Efficacité énergétique dans le résidentiel : diffusion et enjeux des changements comportementaux

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Abstract

"Energy efficiency in the housing sector: behavior changes and diffusion of energy-efficient technologies"

The goal of this thesis is to investigate a crucial question that has been raised in recent years both in policy and in economic literature; that is, the energy efficiency paradox in the housing sector, and the role of behavioral changes in shaping the energy consumption process. Identifying the barriers that stand in the way of the reduction of energy consumption in France, and the national adoption of recent energy-efficient technologies, has enormous implications, as behavioral insights drawn from conventional policy instruments may complement and improve the effectiveness of future policy interventions. Thus, through both country- and household-oriented approaches, this thesis provides fresh empirical evidence of (i) the determinants of energy renovation behavior in France; (ii) the effect of financial aid supporting energy renovation; and (iii) the rebound effect, which ultimately fuels the energy efficiency paradox and deters energy renovation behavior.

This predominantly empirical thesis is organized into three chapters. In the first two chapters, we focus on residential energy renovation behavior and offer empirical evidence of the behavioral and structural barriers hampering the diffusion of energy-efficient technologies. More precisely, particular attention is paid to risk-aversion and environmental consciousness and concerns in **Chapter 1**, while emphasis is made on financial schemes dedicated to boosting energy efficiency investments among households in **Chapter 2**. Finally, **Chapter 3** investigates the short- and long-run direct rebound effect of some selected European countries' residential electricity consumption, a concerning phenomenon often occurring after an energy efficiency renovation, eventually compromising the expected energy savings.

Keywords: Energy efficiency paradox; Behavioral changes; Residential energy demand; Energy policy.

Résumé

« Efficacité énergétique dans le résidentiel : diffusion et enjeux des changements comportementaux »

L'objectif de cette thèse est d'étudier une question cruciale, soulevée ces dernières années à la fois dans la littérature politique et économique, à savoir le paradoxe énergétique dans le secteur résidentiel et le rôle des changements comportements dans le processus de consommation d'énergie. L'identification des barrières faisant obstacle à la réduction de la consommation d'énergie en France et à l'adoption nationale et massive des technologies récentes d'efficacité énergétique a d'énormes implications, car les connaissances comportementales tirées des instruments politiques conventionnels peuvent compléter et améliorer l'efficacité des futures interventions politiques. Ainsi, à travers des approches aux échelles micro et macroéconomique, cette thèse fournit de nouveaux résultats empiriques concernant (i) les déterminants du comportement de rénovation énergétique en France ; (ii) l'effet des aides financières de soutien à la rénovation énergétique ; et (iii) l'effet rebond, qui alimente finalement le paradoxe énergétique et entrave la rénovation énergétique de masse.

Cette thèse à dominante empirique est organisée en trois chapitres. Dans les deux premiers chapitres, nous nous concentrons sur le comportement de rénovation énergétique et étudions les barrières comportementales et structurelles qui entravent la diffusion des technologies d'efficacité énergétique. Plus précisément, dans le **Chapitre 1**, une attention particulière est accordée à l'aversion au risque et aux préoccupations environnementales, tandis que, dans le **Chapitre 2**, l'accent est mis sur les dispositifs financiers destinés à stimuler les investissements en efficacité énergétique des ménages. Enfin, le **Chapitre 3** étudie l'effet rebond direct de court et long terme de la consommation d'électricité résidentielle d'un panel de pays européens, un phénomène préoccupant se produisant souvent après une rénovation énergétique et pouvant compromettre les économies d'énergie attendues par les modèles théoriques.

Mots-clés : Paradoxe énergétique ; Changements comportementaux ; Demande énergétique résidentielle ; Politique énergétique.

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Je dédie cette thèse à mes grands-parents, et surtout à toi, ma petite Mamie.

List of abbreviations

Abbreviation	Significance
3CL	Calculation of the Conventional Consumption
ADEME	Agence De l’Environnement et de la Maîtrise de l’Énergie
AIC	Akaike Information Criterion
ANAH	Agence Nationale de l'Habitat
ANIL	Association Nationale d'Information Logement
ARDL	AutoRegressive-Distributed Lag
BBC	Bâtiment Basse Consommation
BEPOS	Bâtiment à Energie POSitive
BIC	Bayesian Information Criterion
CADF	Cross-sectional Augmented Dickey Fuller
CART	Classification And Regression Tree
CIDD	Crédit d'Impôt Développement Durable
CITE	Crédit d'Impôt pour la Transition Energétique
CO2	Carbon dioxide
CPI	Consumer Price Index
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EPD	Energy Performance Diagnosis
ERSS	Energy Research & Social Science
EU	European Union
EU ETS	European Union Emissions Trading System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GMM	Generalized Method of Moments
H1	First French climatic zone, the coldest winter temperatures
H2	Second French climatic zone, more temperate winters
H3	Third French climatic zone, under the influence of the Mediterranean climate

