(0.42)	(0.27)	(0.16)	(-0.53)	(-1.27)	(-1.84)
Year=2008	542.1	449.1	429.2	197.6***	111.0	91.39
	(1.39)	(1.13)	(1.08)	(2.65)	(1.43)	(1.17)
Importance: pollution	70.46	-465.7	-420.5	124.2	-387.0***	-340.3***
	(0.26)	(-0.72)	(-0.65)	(1.54)	(-4.81)	(-4.21)
Energy fuel	YES	YES	YES	YES	YES	YES
Dwelling characteristics	YES	YES	YES	YES	YES	YES
Household characteristics	YES	YES	YES	YES	YES	YES
City category	YES	YES	YES	YES	YES	YES
Additional political preferences	NO	YES	YES	NO	YES	YES
Region	NO	NO	YES	NO	NO	YES
Constant	-50834.7	-48810.3	-48217.5	-55119.7***	-53846.1***	-53290.4***
	(-0.03)	(-0.04)	(-0.04)	(-516.08)	(-489.87)	(-482.36)
sigma_u						
Constant	3619.1***	3596.0***	3568.6***			
	(9.47)	(9.40)	(9.32)			
sigma_e						
Constant	7147.5***	7137.8***	7132.5***			
	(30.81)	(30.82)	(30.87)			
sigma						
Constant				7957.7***	7938.5***	7922.3***
				(158.57)	(153.30)	(152.32)
Observations	12,516	12,516	12,516	12,516	12,516	12,516

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors for simple tobit regressions

Table 4.11: Tobit regressions results - Intensive margin for eligible equipments

Total expenditures	tobit RE (1)	tobit RE (2)	tobit RE (3)	tobit (1)	tobit (2)	tobit (3)
Treatment variable	1217.9	1244.5	1354.5	1195.5	1228.1	1341.1
	(1.46)	(1.49)	(1.62)	(1.43)	(1.48)	(1.61)
Moved in within two years	3466.4***	3431.4***	3328.7***	3539.8***	3496.2***	3392.9***
	(5.21)	(5.16)	(5.01)	(5.46)	(5.40)	(5.23)
Dwelling built before 1977	2942.0***	2906.1***	2872.5***	2791.0***	2757.1***	2729.0***
	(8.14)	(8.05)	(7.92)	(7.93)	(7.83)	(7.73)
log(annual income)	1011.1***	998.2***	972.6***	994.6***	983.9***	958.9***
	(3.33)	(3.28)	(3.19)	(3.50)	(3.46)	(3.37)
Time dummies (ref: 2005)						
Year=2006	33.05	-29.29	-35.09	-61.69	-119.3	-121.6
	(0.08)	(-0.07)	(-0.08)	(-0.15)	(-0.29)	(-0.30)
Year=2007	395.6	305.9	276.6	210.4	129.2	103.7
	(0.98)	(0.75)	(0.68)	(0.54)	(0.33)	(0.27)
Year=2008	1255.7***	1106.0***	1099.8***	954.4**	818.1**	818.7**
	(3.05)	(2.65)	(2.64)	(2.41)	(2.06)	(2.06)
Importance: pollution	90.87	-804.7	-768.5	128.5	-798.0	-762.8
	(0.33)	(-1.21)	(-1.15)	(0.48)	(-1.35)	(-1.29)
Energy fuel	YES	YES	YES	YES	YES	YES
Dwelling characteristics	YES	YES	YES	YES	YES	YES
Household characteristics	YES	YES	YES	YES	YES	YES
City category	YES	YES	YES	YES	YES	YES
Additional political preferences	NO	YES	YES	NO	YES	YES
Region	NO	NO	YES	NO	NO	YES
Constant	-15327.3	-12472.3	-12785.5	-15316.2***	-12425.5**	-12815.2**
	(-1.44)	(-1.16)	(-1.19)	(-3.18)	(-2.43)	(-2.51)
sigma_u						
Constant	3285.0***	3212.4***	3151.0***			
	(6.04)	(5.83)	(5.62)			
sigma_e						
Constant	8670.7***	8675.4***	8672.5***			
	(34.16)	(34.24)	(34.22)			
sigma						
Constant				9244.0***	9224.4***	9201.8***
				(38.76)	(38.76)	(38.93)
Observations	12,468	12,468	12,468	12,468	12,468	12,468

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors for simple tobit regressions

Table 4.12: Tobit regressions results - Intensive margin for all (eligible and non-eligible) equipments

Non-eligible expenditures	tobit RE (1)	tobit RE (2)	tobit RE (3)	tobit (1)	tobit (2)	tobit (3)
Treatment variable	-656.3	-596.6	-410.9	-648.5***	-588.9***	-426.6*
	(-0.47)	(-0.43)	(-0.30)	(-2.87)	(-2.60)	(-1.87)
Moved in within two years	4306.7***	4222.0***	4039.9***	4315.3***	4228.2***	4041.5***
	(4.05)	(3.97)	(3.80)	(21.97)	(21.37)	(20.33)
Dwelling built before 1977	993.3*	959.8*	919.6	966.4***	935.1***	908.0***
	(1.72)	(1.66)	(1.59)	(6.07)	(5.77)	(5.57)
log(annual income)	1219.5**	1172.4**	1133.1**	1212.1***	1166.2***	1148.4***
	(2.36)	(2.26)	(2.19)	(65.10)	(60.70)	(59.54)
Time dummies (ref: 2005)						
Year=2006	1176.1	1027.0	1034.2	1171.4***	1022.4***	1083.9***
	(1.61)	(1.40)	(1.41)	(9.41)	(8.03)	(8.45)
Year=2007	554.2	426.7	375.3	535.7***	409.4***	426.8***
	(0.77)	(0.59)	(0.52)	(4.17)	(3.11)	(3.22)
Year=2008	1895.0***	1672.5**	1637.4**	1860.3***	1639.6***	1679.4***
	(2.70)	(2.36)	(2.32)	(13.81)	(11.71)	(11.97)
Importance: pollution	17.69	-1277.5	-1326.8	20.02	-1285.0***	-1312.4***
	(0.04)	(-1.13)	(-1.17)	(0.14)	(-8.88)	(-9.01)
Energy fuel	YES	YES	YES	YES	YES	YES
Dwelling characteristics	YES	YES	YES	YES	YES	YES
Household characteristics	YES	YES	YES	YES	YES	YES
City category	YES	YES	YES	YES	YES	YES
Additional political preferences	NO	YES	YES	NO	YES	YES
Region	NO	NO	YES	NO	NO	YES
Constant	-110591.8	-103103.2	-128568.3	-112380.7***	-107610.9***	-108222.8***
	(-0.02)	(-0.03)	(-0.04)	(-588.81)	(-546.29)	(-547.15)
sigma_u						
Constant	2100.8	1989.1	331.1			
	(1.28)	(1.15)	(0.36)			
sigma_e						
Constant	11879.0***	11877.3***	11953.2***			
	(23.83)	(23.84)	(28.82)			
sigma						
Constant				12061.4***	12040.0***	11946.7***
				(131.03)	(126.78)	(125.53)
Observations	12,468	12,468	12,468	12,468	12,468	12,468

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors for simple tobit regressions

Table 4.13: Tobit regressions results - Effect of tax credit rate increase on non-eligible equipments expenditures

considered.

As a robustness test, we perform linear regressions for the intensive margin in the appendix and we find similar results.

4.7 Conclusion

We perform an econometric analysis of the effect of a 15-point tax credit rate increase on investments in home energy efficiency equipments using a difference in difference approach. We do not find any statistically significant effect of the tax credit rate increase on the extensive margin, that is on the number of households who decide to invest in home energy efficiency. This is likely due to our limited number of observations which does not allow us to have a precise estimate of the effect of the tax credit rate increase on the extensive margin. On the other hand, we find evidence that the tax credit rate increase has a significant effect on the intensive margin, that is the amount spent on home energy efficiency equipments. More precisely, we find that the tax credit rate increase induce additional expenditures of about €1,650 on average for equipments targeted by the rate increase. We also find preliminary evidence that there is a substitution effect between equipments targeted by the rate increase and other home energy efficiency equipments. As a result, we find that expenditures on non-eligible equipments are reduced by €420-650 on average.

Our work contributes to the empirical analysis and evaluation of the CIDD scheme and supports the effectiveness of the CIDD to increase the amount spent by households in home energy efficiency investments. Moreover, it also suggests that policymakers could use successfully differences in tax credit rate to target particular home energy efficiency equipments.

Our work presents several limitations. First, we do not measure the impact of home energy efficiency investments on the home energy consumption. Yet, it would be a key step to assess the cost effectiveness of the CIDD scheme. Second, we are not able to assess the long term impact of the tax credit rate increase to understand to which extent housedholds accelerate spendings that they would have done later anyway. Houde and Aldy (2014) look at subsidies for energy-efficient appliances and analyze intertemporal substitution effects. They find that some consumers accelerated the replacement of their old appliances by a few years, but overall the

impact of the program on long-term demand is likely to be very small. Also, Rivers and Shiell (2016) look at subsidies for forced-air natural gas and furnaces and find that in the long run, over 80 percent of grant recipients would have chosen an identical furnace at the time of replacement. Thus, our work calls for further research on the empirical analysis and evaluation of the CIDD scheme.

4.8 Appendix

4.8.1 Intensive margin - Linear regression

Table 4.14 shows the results for the effects of the tax increase on the intensive margin for eligible equipments when using a linear regression. We find positive and partially statistically significant coefficients (significant at the 10% level for 4 specifications out of 6) for our treatment variable with an estimated value between 0.4 and 0.5. This means that on average, we find that households spend between 40% and 50% more on eligible equipments if they can benefit from a tax credit rate increase. This is in line with what we found in our tobit specification.

When we study the effect of the tax credit rate increase on all home energy efficiency expenditures (eligible or not), we find a smaller effect, with an estimated value between 0.20 and .25 for our treatment variable (corresponding to an increase in expenditures between 20% and 25%). However, this effect is not statistically significant. We would also like to see if the substitution effect between eligible and non-eligible equipment is significant. However, the number of observations for which there is a strictly positive difference between total expenditures and eligible expenditures is too small (176) to perform a regression.

Eligible expenditures	OLS RE (1)	OLS RE (2)	OLS RE (3)	OLS (1)	OLS (2)	OLS (3)
Treatment variable	0.477*	0.484*	0.502*	0.379	0.390	0.411*
	(1.86)	(1.88)	(1.95)	(1.57)	(1.62)	(1.72)
Moved in within two years	-0.219	-0.224	-0.227	-0.193	-0.200	-0.205
	(-1.00)	(-1.03)	(-1.05)	(-0.93)	(-0.97)	(-1.00)
Dwelling built before 1977	0.253**	0.251*	0.246*	0.271**	0.272**	0.269**
	(1.97)	(1.95)	(1.85)	(2.17)	(2.17)	(2.09)
log(annual income)	0.223**	0.240**	0.231**	0.244***	0.260***	0.246***
	(2.40)	(2.56)	(2.44)	(2.71)	(2.86)	(2.67)
Time dummies (ref: 2005)						
Year=2006	0.0695	0.0546	0.0359	0.0935	0.0840	0.0676
	(0.55)	(0.42)	(0.28)	(0.71)	(0.63)	(0.51)
Year=2007	0.201	0.183	0.158	0.229*	0.216*	0.192
	(1.63)	(1.47)	(1.26)	(1.82)	(1.71)	(1.52)
Year=2008	0.376***	0.356***	0.345***	0.388***	0.370***	0.360***
	(3.12)	(2.88)	(2.76)	(3.21)	(2.99)	(2.89)
Importance: pollution	-0.143*	-0.126	-0.0661	-0.120	-0.0941	-0.0322
	(-1.75)	(-0.73)	(-0.39)	(-1.45)	(-0.54)	(-0.19)
Energy fuel	YES	YES	YES	YES	YES	YES
Dwelling characteristics	YES	YES	YES	YES	YES	YES
Household characteristics	YES	YES	YES	YES	YES	YES
City category	YES	YES	YES	YES	YES	YES
Additional political preferences	NO	YES	YES	NO	YES	YES
Region	NO	NO	YES	NO	NO	YES
Constant	3.709***	3.603***	3.501***	3.491***	3.351***	3.287***
	(3.20)	(2.88)	(2.73)	(3.07)	(2.74)	(2.62)
Observations	1172	1172	1172	1172	1172	1172

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors

Table 4.14: Linear regressions results - Intensive margin for eligible equipments