HCC	High Council on Climate
HDD	Heating Degree Day
HPE	Haute Performance Energétique
IE	Indirect effect
IEA	International Energy Agency
IIA	Independence of Irrelative Alternatives
INSEE	Institut National de la Statistique et des Etudes Economiques
LLC	Levin-Lin-Chu
LPG	Liquefied Petroleum Gas
LPM	Linear Probability Model
MLE	Maximum Likelihood Estimation
OLS	Ordinary Least Squares
R^{-}	No retrofit
R	Retrofit
RE	Rebound Effect
RE2020	Régulation Environnementale de 2020
RGE	Reconnu Garant de l'Environnement
ROC	Receiver Operating Characteristic
RTxxxx	Réglementation Thermique de xxxx
RTE	Réseau de Transport d'Électricité
SDG	Sustainable Development Goal
SE	Substitution Effet
UK	United Kingdom
UN	United Nations
US	United States
VAT	Value-Added Tax

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General introduction

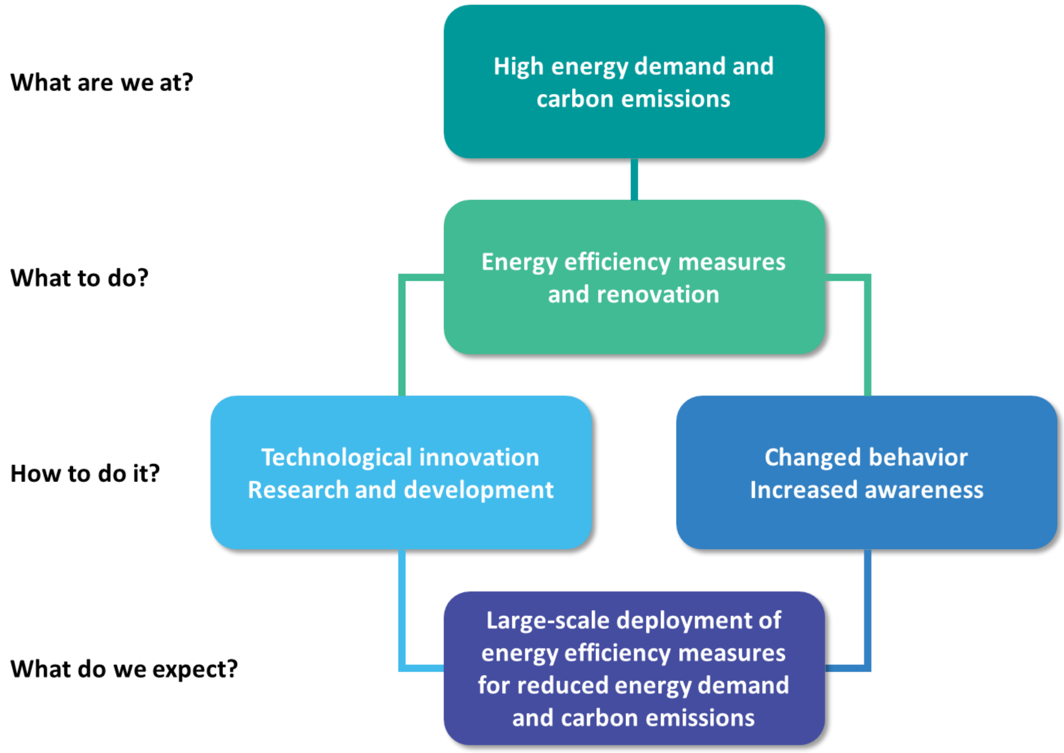
In a time of climate change, the management of energy demand in contemporary societies has never been more paramount. Energy plays an important role in economic growth and development in both developed and developing countries. Containing energy consumption and its environmental impacts has become crucial to developing sustainable economies and fighting against global warming. Indeed, the greenhouse effect primarily drives climate change, notably due to increases in GHG (greenhouse gas) emissions (European Commission, 2022).

To tackle climate change, the 2015 Paris Agreement sets ambitious climate protection goals, including substantial GHG emissions reductions to limit the global temperature increase to 2°C and dedicated financial support to climate change mitigation and the enhancement of abilities to adapt to climate impacts (UN, 2022). The European Union (EU) is committed to a 55%-reduction in GHG emissions by 2030, compared to 1990 levels. It also aims to be climate-neutral by 2050, *i.e.*, an economy with net-zero GHG emissions, making it the first climate-neutral continent.

In the fight against global warming, this international commitment effort also highlights the urgent necessity to improve the efficiency of energy production and consumption. Also referred to as energy efficiency, this concept has continually grown in popularity and interest in the academic literature. Energy efficiency merely consists in reducing the share of energy input in production or achieving the same production level, using performing and innovative techniques, which are then deemed energy-efficient.

Under the Paris Agreement and in line with the EU's European Green Deal, these commitments suggest major implications for the design of future effective energy regulatory schemes. From a political perspective, policies aiming at mitigating CO2 emissions should consider the link to energy consumption (and energy type). Rather than supply-oriented energy policies, aiming at producing more energy to meet growing needs, demand-oriented energy policies would more effectively address the issue by taking early action to identify root causes of rising energy requirements. Such new energy policies should then consider household and dwelling heterogeneity. A reduction in energy consumption is achievable through improving energy efficiency and boosting the adoption of energy-efficient technologies, both in the industrial and residential sectors. Therefore, energy efficiency, and more precisely, the energy renovation of the residential dwelling stock, jointly appear as a tool at governments' disposal to reduce the residential energy demand and CO2 emissions massively. **Figure 1** shows the process through which energy efficiency can help reduce energy demand and CO2 emissions.