All expenditures	OLS RE (1)	OLS RE (2)	OLS RE (3)	OLS (1)	OLS (2)	OLS (3)
Treatment variable	0.251	0.250	0.263	0.198	0.193	0.206
	(1.23)	(1.21)	(1.27)	(0.99)	(0.96)	(1.03)
Moved in within two years	0.0437	0.0425	0.0286	0.0339	0.0345	0.0232
	(0.26)	(0.25)	(0.17)	(0.20)	(0.20)	(0.14)
Dwelling built before 1977	0.0406	0.0436	0.0539	0.0526	0.0581	0.0685
	(0.42)	(0.45)	(0.54)	(0.55)	(0.61)	(0.70)
log(annual income)	0.295***	0.305***	0.311***	0.307***	0.320***	0.321***
	(3.58)	(3.69)	(3.73)	(3.76)	(3.90)	(3.87)
Time dummies (ref: 2005)						
Year=2006	0.189*	0.187*	0.182*	0.226**	0.225**	0.225**
	(1.86)	(1.82)	(1.75)	(2.10)	(2.07)	(2.06)
Year=2007	0.197*	0.196*	0.189*	0.229**	0.228**	0.224**
	(1.94)	(1.92)	(1.84)	(2.22)	(2.21)	(2.16)
Year=2008	0.384***	0.376***	0.374***	0.410***	0.399***	0.402***
	(3.81)	(3.65)	(3.60)	(4.03)	(3.87)	(3.86)
Importance: pollution	-0.109	-0.00627	0.0330	-0.0844	-0.0136	0.0249
	(-1.62)	(-0.04)	(0.22)	(-1.22)	(-0.09)	(0.17)
Energy fuel	YES	YES	YES	YES	YES	YES
Dwelling characteristics	YES	YES	YES	YES	YES	YES
Household characteristics	YES	YES	YES	YES	YES	YES
City category	YES	YES	YES	YES	YES	YES
Additional political preferences	NO	YES	YES	NO	YES	YES
Region	NO	NO	YES	NO	NO	YES
Constant	4.016***	3.734***	3.242***	3.886***	3.689***	3.225***
	(4.08)	(3.48)	(2.95)	(3.96)	(3.50)	(2.98)
Observations	1,632	1,632	1,632	1,632	1,632	1,632

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4.15: Linear regressions results - Intensive margin for all (eligible and non-eligible) equipments

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Chapter 5

Home Energy Efficiency Investments in Response to Energy Price Variations: an Empirical Investigation using French Data

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Abstract

We study how energy prices affect households decisions to invest in home energy efficiency using micro panel data from France. To do so, we exploit the fact that households use different energy fuels for heating and that these energy fuels have distinct price evolution. We do not find evidence that an increase in energy fuel price has an effect on the propensity to invest in home energy efficiency or on the amount spent on home energy efficiency expenditures. These results call for a continuation of the research effort to evaluate the impact of energy prices on households' decision to invest in home energy efficiency.

Nous étudions comment les prix de l'énergie influencent les décisions d'investissement des ménages dans la performance énergétique de leur logement à l'aide de données de panel provenant de France. Pour ce faire, nous exploitons le fait que les ménages utilisent différents combustibles énergétiques pour le chauffage et que ces combustibles ont une évolution distincte des prix. Nous ne trouvons pas de preuves statistiques qu'une augmentation du prix du combustible énergétique a un effet sur la propension à investir en rénovation énergétique ou sur le montant dépensé pour la rénovation. Ces résultats appellent à la poursuite des efforts de recherche pour évaluer l'impact des prix de l'énergie sur la décision des ménages d'investir dans la performance énergétique de leur logement.

5.1 Introduction

In 2010, residential buildings accounted for 24 % of final energy use at the global, more than one half used for heating (32% for space heating and 24% for water heating). Given these numbers, many policy makers view residential energy conservation as a major tool to limit greenhouse gas emissions. There is also robust evidence that, in existing buildings, 50-90% energy savings have been achieved throughout the world through deep retrofit (Intergovernmental Panel on Climate Change, 2014). This explains why many countries set quantitative energy retrofit target. In France, the governmental objective is the renovation of 500,000 dwellings per year from 2017 onward (out of 29 million principal residences).

Policymakers can and currently use several instruments to boost energy efficiency investments in existing buildings: home renovation subsidies, thermal standards, energy labeling, energy auditing. However, increasing energy prices through energy taxation and carbon pricing remains

the most straightforward policy approach to do so. It is expected that, in the long run, households adapt to higher energy prices by purchasing energy-efficient appliances and lighting, insulating their home or improving their heating system. Home insulation and heating system renovation are of particular interest because they deal with the majority of home energy consumption (Intergovernmental Panel on Climate Change, 2014).

In this paper, we seek to estimate the impact of residential energy price increases on household investment decisions in home energy efficiency. It is part of the broader research effort on the energy efficiency gap where a challenge is to evaluate if consumers pay sufficient attention to energy price when they make energy-related decisions (Allcott and Greenstone, 2012). In this literature, the papers that specifically examine investment decisions in home insulation and heating has mostly focused on household reaction to investment subsidies (Daussin-Benichou and Mauroux, 2014; Nauleau, 2014). The main contribution of our paper is the focus on instruments that increase energy prices (in particular, carbon taxes).

We use a panel data from France extracted from a survey describing household energy-related behavior over the period 2000-2013. This dataset contains information about energy efficiency investments made by households along with other information about dwelling, households and heating system characteristics. We take advantage of the fact that households use different energy fuels with different energy prices to identify the effect of a price increase on their investment decision.

We do not find evidence that an increase in energy fuel price has an effect on the propensity to invest in home energy efficiency (*extensive margin*) or on the amount spent on home energy efficiency expenditures (*intensive margin*). Besides, the size of our standard errors does not allow us to eliminate the possibility that an energy price increase can have a substantial effect on home energy efficiency investments. These results call for a continuation of the research effort to evaluate the impact of energy prices on households' decision to invest in home energy efficiency.

The rest of the paper is organized as follows: section 5.2 provides a literature review of the long-run response to energy price increase, section 5.3 introduces the data, section 5.4 presents the econometric specification, results are shown in section 5.5 and section 5.6 concludes.

5.2 Literature Review

The literature on long-run household response to energy prices mostly focuses on appliances and cars, probably because workable data are more easily available. Jacobsen (2015) finds no evidence that increases in electricity prices make consumers more likely to purchase high efficiency Energy Star appliances. On the other hand, Rapson (2014) has results that indicate that consumers are forward-looking and value the stream of future savings derived from energy efficiency for air conditioners. Cohen et al. (2017) also find that consumers factor fairly well energy prices when they purchase refrigerators and that they show only little myopia. When buying cars, recent econometric analysis tend to show that consumers are quite attentive to energy prices when purchasing their automobiles: Allcott and Wozny (2014) find little consumer myopia and Busse et al. (2013) have results that are coherent with consumers who are not myopic with respect to energy prices.

When restricting to home insulation and heating system improvement, the literature is scarcer. Sahari (2017) analyzes heating technology choice for Finnish home builders. She shows that home builders substitute away from electric heating as electricity prices rise, resulting in increased installations of wood heating and ground source heat pumps. While she only focuses on new buildings and on the type of heating fuel, our paper focuses on all buildings and also includes investments in heating system improvement and home insulation. Moreover, our panel data structure allows us to have dwelling and household fixed effects which make our results more robust and which is not possible with her data.

When dealing with home insulation investments and heating system improvement, most papers that we find try to assess the impact of subsidies such as tax credits. Daussin-Benichou and Mauroux (2014) and Nauleau (2014)[1] look at the impact of the French tax credit on households investment decisions. They both find a positive effect even though free riding is rather large. To complement households reaction to subsidies that these papers look at, our paper aims at analyzing how consumers would react to an increase in the carbon tax in terms of home insulation investments and heating system improvements. To the best of our knowledge, this question has not been addressed before.

[1] We use the same dataset as Nauleau (2014).

Finally, papers with a more aggregated or indirect approach suggest that households react to energy prices in the long run. Alberini et al. (2011) adopts an aggregated approach and studies the short term and long term residential demand for electricity and gas. They find higher elasticity of demand in the long run than in the short run, which is a hint for energy management investments. However, whether it is home insulation, heating installation system or energy-efficient appliances, we do not know. Myers (2017) finds that relative fuel price shifts cause relative changes in housing transaction prices consistent with home buyers being attentive to energy costs. This is an incentive for households to adapt their heating technology in the long run. However, she does not directly measure this adaptation. Harjunen and Liski (2014) do a similar job for the Finnish market and they find a difference in price between electricity dwellings and district heating dwellings that reflect the difference in energy prices.

5.3 Data description

5.3.1 Dataset

The data used in this paper mainly comes from the annual Energy Management (EM) survey carried out by ADEME[2] and TNS-Sofres[3]. This survey provides detailed information on French households dwellings, energy information, and their decision to invest in home energy efficiency. A first questionnaire provides data on socio-economic variables, housing information (including heating energy source), and information about dweller's situation (occupation status, move-in date). Those who have invested in home energy efficiency answer a second questionnaire to provide additional information including investment type and costs.

Home energy efficiency investments can be of two kinds: home insulation or improvement of the heating installation. A given household can undertake both types of investments in the same year. Home insulation investments are all investments which aim at limiting energy loss in the building without modifying the energy production and regulation system. They include wall, ceiling, floor and pipes insulation, weatherstripping, window and curtains change. On the other hand, heating installation investments include improvement, installation or replacement

[2]French public agency for environment and energy management (in french: Agence de l'environnement et de maitrise de l'énergie)

[3]Currently named Kantar TNS. French company which carries out surveys.

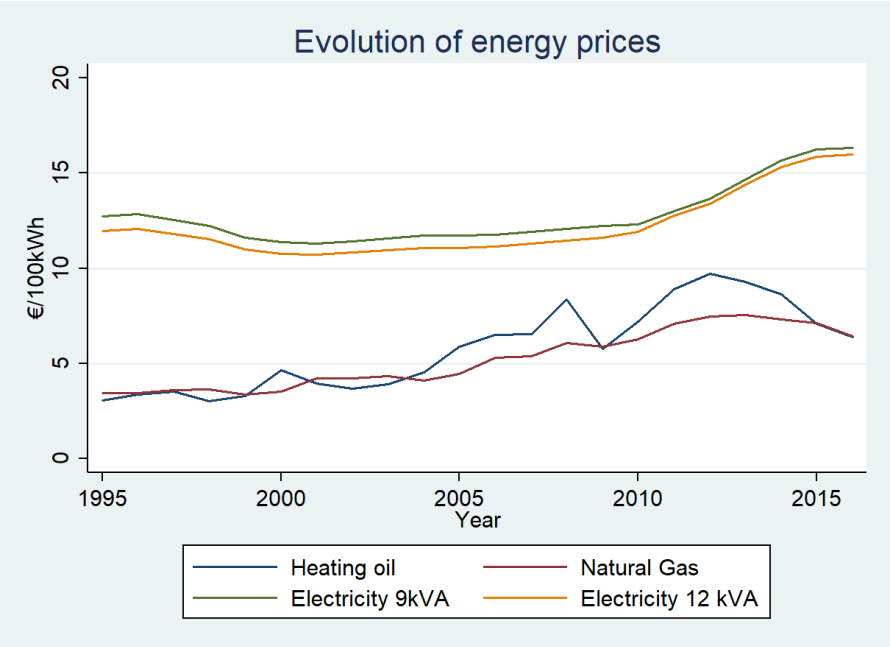
of the boiler/heat pump/fireplace/ventilation system or one of its components, installation or replacement of a water heater, installation of a (programmable) thermostat, a meter, a radiator or a thermostatic radiator valve.

We only take into account house-owners who live in a detached dwelling. Indeed, they have a strong control on the decision to investments and therefore they are the most susceptible to be reactive to an increase in the energy price. In contrast, tenants depend on their landlords for their energy retrofit decisions and households in apartments usually need the agreement of the building council to act. Note that these different situations are addressed by additional policy instruments (for instance, since a law voted in 2014[4], building councils are required to put at least 5% of their annual budget in a fund dedicated to renovation expenditures[5]).

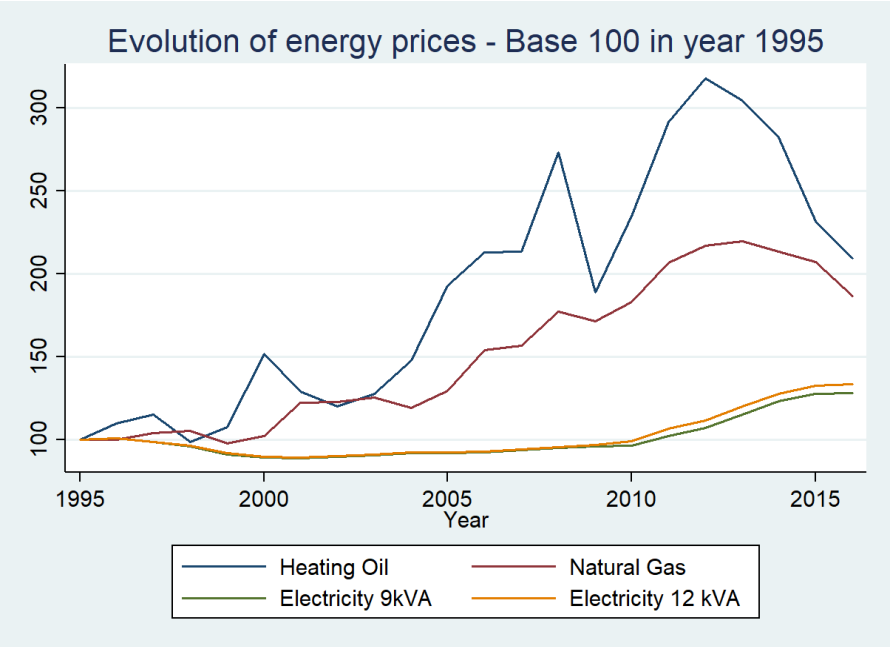
We also restrict our observations to households who use natural gas, electricity or heating oil as a main energy fuel for heating. Indeed, these are the three main energy fuels used in France by far (they represent 90% of the observations in the initial database). A small minority of households (4%) use firewood as a main energy fuel for heating. We choose not to take them into account because of the lack of relevant data for firewood prices. Indeed, firewood price is more heterogeneous and local than electricity, natural gas or heating oil prices because there is no national or global market or national regulation. Unfortunately, we do not have access to local firewood prices. Besides, some households even enjoy free access to firewood because of the proximity of a forest.

The dataset covers the period 2000-2013. It has an unbalanced panel structure. It contains 45,827 observations from 13,597 distinct households. On average, households are present during 3.4 years in the panel. Also, on average, 3,273 households are surveyed annually.

We complement the dataset with energy prices for French households from the Pegase database[6]. It provides annual prices paid by households for electricity, natural gas, heating oil, and other energy fuels.



(a) Energy prices in euro/100kWh



(b) Energy prices - base 100 in year 1995

Figure 5.1: Evolution of energy prices over the period 1995-2016

5.3.2 Descriptive statistics

Figure 5.1a shows the evolution of energy prices over the period 1995-2016. It is notable that electricity is far more costly than heating oil or natural gas (€12-16 per 100kWh versus €3-10 per 100 kWh). We report two prices for electricity depending on the power subscribed. Typically, houses which subscribe for 9kVA have a surface smaller than 100 m^2 while 12kVA is for surfaces larger than 100 m^2. Figure 5.1b shows the relative evolution for energy fuel prices over this period. While all energy fuel prices have an upper trend, heating oil and natural has increase far more than electricity. Heating oil price tripled between 1995 and 2013. At the same time, natural gas prices doubled and electricity price only increased by 26%. Our identification strategy is based on this variation.

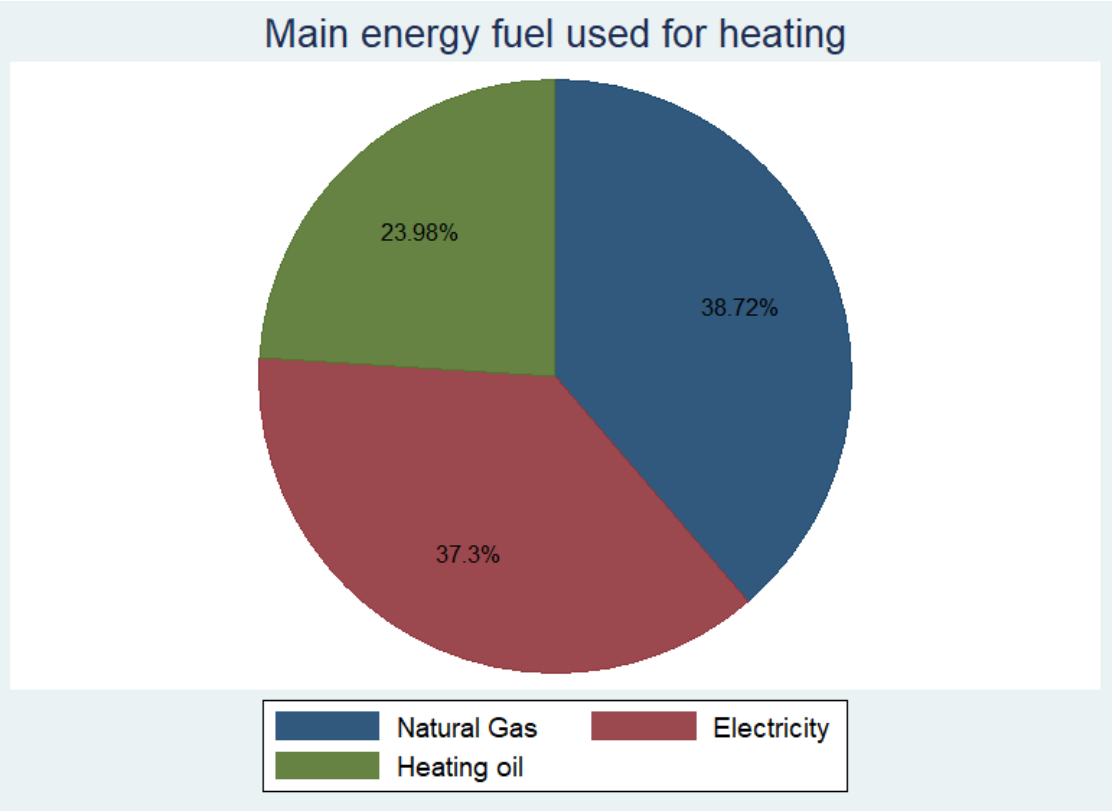


Figure 5.2: Main energy fuel used for heating in the dwelling in our dataset

[4]Bill 2014-366 of March 24th, 2014 for housing access and renovated urbanism, also known as ALUR bill or Duflot II bill

[5]It only concerns buildings which are more than five years old

[6]The Pegase database is maintained by a statistical agency which reports to French ministries in charge of environment, energy, construction, housing and transportation.

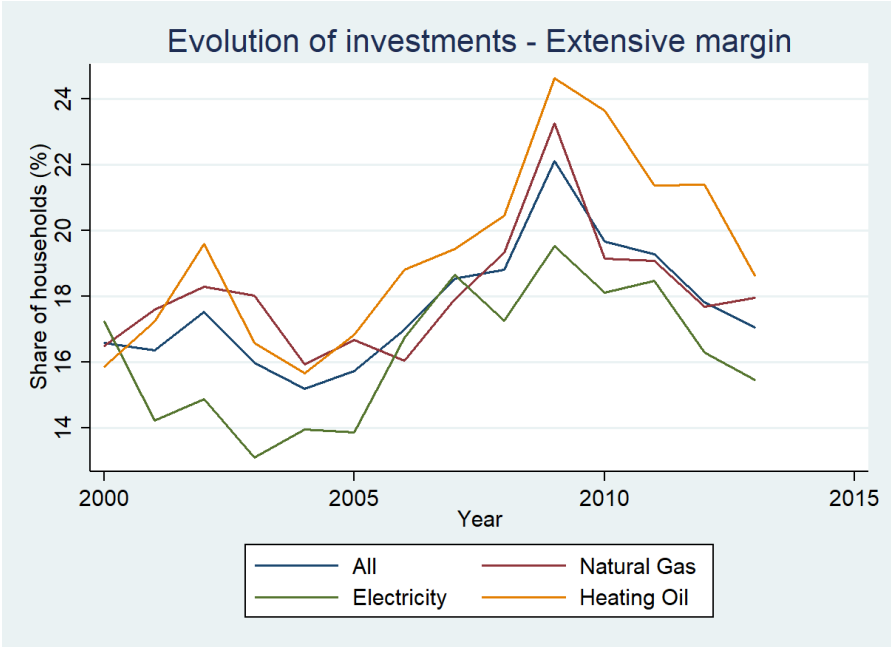
Figure 5.2 shows the distribution of the main heating energy fuel in our database. Natural gas is the most used heating energy fuel with more than one third of the households, closely followed by electricity. Heating oil comes last with less than one quarter of the observations. Note that electricity is more frequent in small apartments and that we restrict our analysis to detached dwellings. Also, even though firewood is minority, it becomes more and more popular. As mentioned earlier, the lack of granular data for firewood prices makes it less suitable for our analysis.

	(1) all		(2) Natural Gas		(3) Electricity		(4) Heating oil	
	mean	sd	mean	sd	mean	sd	mean	sd
Home energy efficiency investment	0.18	-	0.18	-	0.17	-	0.19	-
Total expenditures (euros)	4,195.3	4,560.7	3,970.3	4,111.1	4,284.8	4,850.5	4,437.9	4,831.9
Observations	45,827		17,745		17,092		10,990	

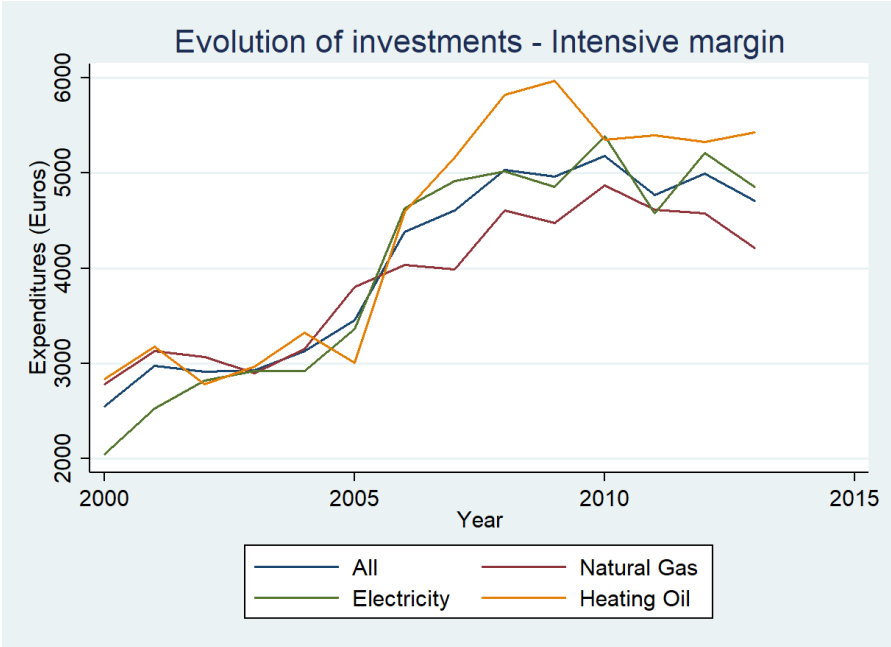
Table 5.1: Descriptive statistics of dependent variables

Figure 5.3a shows the evolution of the number of households who invest according to their main heating energy fuel. We see very similar trends for all energy fuels. From 2000 to 2005 the number of investments is stable, with a slight decrease for electricity. From 2005 to 2009 the number of households who invest in home energy efficiency increase for all energy fuels. When taking into account all households, the share increases from 16% in 2005 to 22% in 2009. In 2005 is introduced a tax credit scheme named "Crédit d'impôt pour le Développement Durable" (CIDD). Its goal is to encourage households to invest in home energy efficiency. It would be a plausible explanation for the increase of the number of households who invest in home energy efficiency over the period 2005-2009. Finally, the share of households who invest decrease over the period 2009-2013 (only 17% in 2013 versus 22% in 2009). A plausible explanation would be the global economic crisis which hit France over this period.

Figure 5.3b shows the evolution of average expenditures in home energy efficiency by households over time. Trends are similar to those for the extensive margin. First, expenditures do not vary much according to heating energy fuel. Second, we also distinguish three periods. First period is 2000-2005 where expenditures are stable at about €3,000. Then, expenditures increase over the period 2005-2009 by about €2,000 (the increase is higher for heating oil: households who use heating oil spent €3,000 more in 2009 compared to 2005). Last, expenditures are stable



(a) Extensive margin (share of households who invest)



(b) Intensive margin (average expenditures in home energy efficiency investments)

Figure 5.3: Evolution of investments in home energy efficiency

	(1) all		(2) Natural Gas		(3) Electricity		(4) Heating oil	
	mean	sd	mean	sd	mean	sd	mean	sd
Annual income (euros)	29,362.2	14,112.4	30,102.4	14,522.2	29,736.8	13,782.6	27,584.5	13,794.5
Length of stay in the dwelling	18.6	14.1	19.7	14.6	15.4	11.7	21.9	15.7
Importance: pollution	0.47	-	0.47	-	0.48	-	0.47	-

Table 5.2: Non categorical control variables - descriptive statistics

over the period 2009-2013.