Figure 1: Flow chart of the utility of energy efficiency
(Source: own elaboration)



Thus, in order to reach the EU's energy consumption and CO2 emissions reduction targets, a major renovation effort of the European building stock is required. Despite the demonstrated economic profitability of energy efficiency solutions for both residential and tertiary buildings (Liu et al., 2018; Luddeni et al., 2018; Belaïd et al., 2021a), their widely believed "win-win" nature (Fowlie et al., 2018), and the plurality of aid schemes for energy renovation, investments remain below expectations. Thereupon, in June 2021, the European Council of the EU emphasized "the need to at least double energy-related renovation rates by 2030 and to promote deep energy renovations". To broaden knowledge of the ins and outs of the discrepancy between expectations and reality, called the energy efficiency paradox, or gap, the present thesis adds meaningful value to the rich strand of empirical research aiming at identifying and deepening the understanding of barriers to energy efficiency. Studying these structural and behavioral barriers is of great importance for energy policymakers, as their mitigation can unlock virtuous behavior favoring the development of energy efficiency.

The main goal of this thesis is then to investigate a crucial question, that has been raised in recent years both in policy and in economic literature; that is the energy efficiency paradox in the housing sector and the role of behavioral changes in shaping the energy consumption process. Identifying the barriers that stand in the way of reducing energy consumption in France and boosting the national adoption of recent energy-efficient technologies have enormous implications. Behavioral insights drawn from conventional policy instruments may complement and improve the effectiveness of future policy interventions. Thus, through both country- and household-oriented approaches, this thesis provides fresh empirical evidence of the rebound effect, and of the determinants of energy renovation behavior, fueling the energy efficiency paradox.

The remainder of this General introduction section proceeds as follows: Section 1 introduces the French residential sector and underlines its potential in accelerating the energy transition; Section 2 presents the multiple benefits of energy efficiency; and Section 3 summarizes the existing energy efficiency policies in France and Europe. Then, in a second and more theoretical part, Section 1 raises questions about the emerging energy efficiency paradox; Section 2 highlights the role of household and dwelling characteristics in the existence of this paradox; and Section 3 discusses the rebound effect. Finally, the third and last part details the structure of this thesis.

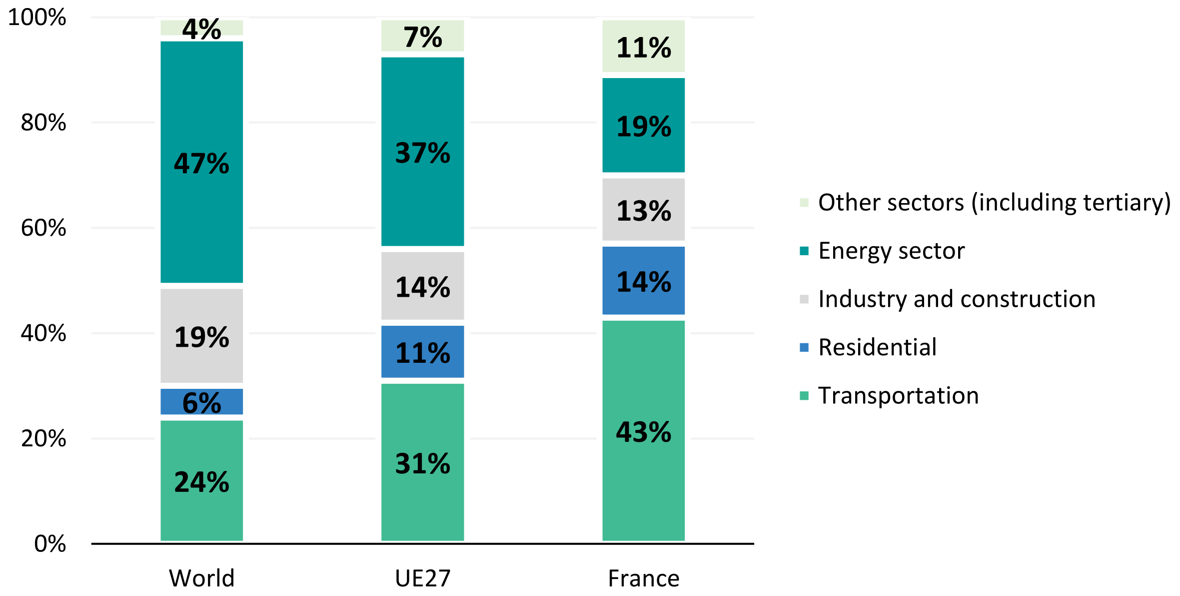
1. The French residential sector in the energy transition

In 2021, there were 37.2 million dwellings in France (INSEE, 2021). The residential sector consumed 29% of the 142 Mtoe final energy consumed (Ministère de la Transition Ecologique et Solidaire, 2020a), and was responsible for 14% of national CO2 emissions (see **Figure 2**). Emissions from the residential sector are highly dependent on climatic conditions: they decrease when temperatures are mild and increase when the climate becomes harsher. As a result, between 1990 and 2019, a period characterized by warm winters, the emissions from the French residential sector fell by 29% (Ministère de la Transition Ecologique et Solidaire, 2022a).