Table 5.1 shows the mean and standard deviation of the two dependent variables used in the paper (binary variable for investment in home energy efficiency and positive continuous variable for total expenditures). On average, households who use heating oil invest more frequently (19%) than households who use natural gas (18%). Electricity users come last with an investment rate of 17%. These differences are statistically significant at the 1% level using the Pearson chi2 test. As far as expenditures are concerned, heating oil users also spend more for their home energy efficiency investments (€4,438 euros on average), followed by electricity users (€4,285) and then natural gas users (€3,970). These differences are also significant at the 1% level using the F statistics in the ANOVA test.

Table 5.2 shows the non categorical control variables (including binary variables) used in our econometric analysis. Households who use natural gas have slightly higher incomes than households who use electricity (€30,102 on average versus €29,737 for electricity users), and substantially higher incomes than households who use heating oil (€27,595 on average). Besides, households who use heating oil have the longest tenure in their dwellings (21.9 years on average) followed by natural gas users (19.7 years) and electricity users (15.5 years). All these differences are statistically significant at the 1% level using the F statistics of the ANOVA test. On the other hand, the stated importance of pollution is not statistically different among households according to their heating energy fuel (on average, 47 % of households mention pollution as being an important matter).

Table 5.3 shows descriptive statistics for variables concerning dwellings characteristics. Construction date is very important because of the improvements in the construction techniques over time and the evolution of construction standards, especially for energy efficiency requirements. France imposes building energy performance standards for new buildings since 1974 with

	(1) all		(2) Natural Gas		(3) Electricity		(4) Heating oil	
	obs	pct	obs	pct	obs	pct	obs	pct
Construction date								
before 1949	12,015	26.22	5,040	28.40	3,001	17.56	3,974	36.16
1949 - 1974	11,840	25.84	6,202	34.95	1,676	9.81	3,962	36.05
1975 - 1981	7,280	15.89	2,239	12.62	3,661	21.42	1,380	12.56
1982 - 1988	5,221	11.39	1,315	7.41	3,436	20.10	470	4.28
1989 - year of observation-1	9,019	19.68	2,858	16.11	4,971	29.08	1,190	10.83
year of observation	452	0.99	91	0.51	347	2.03	14	0.13
Total	45,827	100.00	17,745	100.00	17,092	100.00	10,990	100.00
Size of the dwelling								
less than 50 m2	349	0.76	116	0.66	187	1.09	46	0.42
50-74 m2	3,264	7.14	1,467	8.30	1,089	6.37	708	6.47
75-99 m2	12,888	28.19	5,385	30.45	4,961	29.03	2,542	23.23
100-149 m2	21,376	46.75	8,129	45.97	8,397	49.13	4,850	44.32
150+ m2	7,844	17.16	2,588	14.63	2,458	14.38	2,798	25.57
Total	45,721	100.00	17,685	100.00	17,092	100.00	10,944	100.00
Past investments while enrolled in the panel								
0	32,393	70.69	12,018	67.73	12,657	74.05	7,718	70.23
1	8,451	18.44	3,572	20.13	2,838	16.60	2,041	18.57
2	2,996	6.54	1,336	7.53	902	5.28	758	6.90
3	1,283	2.80	534	3.01	462	2.70	287	2.61
4	442	0.96	196	1.10	137	0.80	109	0.99
5	166	0.36	61	0.34	54	0.32	51	0.46
6	57	0.12	14	0.08	25	0.15	18	0.16
7	30	0.07	9	0.05	14	0.08	7	0.06
8	9	0.02	5	0.03	3	0.02	1	0.01
Total	45,827	100.00	17,745	100.00	17,092	100.00	10,990	100.00

Table 5.3: Dwelling characteristics - Descriptive statistics

the "Réglementation thermique" (RT).[7] Unsurprisingly, dwellings built before the 1973 oil shock use more heating oil and natural gas, and dwellings built after 1974 use more electricity. Also, dwellings which use heating oil tend to be larger. All these differences are statistically significant at the 1% level using the F statistics of the ANOVA test. We also control for past investments made while enrolled in the panel.

	(1) all		(2) Natural Gas		(3) Electricity		(4) Heating oil	
	obs	pct	obs	pct	obs	pct	obs	pct
Household head age								
less than 25 y.o.	62	0.14	23	0.13	27	0.16	12	0.11
25-34 y.o.	3,805	8.30	1,224	6.90	1,810	10.59	771	7.02
35-44 y.o.	8,249	18.00	3,099	17.46	3,303	19.32	1,847	16.81
45-54 y.o.	8,046	17.56	3,032	17.09	3,309	19.36	1,705	15.51
55-64 y.o.	9,328	20.35	3,597	20.27	3,672	21.48	2,059	18.74
65+ y.o.	16,337	35.65	6,770	38.15	4,971	29.08	4,596	41.82
Total	45,827	100.00	17,745	100.00	17,092	100.00	10,990	100.00
Household head socio-professional category								
Farmer	406	0.89	30	0.17	142	0.83	234	2.13
Commercial, Artisan, Business Owner	1,155	2.52	370	2.09	414	2.42	371	3.38
Liberal Profession/Manager	4,172	9.10	1,889	10.65	1,668	9.76	615	5.60
Intermediary Profession	6,521	14.23	2,602	14.66	2,767	16.19	1,152	10.48
Clerk	3,751	8.19	1,456	8.21	1,570	9.19	725	6.60
Worker	7,588	16.56	2,378	13.40	3,232	18.91	1,978	18.00
Inactive	22,234	48.52	9,020	50.83	7,299	42.70	5,915	53.82
Total	45,827	100.00	17,745	100.00	17,092	100.00	10,990	100.00
Household size								
1	7,174	15.65	2,861	16.12	2,604	15.24	1,709	15.55
2	20,689	45.15	8,051	45.37	7,285	42.62	5,353	48.71
3	6,660	14.53	2,602	14.66	2,609	15.26	1,449	13.18
4	8,068	17.61	3,007	16.95	3,217	18.82	1,844	16.78
5+	3,236	7.06	1,224	6.90	1,377	8.06	635	5.78
Total	45,827	100.00	17,745	100.00	17,092	100.00	10,990	100.00

Table 5.4: Household characteristics - Descriptive statistics

Table 5.4 shows descriptive statistics for households characteristics. Heating oil users tend to be older, followed by natural gas users. Electricity users tend to be younger. Their are more inactive households heads among heating oil users and natural gas users (more than half of the observations versus 43% of the observations for electricity users). Also, heating oil users tend to live more in a 2-person household. All these differences are statistically significant at the 1% level using the F statistics of the ANOVA test.

Table 5.5 shows the descriptive statistics for the local characteristics of the dwelling, namely

[7] These standards were upgraded in 1982, 1988, 2000, 2005 and 2012.

	(1) all		(2) Natural Gas		(3) Electricity		(4) Heating oil	
	obs	pct	obs	pct	obs	pct	obs	pct
City category								
Paris area	3,695	8.06	2,182	12.30	1,058	6.19	455	4.14
> 100 000 inhabitants	11,097	24.21	6,576	37.06	3,228	18.89	1,293	11.77
20 000 - 100 000 inhabitants	6,802	14.84	3,836	21.62	1,827	10.69	1,139	10.36
2 000 - 20 000 inhabitants	10,115	22.07	3,579	20.17	4,078	23.86	2,458	22.37
Rural	14,118	30.81	1,572	8.86	6,901	40.38	5,645	51.36
Total	45,827	100.00	17,745	100.00	17,092	100.00	10,990	100.00
Climate zone								
H1	26,163	57.09	11,605	65.40	8,096	47.37	6,462	58.80
H2	15,594	34.03	4,928	27.77	6,811	39.85	3,855	35.08
H3	4,070	8.88	1,212	6.83	2,185	12.78	673	6.12
Total	45,827	100.00	17,745	100.00	17,092	100.00	10,990	100.00

Table 5.5: Local characteristics - Descriptive statistics

its city category and its climate zone[8]. Indeed, dwellings with colder climate consume more energy for heating and therefore are more likely to undertake energy efficiency investments. Moreover, it is possible that it is easier to get an authorization for major renovation work in rural areas where the population is less dense and therefore there is less nuisance than in a more urban area. Natural gas is much more frequent in urban areas compared to other energy fuels, likely because of the presence of a gas network. On the other hand, heating oils is most used in rural area and less used in Paris area (let us recall that heating oil requires a storage volume which makes it less suitable in area like Paris where real estate price is high). Electricity, which is the most expensive energy fuel, is more popular in milder and warmer climate (H1 and H2). All these differences are statistically significant at the 1% level using the F statistics of the ANOVA test.

5.4 Econometric model

5.4.1 Extensive margin

Our identification strategy is based on the variation in prices between energy fuel used by households. The main econometric specification used in this paper to identify the effect of prices on

[8]Figure 5.4 in the appendix shows the different climate zones in Metropolitan France

the propensity to invest (the extensive margin) is the following logit framework:

$$\mathbb{P}(Investment_{it} = 1) = f\left(\alpha \log(\hat{p}_{it}) + \beta X_{it} + \mu_i + \delta_t + \epsilon_{it}\right) \tag{5.1}$$

where:

- i is a couple (household, dwelling)
- t is the year
- $Investment_{it}$ is a binary variable which indicates if the couple (household, dwelling) i has made an investment in home energy efficiency at time t.
- f is the function $x \mapsto \frac{\exp^x}{1+\exp^x}$.
- $\hat{p}_{it}$ is the price forecast of energy fuel used by i in the future at time t
- X_{it} is the vector of control variables which may vary over time: main heating energy fuel used in the dwelling, annual income, length of stay, number of past investments while enrolled in the panel, household characteristics (age and socio-professional category of the household head, size of the household)
- μ_i is the household-dwelling fixed effect. It allows to control for all unobserved characteristics of the household and dwelling
- δ_t represents time dummies that account for all yearly changes that affect uniformly the whole sample such as macroeconomic conditions (including inflation) or new policies such as the CIDD tax credit scheme.

Energy price forecast $\hat{p}_{it}$ of energy fuel used in dwelling i at time t Home energy efficiency expenditures are long-term investments. Energy-saving benefits do not depend on current energy prices whereas they depend on future energy prices. Thus, households need to forecast energy prices when they weigh investment opportunities. To model household beliefs about future energy prices, we use an adaptive expectation model. In such a model, people form their expectation about what will happen in the future based on what happened in the past.

Formerly:

$$\hat{p}_{zt} = \lambda \sum_{j=0}^{\infty} (1-\lambda)^j p_{z,t-j} \tag{5.2}$$

Typically, we use $\lambda = 0.5$ and equation 5.2 becomes:

$$\hat{p}_{it} = \frac{1}{2} p_{z,t} + \frac{1}{4} p_{z,t-1} + \frac{1}{8} p_{z,t-2} + \frac{1}{16} p_{z,t-3} + \dots \tag{5.3}$$

where z denotes the energy fuel used by household i at time t and $p_{z,t}$ denotes the price of energy fuel z at time t.

Because households do face energy prices when they pay their energy bill, it seems legitimate to include past energy prices in the households information set. It is possible that households use other sources of information to improve their energy price forecast. However, this information search is costly, unlike using past energy prices, and additional information is also very uncertain. Therefore, we believe such a restriction is a good approximation of how households forecast energy prices. In the appendix, we show results for alternative forecasting methods: current prices and moving average of past and future energy prices.

Endogeneity concerns Our identification strategy can lead to legitimate endogeneity concerns for our main independent variable: the energy price forecast. Indeed, we estimate a demand equation where energy efficiency is modeled as a substitute for energy use. Therefore, an increase in energy efficiency investment leads to a decrease in energy use and therefore has an impact on energy prices. We argue that energy prices are largely exogenous. Indeed, they are mostly determined by global commodity markets. Heating oil prices mostly depend on the global oil market and there is a regional market for natural gas. Electricity prices also depend to a lesser extent on global commodity markets, namely uranium, oil and natural gas. As a result, we argue that the French energy retrofit market has a negligible effect on energy prices and therefore endeogenity is not an issue. Nonetheless, we recognize that our analysis would be more robust with an adequate instrumental variable.

Additional specifications We also perform additional regressions with a random effect logit model and a simple logit model. To verify the assumptions of these two models, we add additional

control variables to account for individual characteristics which would lead to a potential omitted variable bias: dwelling characteristics, stated preference on pollution, local conditions. With these additional specifications, we hope to gain efficiency without losing consistency.

5.4.2 Intensive margin

For the intensive margin, that is the amount spent in home energy efficiency investments, we use a similar identification strategy with a Tobit model instead of a logit model. There does not exist a sufficient statistic allowing the fixed effects to be conditioned out of the likelihood. As a result, our main specification becomes the following random effects tobit model:

$$log(Expenditures_i) = \begin{cases} log(Expenditures_i^*) & \text{if } Expenditures_i^* > 1, \\ 0 & \text{if } Expenditures_i^* \leq 1. \end{cases} \tag{5.4}$$

where:

$$log(Expenditures_i^*) = \alpha \log(\hat{p}_{it}) + \beta X_{it} + \mu_i + \delta_t + \epsilon_{it} \tag{5.5}$$

We use the same control variables as for the extensive margin. As an alternative specification, we use a simple tobit model which trades efficiency with a greater risk of bias. Besides, we perform robustness tests with a linear specification (fixed effects, random effects and simple OLS) were we restrict our observations to households who invest in home energy efficiency. As for the extensive margin, we use alternative energy price forecast definition as robustness tests. All these results are presented in the appendix.

5.5 Results

5.5.1 Extensive margin

We first look at the impact of energy price forecast on the extensive margin, that is the prospensity to invest in energy efficiency. Results are presented in table 5.6.

We find a positive but not statistically significant effect of the energy fuel price forecast on the propensity to invest. Our robustness tests in the appendix also fail to reach statistical significance. Thus, our results do not provide evidence to support the idea that increasing energy prices would lead to more investments in home energy efficiency. Our standard errors are quite large so we are not able to bring meaningful insights on the size of the effect. Indeed, our most conservative estimate is that a 10% increase in energy price would lead to at most a 7% increase in the odds of investing in home energy efficiency with a 95% confidence level. 7% is quite substantial so we cannot conclude that an increase in energy fuel price would not lead to a substantial increase in the propensity to invest.

5.5.2 Intensive margin

We then look at the impact of expected energy price on the intensive margin, that is the amount invested in energy management for households who carry out investments. Results are presented in table 5.7.

We find a negative but not statistically significant effect of the energy fuel price forecast on the amount spent on home energy efficiency investments. Our robustness tests in the appendix also fail to reach statistical significance. Thus, our results do not provide evidence to support the idea that increasing energy prices would lead to more expenditures in home energy efficiency. Our standard errors are quite large so we are not able to bring meaningful insights on the size of the effect. Indeed, our most conservative estimate is that a 10% increase in energy price would lead to at most a 12% increase in the amount spent in home energy efficiency with a 95% confidence level. 12% is quite substantial so we cannot conclude that an increase in energy fuel price would not lead to a substantial increase in the amount spent home energy efficiency investments.

	logit FE		logit RE		logit	
Home energy efficiency investment						
log(Energy Price Forecast)	0.294	(0.243)	0.147	(0.174)	0.0580	(0.138)
Energy fuel for heating (ref: Natural Gas)						
Electricity	-0.185	(0.277)	-0.104	(0.150)	-0.0339	(0.117)
Heating oil	-0.961***	(0.196)	0.0636	(0.0568)	0.0650	(0.0411)
log(annual income)	0.134	(0.0883)	0.252***	(0.0415)	0.207***	(0.0319)
Length of stay in the dwelling	0.0161	(0.0160)	-0.0503***	(0.00424)	-0.0439***	(0.00307)
Length of stay in the dwelling × Length of stay in the dwelling	-0.000186	(0.000218)	0.000653***	(0.0000719)	0.000569***	(0.0000503)
Past investments while enrolled in the panel (ref: 0)						
Past work=1	-2.936***	(0.0650)	0.0206	(0.0477)	0.321***	(0.0337)
Past work=2	-4.847***	(0.106)	-0.00712	(0.0751)	0.554***	(0.0480)
Past work=3	-6.635***	(0.150)	-0.382***	(0.109)	0.503***	(0.0707)
Past work=4	-7.620***	(0.196)	-0.279*	(0.153)	0.861***	(0.110)
Past work=5	-8.948***	(0.272)	-0.392	(0.242)	0.912***	(0.181)
Past work=6	-9.697***	(0.387)	-0.310	(0.315)	1.276***	(0.286)
Past work=7	-11.48***	(0.522)	-1.098*	(0.567)	0.908**	(0.424)
Past work=8	-11.80***	(0.870)	-0.611	(1.141)	1.457*	(0.812)
Socio-professional category (ref: Farmer)						
Commercial, Artisan, Business Owner	3.042***	(0.976)	0.306	(0.233)	0.222	(0.184)
Liberal Profession/Manager	1.918**	(0.922)	0.354*	(0.213)	0.293*	(0.170)
Intermediary Profession	2.046**	(0.909)	0.423**	(0.210)	0.307*	(0.167)
Clerk	1.697*	(0.923)	0.375*	(0.214)	0.266	(0.170)
Worker	2.343**	(0.918)	0.425**	(0.209)	0.312*	(0.166)
Inactive	2.571***	(0.896)	0.558***	(0.213)	0.461***	(0.170)
Household head age (ref: less than 25 y.o.)						
25-34 y.o.	0.598	(0.943)	0.345	(0.416)	0.271	(0.324)
35-44 y.o.	0.613	(0.959)	0.0132	(0.415)	-0.0713	(0.324)
45-54 y.o.	0.600	(0.971)	-0.168	(0.415)	-0.213	(0.324)
55-64 y.o.	0.831	(0.981)	-0.165	(0.416)	-0.238	(0.324)
65+ y.o.	0.788	(0.990)	-0.481	(0.418)	-0.587*	(0.326)
Household size (ref: 1)						
2	-0.141	(0.178)	0.0766	(0.0606)	0.0265	(0.0432)
3	-0.146	(0.209)	0.107	(0.0741)	0.0567	(0.0551)
4	-0.188	(0.236)	-0.0345	(0.0788)	-0.0608	(0.0577)
5+	-0.375	(0.296)	-0.0401	(0.0960)	-0.0693	(0.0712)
Dwelling construction date (ref: before 1949)						
1949 - 1974			0.127**	(0.0496)	0.106***	(0.0367)
1975 - 1981			-0.0754	(0.0583)	-0.0462	(0.0433)
1982 - 1988			-0.329***	(0.0677)	-0.243***	(0.0498)
1989 - year of observation-1			-1.420***	(0.0665)	-1.138***	(0.0484)
year of observation			-0.689***	(0.150)	-0.504***	(0.127)
Dwelling size (ref: less than 50m2)						
50-74 m2			-0.163	(0.220)	-0.110	(0.174)
75-99 m2			0.0578	(0.215)	0.0577	(0.168)
100-149 m2			0.205	(0.215)	0.167	(0.168)
150+ m2			0.251	(0.218)	0.187	(0.171)
City category (ref.: Paris area)						
> 100 000 inhabitants			0.118	(0.0768)	0.0975*	(0.0565)
20 000 - 100 000 inhabitants			0.138*	(0.0818)	0.110*	(0.0608)
2 000 - 20 000 inhabitants			0.106	(0.0796)	0.0863	(0.0587)
Rural			0.124	(0.0792)	0.119**	(0.0584)
Importance: pollution			0.0742**	(0.0333)	0.0799***	(0.0275)
Climate zone (ref: H1)						
H2			-0.102**	(0.0419)	-0.0506*	(0.0303)
H3			-0.0901	(0.0710)	-0.0835	(0.0522)
Time dummies	YES		YES		YES	
Constant			-4.410***	(0.689)	-3.518***	(0.537)
Constant			0.0645	(0.0825)		
Observations	21,905		40,154		40,154	

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors except for FE logit

Table 5.6: Impact of heating fuel price forecast on the decision to invest in home energy efficiency - Adaptative expectation model for forecasting

	tobit RE		tobit	
log(Expenditures)				
log(Energy Price Forecast)	-0.976	(1.085)	-1.239	(1.045)
Energy fuel for heating (ref: Natural Gas)				
Electricity	0.414	(0.920)	0.641	(0.883)
Heating oil	0.240	(0.350)	0.255	(0.307)
log(annual income)	1.955***	(0.265)	1.907***	(0.239)
Length of stay in the dwelling	-0.270***	(0.0266)	-0.265***	(0.0230)
Length of stay in the dwelling × Length of stay in the dwelling	0.00355***	(0.000461)	0.00348***	(0.000383)
Household size (ref: 1)				
2	0.227	(0.357)	-0.0191	(0.318)
3	0.192	(0.455)	-0.0997	(0.411)
4	-0.700	(0.480)	-0.899**	(0.432)
5+	-1.400**	(0.598)	-1.511***	(0.546)
Past investments while enrolled in the panel (ref: 0)				
Past work=1	0.736***	(0.282)	2.196***	(0.250)
Past work=2	1.176***	(0.428)	3.922***	(0.351)
Past work=3	-0.892	(0.625)	3.256***	(0.531)
Past work=4	0.765	(0.917)	6.062***	(0.799)
Past work=5	-0.0749	(1.398)	6.326***	(1.289)
Past work=6	1.436	(2.150)	8.893***	(1.958)
Past work=7	-3.532	(3.262)	5.398*	(3.189)
Past work=8	-0.432	(5.199)	9.948*	(5.265)
Dwelling construction date (ref: before 1949)				
1949 - 1974	1.094***	(0.316)	1.014***	(0.276)
1975 - 1981	-0.0839	(0.371)	-0.00262	(0.326)
1982 - 1988	-1.070**	(0.421)	-0.882**	(0.369)
1989 - year of observation-1	-7.670***	(0.398)	-7.113***	(0.351)
year of observation	-11.61***	(1.486)	-11.09***	(1.546)
less than 50 m2	0	(.)	0	(.)
50-74 m2	-0.446	(1.349)	-0.224	(1.310)
75-99 m2	0.352	(1.314)	0.581	(1.271)
100-149 m2	1.273	(1.314)	1.398	(1.270)
150+ m2	1.282	(1.335)	1.327	(1.288)
Socio-professional category (ref: Farmer)				
Commercial, Artisan, Business Owner	2.188	(1.515)	1.744	(1.434)
Liberal Profession/Manager	3.123**	(1.396)	2.749**	(1.315)
Intermediary Profession	3.663***	(1.377)	3.070**	(1.298)
Clerk	3.525**	(1.399)	3.044**	(1.316)
Worker	3.220**	(1.369)	2.705**	(1.292)
Inactive	4.652***	(1.391)	4.269***	(1.320)
Household head age (ref: less than 25 y.o.)				
25-34 y.o.	9.958**	(4.127)	10.04**	(4.286)
35-44 y.o.	8.537**	(4.124)	8.365*	(4.282)
45-54 y.o.	7.936*	(4.125)	7.774*	(4.282)
55-64 y.o.	7.876*	(4.128)	7.647*	(4.280)
65+ y.o.	5.575	(4.138)	4.980	(4.286)
City category (ref.: Paris area)				
> 100 000 inhabitants	0.767	(0.486)	0.749*	(0.424)
20 000 - 100 000 inhabitants	0.950*	(0.520)	0.930**	(0.456)
2 000 - 20 000 inhabitants	0.942*	(0.500)	0.919**	(0.438)
Rural	0.949*	(0.498)	0.990**	(0.438)
Importance: pollution	0.321	(0.215)	0.367*	(0.206)
Climate zone (ref: H1)				
H2	-0.280	(0.260)	-0.0960	(0.226)
H3	-0.694	(0.436)	-0.688*	(0.392)
Time dummies	YES		YES	
Constant	-41.20***	(5.433)	-40.19***	(5.353)
sigma_u				
Constant	5.288***	(0.238)		
sigma_e				
Constant	11.50***	(0.160)		
sigma				
Constant			12.56***	(0.0626)
Observations	37,996		37,996	

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors for simple tobit

Table 5.7: Impact of energy price forecast on the amount invested in home energy efficiency - Adaptative expectation model for forecasting

5.6 Conclusion

We study how energy prices affect households decisions to invest in home energy efficiency using panel data from France. To do so, we use the fact that households use different energy fuels for heating and that these energy fuels have distinct price evolution. We fail to find evidence that an increase in energy fuel price has an effect on the propensity to invest in home energy efficiency or on the amount spent on home energy efficiency expenditures. Besides, the size of our standard errors does not allow us to eliminate the possibility that an energy price increase can have a substantial effect on home energy efficiency investments.