Figure 2: Sectoral distribution of CO2 emissions from energy combustion in France in 2019 (in share of total CO2 emissions)

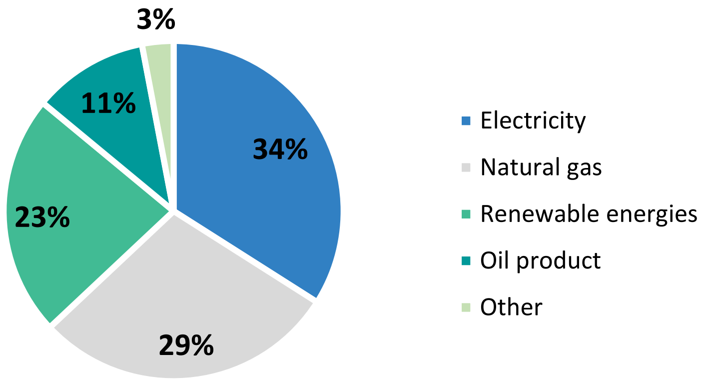
(Source: own elaboration based on Ministère de la Transition Ecologique et Solidaire (2022a))

Note: climate-corrected data.



The energy consumption of the French residential sector is by far dominated by electricity (see **Figure 3**): more than one third of total energy consumption is electricity (34%). The popularity of this energy, mainly used for heating purposes, comes from low installation costs, ease of implementation, state tax incentives, and stable price point, often fluctuating less than other fossil energies. Electricity is then followed by natural gas (29%) and renewable energies (23%) (hydropower, wind power, tidal power, photovoltaic and thermal solar energy, wood fuel, biogas, biofuels, and heat pumps).

Figure 3: Residential energy use by energy in France in 2019 (in share of total energy use)
(Source: own elaboration based on Ministère de la Transition Ecologique et Solidaire (2021a))
Note: Renewable energies include hydropower, wind power, tidal power, photovoltaic and thermal solar energy, wood fuel, biogas, biofuels, and heat pumps; climate-corrected data.



Thanks to the 3CL method developed by the Energy Performance Diagnosis (EPD), the energy consumption and GHG emission rates of a dwelling can be estimated, enabling to classify dwellings. The EPD, introduced in 2006, indicates, depending on the case, either the quantity of energy actually consumed, based on energy bills, or the estimated energy consumption for standardized use of the building or dwelling, as the building's real consumption directly depends on the conditions of use and the effective heating temperature. Two indicators are provided for an objective comparison of the quality of homes and buildings offered for sale or rent: (i) the energy label, from most (energy label A) to least energy-efficient dwelling (energy label G), expressed in annual kWh of primary energy/m²; and (ii) the climate label, from least (climate label A) to most GHG-emitter dwelling (climate label G), expressed in annual kgCO2/m². **Figure 4** shows the two rating schemes. Besides, **Figure 5** illustrates the distribution of the French dwelling stock by housing type and energy label in 2018, which follows a normal distribution. 1.9 million homes (6.6% of the housing stock) are energy efficient (labels A and B). On the distribution's right tail, 4.8 million dwellings (nearly 16.7% of the stock) are very energy-intensive (labels F and G). Very energy-intensive housing is more frequent among individual houses than apartments located in collective housing (18.4% vs. 14.7%). Energy labels D and E are the most frequent (34.2% and 24.4% of the stock, respectively), with even 36.2% of the apartments belonging to the energy label D (Ministère de la Transition Ecologique et Solidaire, 2021a).

Figure 4: EPD energy (left) and climate (right) labels

(Source: own elaboration based on Ministère de la Transition Ecologique et Solidaire (2022b))