Our paper calls for further research on this very crucial topic for policymakers. Indeed, current renovation and energy retrofit rates in Europe are considered to be too low. Being able to assess the effectiveness of the different policy instruments at hand is therefore of a primary importance.

We see at least two directions for future research on this topic. A first one is to use a different dataset with a more balanced structure and which covers a longer period. A second one is to develop more efficient identification strategies which in particular deal with potential endogeneity concerns that are mentioned in this paper.

Last but not least, we recall that energy prices can affect households in different manners that are not covered in this paper. One natural extension of this research would be to study how energy fuel prices affect the choice of heating fuel in a dwelling when there is a boiler replacement. An hypothesis would be that instead of investing in energy efficiency because of an energy price increase, households opt to change their heating fuel.

5.7 Appendix

5.7.1 Moving average

We use the average of the two past energy prices, the current energy price and the two future energy prices as the energy price forecast:

$$\hat{p}_{it} = \frac{p_{z,t-2} + p_{z,t-1} + p_{z,t} + p_{z,t+1} + p_{z,t+2}}{5}$$

where z is the energy fuel used by household i at time t.

Extensive margin

Table 5.8 shows the results for the extensive margin. Similarly to our main specification, we do not find any statistically significant effect of an increase of the energy price forecast on the propensity to invest in home energy efficiency.

Intensive margin

Table 5.9 shows the results for the intensive margin. Similarly to our main specification, we do not find any statistically significant effect of an increase of the energy price forecast on the amount spent in home energy efficiency.

5.7.2 Current price

Heating fuel price forecast becomes the fuel energy price at time t:

$$\hat{p}_{it} = p_{z,t}$$

where z is the energy fuel used by household i at time t.

Extensive margin

Table 5.10 shows the results for the extensive margin. Similarly to our main specification, we do not find any statistically significant effect of an increase of the energy price forecast on the propensity to invest in home energy efficiency.

Intensive margin

Table 5.11 shows the results for the intensive margin. Similarly to our main specification, we do not find any statistically significant effect of an increase of the energy price forecast on the amount spent in home energy efficiency.

5.7.3 Linear model for intensive margin

We use a linear regression model for expenditures:

$$log(Expenditures_i) = \alpha \log(\hat{p}_{it}) + \beta X_{it} + \mu_i + \delta_t + \epsilon_{it} \tag{5.6}$$

Results are presented in table 5.12. Similarly to our main specification, we do not find any statistically significant effect of an increase of the energy price forecast on the amount spent in home energy efficiency. We also use a linear framework with our alternative specifications for energy price forecast and we still do not find any statistically significant results.

	logit FE		logit RE		logit	
Home energy efficiency investment						
log(Energy Price Moving Average)	0.212	(0.314)	0.0120	(0.227)	-0.0501	(0.180)
Energy fuel for heating (ref: Natural Gas)						
Electricity	-0.113	(0.303)	0.00507	(0.179)	0.0504	(0.140)
Heating oil	-0.964***	(0.198)	0.0790	(0.0625)	0.0795*	(0.0462)
log(annual income)	0.133	(0.0883)	0.253***	(0.0414)	0.208***	(0.0319)
Length of stay in the dwelling	0.0153	(0.0160)	-0.0503***	(0.00424)	-0.0439***	(0.00307)
Length of stay in the dwelling × Length of stay in the dwelling	-0.000174	(0.000218)	0.000653***	(0.0000718)	0.000568***	(0.0000502)
Past investments while enrolled in the panel (ref: 0)						
Past work=1	-2.937***	(0.0650)	0.0212	(0.0477)	0.321***	(0.0337)
Past work=2	-4.847***	(0.106)	-0.00499	(0.0750)	0.555***	(0.0480)
Past work=3	-6.636***	(0.150)	-0.380***	(0.109)	0.504***	(0.0706)
Past work=4	-7.622***	(0.196)	-0.276*	(0.152)	0.862***	(0.110)
Past work=5	-8.948***	(0.272)	-0.387	(0.242)	0.914***	(0.181)
Past work=6	-9.698***	(0.387)	-0.306	(0.315)	1.276***	(0.287)
Past work=7	-11.49***	(0.522)	-1.097*	(0.567)	0.907**	(0.424)
Past work=8	-11.80***	(0.871)	-0.606	(1.139)	1.458*	(0.811)
Socio-professional category (ref: Farmer)						
Commercial, Artisan, Business Owner	3.046***	(0.977)	0.304	(0.233)	0.221	(0.184)
Liberal Profession/Manager	1.925**	(0.923)	0.353*	(0.213)	0.292*	(0.170)
Intermediary Profession	2.056**	(0.910)	0.421**	(0.210)	0.305*	(0.167)
Clerk	1.700*	(0.924)	0.373*	(0.214)	0.264	(0.170)
Worker	2.348**	(0.919)	0.423**	(0.209)	0.311*	(0.166)
Inactive	2.575***	(0.897)	0.556***	(0.213)	0.460***	(0.170)
Household head age (ref: less than 25 y.o.)						
25-34 y.o.	0.598	(0.943)	0.340	(0.416)	0.268	(0.324)
35-44 y.o.	0.613	(0.958)	0.00838	(0.415)	-0.0739	(0.324)
45-54 y.o.	0.603	(0.971)	-0.171	(0.415)	-0.215	(0.324)
55-64 y.o.	0.831	(0.980)	-0.170	(0.416)	-0.241	(0.325)
65+ y.o.	0.786	(0.990)	-0.485	(0.419)	-0.589*	(0.327)
Household size (ref: 1)						
2	-0.142	(0.178)	0.0763	(0.0606)	0.0264	(0.0432)
3	-0.146	(0.209)	0.107	(0.0740)	0.0568	(0.0551)
4	-0.188	(0.236)	-0.0341	(0.0787)	-0.0604	(0.0577)
5+	-0.374	(0.296)	-0.0397	(0.0960)	-0.0689	(0.0712)
Dwelling construction date (ref: before 1949)						
1949 - 1974			0.127**	(0.0496)	0.106***	(0.0367)
1975 - 1981			-0.0737	(0.0583)	-0.0451	(0.0433)
1982 - 1988			-0.327***	(0.0677)	-0.242***	(0.0498)
1989 - year of observation-1			-1.420***	(0.0665)	-1.139***	(0.0484)
year of observation			-0.688***	(0.150)	-0.505***	(0.127)
Dwelling size (ref: less than 50m2)						
50-74 m2			-0.164	(0.220)	-0.110	(0.174)
75-99 m2			0.0556	(0.215)	0.0565	(0.168)
100-149 m2			0.200	(0.215)	0.164	(0.168)
150+ m2			0.246	(0.218)	0.183	(0.171)
City category (ref.: Paris area)						
> 100 000 inhabitants			0.118	(0.0767)	0.0975*	(0.0565)
20 000 - 100 000 inhabitants			0.138*	(0.0818)	0.110*	(0.0609)
2 000 - 20 000 inhabitants			0.106	(0.0796)	0.0866	(0.0587)
Rural			0.125	(0.0791)	0.119**	(0.0584)
Importance: pollution			0.0741**	(0.0333)	0.0798***	(0.0275)
Climate zone (ref: H1)						
H2			-0.102**	(0.0419)	-0.0508*	(0.0303)
H3			-0.0894	(0.0710)	-0.0832	(0.0522)
Time dummies	YES		YES		YES	
Constant			-4.218***	(0.725)	-3.363***	(0.566)
Constant			0.0625	(0.0825)		
Observations	21,905		40,154		40,154	

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors except for FE logit

Table 5.8: Impact of heating fuel price forecast on the decision to invest in home energy efficiency - Moving average of past and future energy prices for forecasting

	tobit RE		tobit	
log(Expenditures)				
log(Energy Price Moving Average)	-2.092	(1.410)	-2.186	(1.355)
Energy fuel for heating (ref: Natural Gas)				
Electricity	1.195	(1.095)	1.281	(1.050)
Heating oil	0.435	(0.386)	0.435	(0.346)
log(annual income)	1.957***	(0.265)	1.908***	(0.239)
Length of stay in the dwelling	-0.270***	(0.0266)	-0.266***	(0.0230)
Length of stay in the dwelling × Length of stay in the dwelling	0.00355***	(0.000461)	0.00349***	(0.000383)
Household size (ref: 1)				
2	0.225	(0.357)	-0.0201	(0.318)
3	0.191	(0.455)	-0.100	(0.411)
4	-0.698	(0.480)	-0.897**	(0.432)
5+	-1.400**	(0.598)	-1.511***	(0.546)
Past investments while enrolled in the panel (ref: 0)				
Past work=1	0.736***	(0.282)	2.196***	(0.250)
Past work=2	1.180***	(0.428)	3.924***	(0.351)
Past work=3	-0.895	(0.625)	3.253***	(0.531)
Past work=4	0.762	(0.917)	6.060***	(0.799)
Past work=5	-0.0819	(1.398)	6.321***	(1.288)
Past work=6	1.427	(2.150)	8.887***	(1.958)
Past work=7	-3.545	(3.262)	5.396*	(3.191)
Past work=8	-0.444	(5.199)	9.942*	(5.262)
Dwelling construction date (ref: before 1949)				
1949 - 1974	1.094***	(0.316)	1.015***	(0.276)
1975 - 1981	-0.0752	(0.371)	0.00320	(0.326)
1982 - 1988	-1.059**	(0.421)	-0.875**	(0.369)
1989 - year of observation-1	-7.671***	(0.398)	-7.114***	(0.351)
year of observation	-11.61***	(1.486)	-11.10***	(1.546)
Dwelling size (ref: less than 50m2)				
50-74 m2	-0.458	(1.349)	-0.233	(1.310)
75-99 m2	0.339	(1.314)	0.572	(1.271)
100-149 m2	1.247	(1.314)	1.379	(1.271)
150+ m2	1.257	(1.335)	1.309	(1.288)
Socio-professional category (ref: Farmer)				
Commercial, Artisan, Business Owner	2.173	(1.515)	1.733	(1.434)
Liberal Profession/Manager	3.113**	(1.396)	2.740**	(1.315)
Intermediary Profession	3.650***	(1.377)	3.060**	(1.298)
Clerk	3.512**	(1.399)	3.034**	(1.316)
Worker	3.208**	(1.369)	2.696**	(1.292)
Inactive	4.638***	(1.391)	4.259***	(1.320)
Household head age (ref: less than 25 y.o.)				
25-34 y.o.	9.929**	(4.124)	10.02**	(4.293)
35-44 y.o.	8.511**	(4.121)	8.344*	(4.290)
45-54 y.o.	7.912*	(4.122)	7.754*	(4.289)
55-64 y.o.	7.849*	(4.125)	7.625*	(4.288)
65+ y.o.	5.550	(4.135)	4.960	(4.294)
City category (ref.: Paris area)				
> 100 000 inhabitants	0.768	(0.486)	0.749*	(0.424)
20 000 - 100 000 inhabitants	0.954*	(0.520)	0.933**	(0.456)
2 000 - 20 000 inhabitants	0.946*	(0.500)	0.922**	(0.438)
Rural	0.953*	(0.498)	0.992**	(0.438)
Importance: pollution	0.320	(0.215)	0.366*	(0.206)
Climate zone (ref: H1)				
H2	-0.281	(0.260)	-0.0961	(0.226)
H3	-0.692	(0.436)	-0.688*	(0.392)
Time dummies	YES		YES	
Constant	-39.50***	(5.605)	-38.72***	(5.501)
sigma_u				
Constant	5.289***	(0.238)		
sigma_e				
Constant	11.50***	(0.160)		
sigma				
Constant			12.56***	(0.0626)
Observations	37,996		37,996	

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors except for simple tobit

Table 5.9: Impact of heating fuel price forecast on the decision to invest in home energy efficiency - Moving average of past and future energy prices for forecasting

	logit FE		logit RE		logit	
Home energy efficiency investment						
log(Current energy fuel price)	-0.0195	(0.220)	-0.00452	(0.158)	-0.0310	(0.130)
Energy fuel for heating (ref: Natural Gas)						
Electricity	0.0499	(0.257)	0.0174	(0.128)	0.0358	(0.103)
Heating oil	-0.943***	(0.197)	0.0813	(0.0567)	0.0761*	(0.0414)
log(annual income)	0.132	(0.0883)	0.253***	(0.0414)	0.208***	(0.0319)
Length of stay in the dwelling	0.0144	(0.0160)	-0.0503***	(0.00424)	-0.0439***	(0.00307)
Length of stay in the dwelling × Length of stay in the dwelling	-0.000159	(0.000218)	0.000653***	(0.0000718)	0.000568***	(0.0000502)
Past investments while enrolled in the panel (ref: 0)						
Past work=1	-2.936***	(0.0650)	0.0212	(0.0477)	0.321***	(0.0337)
Past work=2	-4.845***	(0.106)	-0.00482	(0.0750)	0.555***	(0.0480)
Past work=3	-6.638***	(0.150)	-0.379***	(0.109)	0.504***	(0.0706)
Past work=4	-7.622***	(0.197)	-0.275*	(0.152)	0.862***	(0.110)
Past work=5	-8.948***	(0.272)	-0.387	(0.242)	0.914***	(0.181)
Past work=6	-9.698***	(0.387)	-0.306	(0.316)	1.276***	(0.287)
Past work=7	-11.49***	(0.522)	-1.097*	(0.567)	0.907**	(0.424)
Past work=8	-11.80***	(0.871)	-0.606	(1.139)	1.458*	(0.811)
Socio-professional category (ref: Farmer)						
Commercial, Artisan, Business Owner	3.056***	(0.975)	0.304	(0.233)	0.221	(0.184)
Liberal Profession/Manager	1.938**	(0.920)	0.353*	(0.213)	0.292*	(0.170)
Intermediary Profession	2.070**	(0.907)	0.421**	(0.210)	0.305*	(0.167)
Clerk	1.707*	(0.921)	0.373*	(0.214)	0.265	(0.170)
Worker	2.357**	(0.916)	0.423**	(0.209)	0.311*	(0.166)
Inactive	2.580***	(0.895)	0.556***	(0.213)	0.460***	(0.170)
Household head age (ref: less than 25 y.o.)						
25-34 y.o.	0.596	(0.944)	0.339	(0.416)	0.269	(0.324)
35-44 y.o.	0.612	(0.959)	0.00813	(0.415)	-0.0733	(0.324)
45-54 y.o.	0.602	(0.972)	-0.171	(0.415)	-0.215	(0.324)
55-64 y.o.	0.825	(0.981)	-0.170	(0.416)	-0.240	(0.324)
65+ y.o.	0.777	(0.991)	-0.485	(0.419)	-0.588*	(0.326)
Household size (ref: 1)						
2	-0.143	(0.178)	0.0762	(0.0606)	0.0265	(0.0432)
3	-0.145	(0.209)	0.107	(0.0740)	0.0568	(0.0551)
4	-0.186	(0.236)	-0.0341	(0.0787)	-0.0604	(0.0577)
5+	-0.373	(0.296)	-0.0396	(0.0960)	-0.0689	(0.0712)
Dwelling construction date (ref: before 1949)						
1949 - 1974			0.127**	(0.0496)	0.106***	(0.0367)
1975 - 1981			-0.0736	(0.0583)	-0.0453	(0.0433)
1982 - 1988			-0.327***	(0.0676)	-0.242***	(0.0498)
1989 - year of observation-1			-1.420***	(0.0665)	-1.138***	(0.0484)
year of observation			-0.688***	(0.150)	-0.504***	(0.127)
Dwelling size (ref: less than 50m2)						
50-74 m2			-0.164	(0.220)	-0.110	(0.174)
75-99 m2			0.0554	(0.215)	0.0566	(0.168)
100-149 m2			0.200	(0.215)	0.165	(0.168)
150+ m2			0.245	(0.218)	0.184	(0.171)
City category (ref.: Paris area)						
> 100 000 inhabitants			0.118	(0.0767)	0.0975*	(0.0565)
20 000 - 100 000 inhabitants			0.138*	(0.0818)	0.110*	(0.0608)
2 000 - 20 000 inhabitants			0.106	(0.0796)	0.0866	(0.0587)
Rural			0.125	(0.0791)	0.119**	(0.0584)
Importance: pollution			0.0741**	(0.0333)	0.0798***	(0.0275)
Climate zone (ref: H1)						
H2			-0.102**	(0.0419)	-0.0507*	(0.0303)
H3			-0.0893	(0.0710)	-0.0832	(0.0522)
Time dummies	YES		YES		YES	
Constant			-4.193***	(0.686)	-3.391***	(0.536)
Constant			0.0624	(0.0825)		
Observations	21,905		40,154		40,154	

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors except for FE logit

Table 5.10: Impact of heating fuel price forecast on the decision to invest in home energy efficiency - Current energy fuel price for forecasting

	tobit RE		tobit	
log(Expenditures)				
log(Current Energy Fuel Price)	-1.359	(1.002)	-1.437	(0.978)
Energy fuel for heating (ref: Natural Gas)				
Electricity	0.632	(0.796)	0.705	(0.772)
Heating oil	0.301	(0.350)	0.297	(0.309)
log(annual income)	1.954***	(0.265)	1.905***	(0.239)
Length of stay in the dwelling	-0.270***	(0.0266)	-0.266***	(0.0230)
Length of stay in the dwelling × Length of stay in the dwelling	0.00355***	(0.000461)	0.00349***	(0.000384)
Household size (ref: 1)				
2	0.229	(0.357)	-0.0172	(0.318)
3	0.193	(0.455)	-0.0983	(0.411)
4	-0.699	(0.480)	-0.898**	(0.432)
5+	-1.400**	(0.598)	-1.511***	(0.546)
Past investments while enrolled in the panel (ref: 0)				
Past work=1	0.735***	(0.282)	2.195***	(0.250)
Past work=2	1.176***	(0.428)	3.922***	(0.351)
Past work=3	-0.899	(0.625)	3.251***	(0.531)
Past work=4	0.756	(0.917)	6.055***	(0.799)
Past work=5	-0.0782	(1.398)	6.326***	(1.288)
Past work=6	1.410	(2.150)	8.874***	(1.957)
Past work=7	-3.528	(3.261)	5.414*	(3.193)
Past work=8	-0.465	(5.199)	9.924*	(5.263)
Dwelling construction date (ref: before 1949)				
1949 - 1974	1.095***	(0.316)	1.015***	(0.276)
1975 - 1981	-0.0794	(0.371)	-0.000471	(0.326)
1982 - 1988	-1.065**	(0.421)	-0.880**	(0.369)
1989 - year of observation-1	-7.667***	(0.398)	-7.110***	(0.351)
year of observation	-11.60***	(1.486)	-11.09***	(1.546)
Dwelling size (ref: less than 50m2)				
50-74 m2	-0.450	(1.349)	-0.225	(1.310)
75-99 m2	0.346	(1.314)	0.578	(1.271)
100-149 m2	1.264	(1.314)	1.396	(1.270)
150+ m2	1.277	(1.335)	1.328	(1.288)
Socio-professional category (ref: Farmer)				
Commercial, Artisan, Business Owner	2.179	(1.515)	1.739	(1.434)
Liberal Profession/Manager	3.115**	(1.396)	2.743**	(1.315)
Intermediary Profession	3.652***	(1.377)	3.062**	(1.298)
Clerk	3.515**	(1.399)	3.037**	(1.316)
Worker	3.211**	(1.369)	2.700**	(1.292)
Inactive	4.643***	(1.391)	4.263***	(1.320)
less than 25 y.o.	0	(.)	0	(.)
25-34 y.o.	9.948**	(4.125)	10.04**	(4.289)
35-44 y.o.	8.531**	(4.122)	8.365*	(4.285)
45-54 y.o.	7.929*	(4.123)	7.771*	(4.285)
55-64 y.o.	7.869*	(4.126)	7.644*	(4.283)
65+ y.o.	5.566	(4.136)	4.977	(4.289)
City category (ref.: Paris area)				
> 100 000 inhabitants	0.767	(0.486)	0.748*	(0.424)
20 000 - 100 000 inhabitants	0.952*	(0.520)	0.931**	(0.456)
2 000 - 20 000 inhabitants	0.943*	(0.500)	0.920**	(0.438)
Rural	0.951*	(0.498)	0.991**	(0.438)
Importance: pollution	0.319	(0.215)	0.365*	(0.206)
Climate zone (ref: H1)				
H2	-0.280	(0.260)	-0.0954	(0.226)
H3	-0.694	(0.436)	-0.690*	(0.392)
Time dummies	YES		YES	
Constant	-40.58***	(5.415)	-39.82***	(5.339)
sigma_u				
Constant	5.290***	(0.238)		
sigma_e				
Constant	11.50***	(0.160)		
sigma				
Constant			12.56***	(0.0626)
Observations	37,996		37,996	

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors for simple tobit

Table 5.11: Impact of heating fuel price forecast on the decision to invest in home energy efficiency - Current energy prices for forecasting

	OLS FE		OLS RE		OLS	
log(Expenditures)						
log(Energy Price Forecast)	0.340	(0.348)	0.336*	(0.202)	0.259	(0.195)
Energy fuel for heating (ref: Natural Gas)						
Electricity	0.0948	(0.415)	-0.257	(0.168)	-0.198	(0.162)
Heating oil	-0.545**	(0.255)	-0.0592	(0.0611)	-0.0153	(0.0564)
log(annual income)	0.279*	(0.163)	0.156***	(0.0519)	0.167***	(0.0478)
Length of stay in the dwelling	0.0158	(0.0173)	0.00348	(0.00427)	0.00260	(0.00393)
Length of stay in the dwelling × Length of stay in the dwelling	-0.0000470	(0.000227)	-0.00000878	(0.0000716)	-0.00000444	(0.0000653)
Past investments while enrolled in the panel (ref: 0)						
Past work=1	-0.106*	(0.0633)	-0.0171	(0.0402)	-0.0298	(0.0440)
Past work=2	-0.191*	(0.100)	-0.0790	(0.0564)	-0.106*	(0.0582)
Past work=3	-0.423***	(0.142)	-0.198**	(0.0789)	-0.219***	(0.0785)
Past work=4	-0.398**	(0.192)	-0.0849	(0.123)	-0.138	(0.124)
Past work=5	-0.665***	(0.252)	-0.272	(0.178)	-0.288	(0.178)
Past work=6	-0.497	(0.340)	-0.121	(0.291)	-0.265	(0.336)
Past work=7	0.433	(0.356)	1.068***	(0.190)	0.753***	(0.237)
Past work=8	-0.463	(0.751)	0.250	(0.731)	-0.00944	(0.874)
Socio-professional category (ref: Farmer)						
Commercial, Artisan, Business Owner	0	(.)	0.113	(0.251)	0.0778	(0.232)
Liberal Profession/Manager	-1.263	(0.769)	-0.167	(0.220)	-0.161	(0.208)
Intermediary Profession	-2.035***	(0.742)	-0.141	(0.214)	-0.0983	(0.204)
Clerk	-1.976**	(0.770)	-0.217	(0.219)	-0.183	(0.208)
Worker	-1.543**	(0.717)	-0.176	(0.214)	-0.146	(0.203)
Inactive	-1.832**	(0.729)	-0.130	(0.216)	-0.0855	(0.205)
Household head age (ref: less than 25 y.o.)						
25-34 y.o.	0	(.)	1.922***	(0.310)	1.846***	(0.300)
35-44 y.o.	-0.0817	(0.197)	1.952***	(0.309)	1.871***	(0.299)
45-54 y.o.	-0.251	(0.281)	2.058***	(0.310)	1.994***	(0.300)
55-64 y.o.	0.0204	(0.329)	2.116***	(0.312)	2.055***	(0.301)
65+ y.o.	0.0621	(0.363)	2.163***	(0.318)	2.104***	(0.308)
Household size (ref: 1)						
2	0.131	(0.277)	0.00386	(0.0590)	-0.0175	(0.0537)
3	-0.0716	(0.320)	-0.0217	(0.0770)	-0.0291	(0.0723)
4	-0.174	(0.358)	-0.0607	(0.0839)	-0.0641	(0.0773)
5+	-0.625	(0.392)	0.0950	(0.103)	0.122	(0.0974)
Dwelling construction date (ref: before 1949)						
1949 - 1974			0.133**	(0.0541)	0.142***	(0.0488)
1975 - 1981			0.0893	(0.0625)	0.127**	(0.0573)
1982 - 1988			0.0295	(0.0713)	0.0543	(0.0661)
1989 - year of observation-1			-0.239***	(0.0769)	-0.228***	(0.0717)
year of observation			0.839***	(0.256)	0.899***	(0.247)
Household size (ref: 1)						
50-74 m2			0.396**	(0.169)	0.404**	(0.186)
75-99 m2			0.377**	(0.164)	0.421**	(0.178)
100-149 m2			0.483***	(0.164)	0.484***	(0.178)
150+ m2			0.596***	(0.170)	0.625***	(0.182)
City category (ref.: Paris area)						
> 100 000 inhabitants			-0.195**	(0.0783)	-0.204***	(0.0727)
20 000 - 100 000 inhabitants			-0.153*	(0.0821)	-0.152**	(0.0762)
2 000 - 20 000 inhabitants			-0.251***	(0.0827)	-0.243***	(0.0763)
Rural			-0.0914	(0.0811)	-0.111	(0.0751)
Importance: pollution			-0.0714*	(0.0376)	-0.0629*	(0.0373)
Climate zone (ref: H1)						
H2			0.0249	(0.0445)	0.0245	(0.0402)
H3			0.0863	(0.0707)	0.101	(0.0649)
Time dummies	YES		YES		YES	
Constant	5.451***	(1.989)	3.102***	(0.702)	3.105***	(0.673)
Observations	5,778		5,110		5,110	