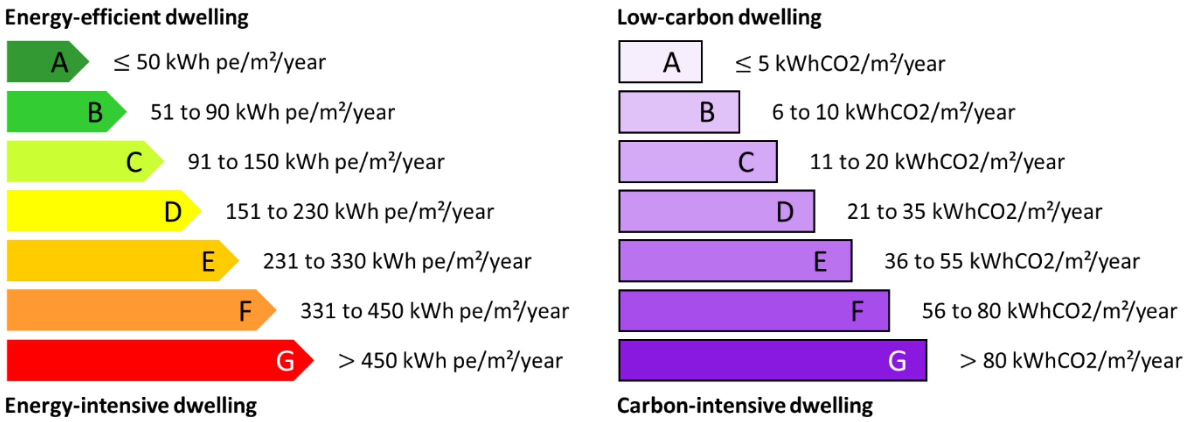
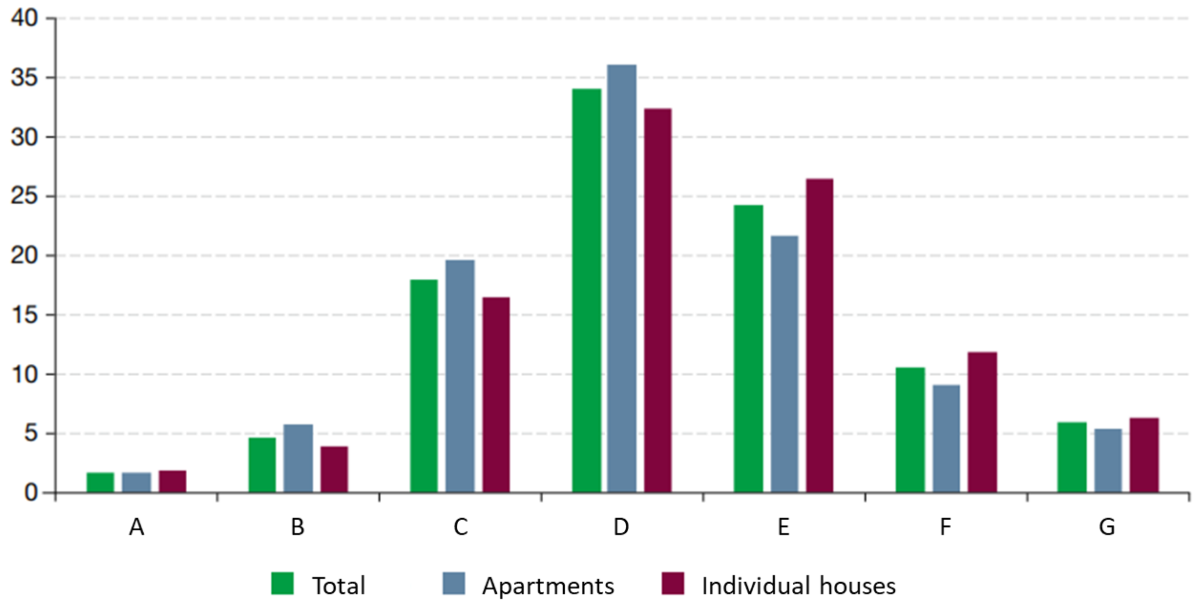


Figure 5: Distribution of the dwelling stock by housing type and energy class in France in 2018 (in share of total dwelling stock)

(Source: Ministère de la Transition Ecologique et Solidaire, 2021a)



Classifying the French housing stock according to energy labels shows that it has an average energy performance. Efforts to renovate the ageing dwelling stock are then necessary. Employing a large cross-sectional database collected in 2013, Belaïd et al. (2021a) offer a more detailed typology of the French dwelling stock, considering more characteristics in addition to energy performance, including dwelling type, size, age, and heating energy source. Yielding four distinct clusters, a number obtained applying

Ward's criterion, based on the "Elbow" method of the Ascending Hierarchical Classification algorithm of the Multiple Correspondence Analysis, this classification can help policymakers regarding the target of their policies in order to identify the least efficient dwelling to renovate in priority. The four classes are characterized as follows (see **Table 1** for a summarized version):

- Class 1 is made of small collective dwellings built after 1948 and before the first thermic regulation in 1975. The surface coefficient of heat exchange in these dwellings is very high, indicating poor insulation of the envelope. Since the dwellings of this class are rather small (less than 75m²) and in collective buildings, their real energy consumption is relatively low. Their systematic energy source is wood. This class accounts for 25% of the total French dwelling stock.
- Class 2 gathers large individual houses (larger than 130m²) built before 1948 and has a high real energy consumption, resulting from their size and poor energy-efficiency since these dwellings were built before any thermic regulation existed. Consequently, their surface coefficient of heat exchange is high. Their systematic energy source is Liquefied Petroleum Gas (LPG). This class accounts for 30% of the total French dwelling stock.
- Class 3 encompasses detached and semi-detached dwellings built between 1975 and 1988 and of intermediate energy efficiency. Being of medium size (75–100m²), these dwellings reach an average surface coefficient heat exchange, meaning that the wall insulation is more efficient than that of the first two classes. Their systematic energy source is fuel. This class accounts for 30% of the total French dwelling stock.
- Class 4 is made of the most recent dwellings (built after 2000) that are individual and detached houses of intermediary surface (100–130m²). Considering all the existing thermic regulations, these dwellings are also the most energy-efficient ones. Their surface coefficient of heat exchange is low. Their systematic energy source is electricity. This class accounts for 15% of the total French dwelling stock.

Table 1: Summary description of the classes identified
(Source: Belaïd et al., 2021a)

Class	Main characteristics
Class 1 (25%)	Small collective dwellings built between 1948 and 1975. Poor insulation of the envelope. Wood as main energy source.
Class 2 (30%)	Large individual houses built before 1948. High real energy consumption. Poor energy efficiency. LPG as main energy source.
Class 3 (30%)	Detached and semi-detached dwellings built between 1975 and 1988. Intermediate surface. Intermediate energy efficiency. Fuel as main energy source.
Class 4 (15%)	Recent dwellings of intermediate surface. Best energy efficiency performance. Electricity as main energy source.

Class 2 gathers the least energy-efficient dwellings, which represent 30% of the French dwelling stock. This class then concentrates the most receptive dwellings in terms of retrofit, in other words, dwellings in which energy efficiency solutions are the most likely to show positive results. Alone, they account for more than a third (37%) of the energy performance improvement recommendations made by energy experts, reliably based on housing characteristics (Belaïd et al., 2021a).

The discovered outcomes of Belaïd et al. (2021a) act as a demonstration of the need to encourage the adoption of energy-efficient technologies in the residential sector, which, itself, has serious potential for CO2 emission reductions, aligning with France's and the EU's GHG emissions reduction strategies. In its 2019 report, the International Energy Agency estimated that about 80% of the economic potential of energy efficiency in buildings remains untapped.

2. Energy efficiency and its multiple benefits

Energy renovation on a country-scale, and more broadly, energy efficiency, may confer benefits from three different perspectives. Firstly, it is becoming increasingly difficult to ignore the most obvious potential benefits of energy efficiency investments, which are environmental benefits. Interestingly, Belaïd et al. (2021a) estimate the total cost of renovating the entire French housing stock, as well as the resulting energy and environmental gains, relying on the designing of a large cross-sectional database collected in 2013, including rich technical information of about 1,400 dwellings. Results indicate that retrofitting the entire French dwelling stock would cost around 32 billion euros, allow energy gains of nearly 4.8 Mtoe, and a 31%-reduction in CO2 emissions, corresponding to 15.3 Mton of CO2. Renovating only the least efficient dwellings (large individual houses built before 1948, highly energy-intensive, representing 30% of the French dwelling stock), *i.e.*, the main target of energy efficiency policies, would reduce CO2 emissions by 7.74 Mton, which represents half of CO2 emissions reduction that is attainable by retrofitting the total French dwelling stock. These figures perfectly illustrate the power of energy efficiency in reducing energy consumption and its environmental impact. All in all, having more energy-efficient buildings would drive down fossil fuel usage, leading to less GHG emissions (Patiño-Cambeiro et al., 2019), which is key to achieve the EU target of a decarbonized building stock by 2050. Lowering GHG emissions is necessary for combatting human-influenced climate change, and also in limiting pollution.

Secondly, the economic benefits are less obvious, but prevalent. With more emphasis on energy efficiency renovation projects, employment could go up considerably and imply a good potential for job creation. This could be especially beneficial considering the high unemployment rate of 7.3% in the first quarter of 2022 in France (INSEE, 2022a). On a more macro-level, greater energy efficiency in European buildings could mean less energy dependence on other countries, and benefits would heavily outweigh the renovation costs (Patiño-Cambeiro et al., 2019).

Finally, from a societal point of view, energy efficiency investments have the potential to attain two objectives at the same time. Many aging buildings in France, and more broadly in Europe, are in desperate need of renovation. On the one hand, energy-efficient renovations address this problem while lowering energy consumption, and, on the other hand, they foster healthier environments since energy-efficient homes tend to be warmer and less moldy than energy inefficient homes, and also have better air quality. Less sickening environments will increase well-being while encouraging economic growth (Grey et al., 2017).

On an even more global scale, energy efficiency and effectively implemented energy renovation programs undeniably participate in the achievement of the 13th Sustainable Development Goal (SDG) of the United Nations (UN), by acting to combat climate change and its impacts. However, the effects of a massive energy renovation plan go far beyond this objective. Through its multidimensional scope of action (reduced energy demand, adverse environmental and health impacts, and improved dwellings conditions, affordability of energy services, innovation, economic prosperity, employment, and decent work), energy efficiency can generate various advantages and contribute significantly to other several SDGs, by "setting forth a challenge for humanity to decouple economic growth from climate change, poverty and inequality" (World Green Building Council, 2022). This includes, on top of SDG13, the SDG3, 7, 8, 9, 11, 12, 15, and 17, as depicted in **Figure 6**.

Figure 6: Contribution of buildings decarbonization to the SDG achievement (Source: own elaboration based on World Green Building Council (2022))

3. Overview of energy (efficiency) policies in France and Europe

Given the existence of ambitious policy goals aimed at reducing overall global energy consumption, the renovation of the existing dwelling stock represents a challenging issue for both researchers and policymakers, as unintended side effects of individual behavior and future conditions. Thus, this section explores the existing energy efficiency policies in France and Europe.