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Eicker–Huber–White robust standard errors except for FE OLS

Table 5.12: Impact of energy price forecast on the amount invested in home energy efficiency - Linear model - Adaptative expectation model for forecasting

5.7.4 Map Climate Zones

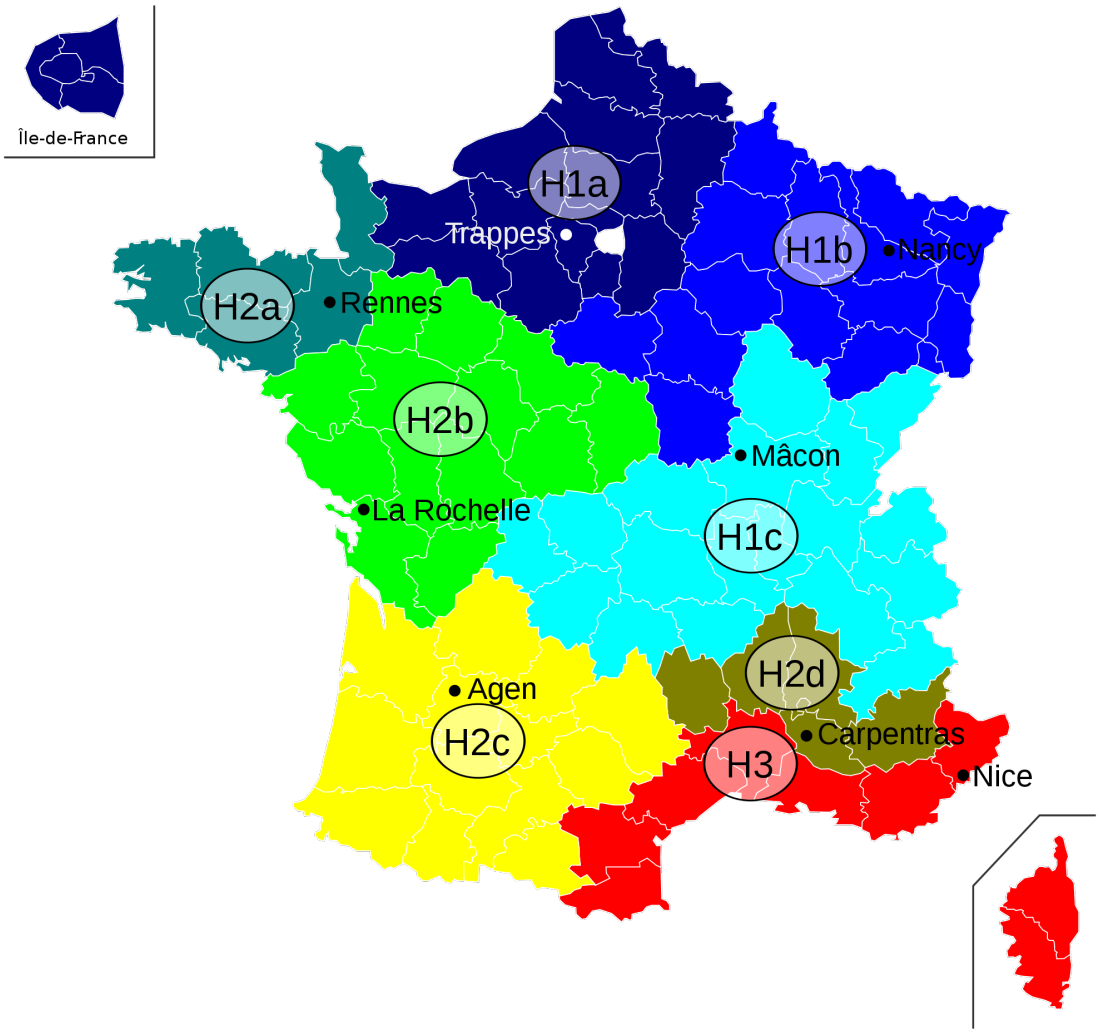


Figure 5.4: Climate zones in France

Figure 5.4 shows the different climate zones in metropolitan France. H1 zone corresponds to a continental climate (cold in winter, hot in summer, and mostly dry), H2 zone corresponds to an oceanic climate (more temperate and more humid) and H3 corresponds to a Mediterranean climate (warm and sunny).

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Concluding Remarks

Abstract

This chapter is the conclusion of the thesis. We provide a summary of the main findings in the thesis along with some directions for future research.

Ce chapitre est la conclusion de la thèse. Nous présentons un résumé des principaux résultats de la thèse ainsi que quelques orientations pour de futures recherches.

Summary of the main findings

Chapter 1 surveyed the literature concerning the effects of energy performance labels and ratings for buildings. We find that building energy performance does not fulfill the conditions for voluntary disclosure (unraveling). Whether or not mandatory certification is welfare improving and the size of the potential welfare gains are still open questions. Indeed, there is a lack of empirical research dealing with the effects of labels on the energy performance of the building stock. Also, our survey of the literature tends to confirm that higher energy performance is valued in the real estate market, and certification seems to increase this valuation. Besides, the sale premium is usually higher than the rental premium.

Chapter 2 presented a theoretical analysis of Energy Performance Certificates (EPCs), an EU certification scheme which provides potential home buyers or tenants with information on a property's energy performance. Although EPCs minimize total private costs, 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. We also provide conditions for which

EPCs are complements or substitutes of other policy instruments: carbon tax, subsidies and performance standards.

Chapter 3 continued the analysis of the EPC with a simulation-based approach. We find that an EPC policy requires moderate investment cost, moderate to high energy savings, and a low discount rate to be effective. Besides, the more heterogeneous is individual energy demand, the lower energy consumption is under EPC. Our simulations also suggest that the scenario with energy reduction under EPC is very much more likely. These findings support the idea that EPC needs to be supplemented by other policy instruments including carbon taxes, energy retrofit subsidies, and low-interest energy retrofit loans.

Chapter 4 studied the impact of a tax credit scheme named "Crédit d'Impôt pour le Développement Durable" which is implemented in France since 2005 and which aims at encouraging households to invest in building energy efficiency equipments. Using a difference-in-difference approach, we find that a 15-point tax credit rate increase induces additional expenditures of €1,650 (+ 49%) on average for equipments targeted by the rate increase. We also find preliminary evidence that there is a substitution between eligible and non-eligible investments. As a result, we find that expenditures on non-eligible equipments are reduced by €420-650 on average. Our findings support the effectiveness of the CIDD to increase the amount spent by households in building energy efficiency investments and suggest that policymakers could use successfully differences in tax credit rates to target particular home energy efficiency investments.

Chapter 5 studied how energy prices affect households decisions to invest in home energy efficiency using micro panel data from France. We do not find evidence that an increase in energy fuel price has an effect on the propensity to invest or on the amount spent in energy efficiency. These results call for a continuation of the research effort to evaluate the impact of energy prices on households' decision to invest in home energy efficiency.

Directions for future research

A goal of the economic analysis of building energy performance policies is to measure their cost-effectiveness with respect to the policy goal of reducing GHG emissions. In practice, it means computing the cost of the abatement of one tonne of CO2. To do so, it is necessary to measure

the effect of energy retrofit on the energy consumption. Also, it requires to take into account a potential rebound effect and therefore to have some measurement of the use of energy service (such as the temperature in the dwelling). This full analysis of the cost-effectiveness of a home energy efficiency program has already been made in the U.S. by Fowlie et al. (2015). Doing a similar analysis in the French context with data on energy consumption and energy service before and after the energy retrofit would be a relevant extension to this thesis.

EPCs do not only assess building energy performance but also provide practical advice for cost-effective energy retrofit investments. Measuring the effects of these recommendations on investments in energy retrofit would also be a natural extension to this thesis. So far, empirical analysis have shown a limited impact of audits on investments in energy savings. For instance, Revell (2014) studied the environmental impact of a home energy visit program that was delivered in London (U.K.). The impact of the visits on the installation of significant measures was negligible, as was the impact on behaviour change. Another example of analysis of the impact of energy audits is Murphy (2014). She explored the role of audits on investment in energy efficiency measures by private owner-occupied householders in the Netherlands and found that the main influence of the energy audit was to confirm information held by householders. A significant portion of audit recommendations was ignored, the main reason being that householders considered their dwellings to be adequately energy efficient. Pursuing these evaluation efforts in the case of France with EPC recommendations would be a natural extension to this thesis. A database which would include EPC recommendations could be processed via textual analysis. For each EPC would be extracted the number of recommendation and their magnitude. Then, we could compare similar households with different recommendations and analyze how they react to these recommendations.

Energy efficiency contractors are understudied in the economics literature, most likely because of the lack of data on the supply side of building energy performance. However, understanding the way they react to demand and policy changes is crucial to assess building energy efficiency polices. Better understanding the market structure and the market power of energy efficiency contractors would also be a welcome extension to this thesis.

Last, another requirement of the economic analysis of building energy performance policies is to assess the distributional impacts of the policy instruments. This is especially important

for the tax credit scheme and the energy taxes where public revenue and spending might be sizeable. To do so, one needs to assess how households react to tax credit or increased energy prices according to their incomes. This would also be a welcome extension to the thesis.

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RÉSUMÉ

Cette thèse de doctorat cherche à mieux comprendre certaines caractéristiques du marché de la performance énergétique des bâtiments dans le secteur résidentiel et à évaluer l'efficacité de trois interventions publiques visant à encourager la rénovation énergétique : Diagnostic de performance énergétique (DPE), crédit d'impôt pour le développement durable (CIDD) et taxation de l'énergie. Le premier chapitre de la thèse passe en revue la littérature sur la certification de la performance énergétique des bâtiments et conclut que les ménages la valorisent lorsqu'ils achètent ou louent un logement. Le deuxième chapitre présente une analyse théorique de l'impact du DPE et démontre que le DPE peut réduire ou augmenter la consommation d'énergie en fonction de l'horizon temporel et de l'hétérogénéité de la demande d'énergie dans la population. Le troisième chapitre développe une simulation basée sur le modèle susmentionné et suggère que le DPE doit être combiné avec d'autres interventions publiques pour être efficace. S'appuyant sur des données de panel françaises, le quatrième chapitre analyse économétriquement l'impact d'une augmentation du CIDD et montre qu'elle stimule significativement les dépenses pour les investissements éligibles. Le dernier chapitre analyse économétriquement comment les prix de l'énergie influent sur les décisions des ménages en rénovation énergétique et ne trouve pas de preuve statistique de l'effet d'une hausse des prix de l'énergie.

MOTS CLÉS

Efficacité énergétique, bâtiments, secteur résidentiel, labels énergétiques, crédit d'impôt, taxe carbone

ABSTRACT

This PhD dissertation aims at better understanding some features of the market for building energy performance in the residential sector and at evaluating the effectiveness of three policy interventions to encourage energy retrofit: Energy Performance Certificates (EPCs), tax credit for energy retrofit, and energy taxation. The first chapter of the thesis surveys the literature on building energy performance certification: there is strong evidence that households value building energy performance when buying or renting a dwelling. The second chapter provides a theoretical analysis of the impact of EPCs and shows that EPCs can decrease or increase energy consumption depending on the time horizon and the heterogeneity of energy demand in the population. The third chapter develops a simulation based on the aforementioned model and suggests that EPCs need to be supplemented by other policy instruments to reduce energy consumption. Relying on French micro-panel data, the fourth chapter econometrically analyzes the impact of a tax credit rate increase for energy retrofit and finds that it can substantially boost expenditures for investments targeted by the tax credit. The last chapter econometrically analyzes how energy prices affect households' decisions to invest in building energy performance and does not find any statistical evidence of an effect of an increase in energy fuel price.

KEYWORDS

Energy efficiency, buildings, residential, energy label, tax credit, carbon tax