In France[1], various incentive and regulatory schemes have been designed to stimulate energy renovation work, making up the country's energy policy. The primary incentive schemes are: (i) the CITE (Tax Credit for Energy Transition), former CIDD (Sustainable Development Tax Credit), designed in 2015 as part of the energy transition, which consists of a credit at a single rate of 30% for all energy improvement work; (ii) the zero rate eco-loan, introduced by the 2009 Finance Act following the 2007 Grenelle Environment Forum, which is a zero-rate loan with no resource conditions, to finance a coherent set of energy performance improvement work; and (iii) the "Live Better" program ("Habiter Mieux") of the ANAH (French National Housing Agency), which subsidizes energy renovation work, subject to resource conditions and to increase energy efficiency by at least 25%.

The French government has also recently set a goal of zero oil-fired heating boilers within ten years. Concretely, this initiative offers a conversion premium between 3,000 and 5,000€, depending on the household's income, for replacing an old heating oil-fired boiler with a hybrid heat pump (Ministère de la Transition Ecologique et Solidaire, 2019). In parallel, as part of its GHG emissions reduction strategy, the French government recently published a decree prohibiting the installation of heating or hot water production equipment using heating oil, from July 1, 2022, unless other energy sources cannot be used. Appliances already installed may continue to be used, maintained, and repaired, but financial aid of up to 11,000€ is provided to encourage their replacement (Ministère de la Transition Ecologique et Solidaire, 2022c).

More globally, the Energy-Climate law, adopted on November 8, 2019, sets ambitious goals for French climate and energy policy (Ministère de la Transition Ecologique et Solidaire, 2020b). This law is part of the national and international evolution of regulations towards a better consideration of energy and climate issues, in particular in the aftermath of the 2007 Grenelle Environment Forum, debates and consultations on energy, having yielded the Law on the Energy Transition for Green Growth, or Energy Transition Law, in May 2015. As a complement to its carbon neutrality by 2050 objective, which is conceivable by decreasing by 50% the country's final energy consumption compared to 2012 levels, the Energy-Climate law has several primary objectives, also summarized in **Figure 7**:

- Reduce France's dependence on fossil fuels and accelerate the development of renewable energies: the law sets a new target of a 40%-reduction (30% previously) in fossil fuel consumption by 2030, compared to 2012 levels. The law also confirms the end of coal-fired electricity generation by 2022, and the mandatory installation of solar panels, or any other

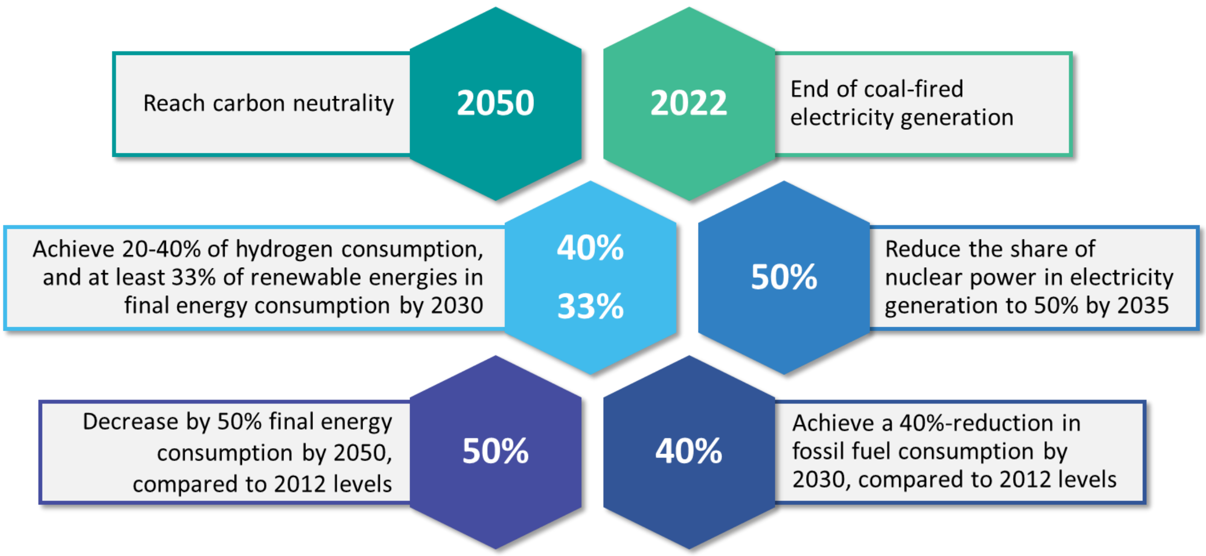
[1] French residential energy efficiency renovation policies shall be further discussed in **Chapter 2**, Section 2.

process for the production of renewable energy or vegetation, for new warehouses and commercial buildings. Finally, it encourages the low-carbon and renewable hydrogen sector, with a view to achieving between 20 and 40% of total industrial hydrogen consumption by 2030, and at least 33% of renewable energies in final energy consumption.

- Reduce France’s dependence on nuclear power: after the very controversial closure of the two reactors of the oldest nuclear power plant, Fessenheim, in summer 2020, the law intends to pursue the diversification of the country’s electricity mix by reducing the share of nuclear power to 50% by 2035.
- Fight against highly energy-intensive buildings: the objective is to renovate all the least energy-efficient dwellings within ten years. Built upon a progressive scale over the next decade, the law establishes an obligation to carry out renovation work in energy-intensive housing.
- Create tools for steering, governing, and evaluating our climate policy: the law established an independent body, the High Council on Climate (HCC), “tasked with issuing advice and recommendations to the government on the implementation of public measures and policies to reduce France's GHG emissions, in keeping with its international pledges – in particular the Paris Agreement and target to achieve carbon neutrality by 2050” (HCC, 2022).
- Better control of energy prices: the law allows the government to raise, by decree, the regulated access to nuclear energy. The regulated gas tariffs are abolished for any new subscription. For electricity, households and micro-businesses preserve the benefit of regulated rates.
- Strengthen controls to fight against fraud in energy savings certificates: in order to reduce fraud attempts, the law reinforces control requirements for energy savings certificates applicants, increases the penalties in case of a breach, and facilitates exchanges between competent administrations.

Figure 7: The Energy-Climate law summarized in a few figures

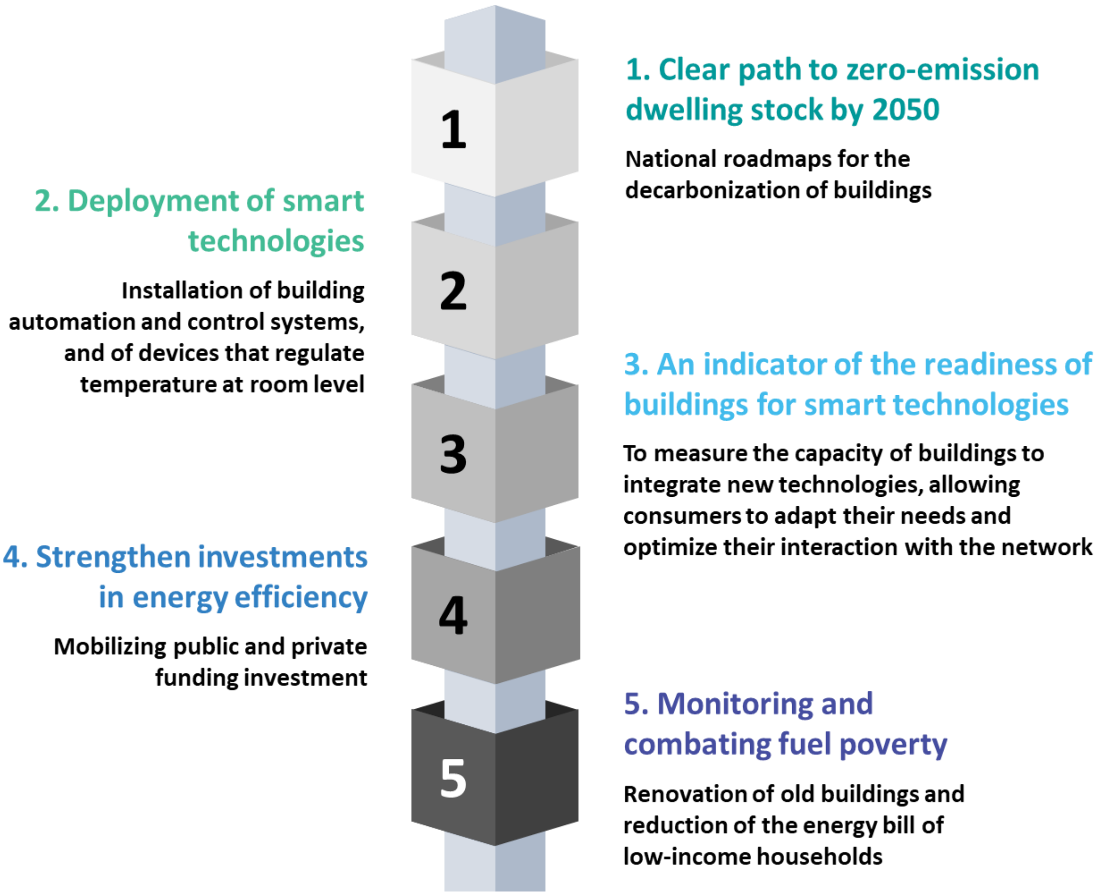
(Source: own elaboration)



On a larger scale, the EU has put heavy emphasis on becoming a world leader in energy efficiency and pushing pro-environmental agendas. Set out in the 2019 European Green Deal, several influential initiatives were implemented, in particular the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED). Firstly, The EPBD, implemented in 2010 and revised in 2018, is the cornerstone regulation aiming to address energy efficiency in the EU building sector according to 2030 and 2050 energy efficiency targets. The key complementary goals of the EPBD are to (i) stimulate the renovation of existing buildings by 2050; (ii) reinforce the modernization of the whole existing dwelling stock by implementing smart environmentally-friendly technologies; and (iii) reach a low and zero-emission dwelling stock by 2050 (European Commission, 2020d). Secondly, the EED, designed in 2012 and revised 2018, sets the 2030 energy efficiency target to be at least 32,5%. It also includes a possible upward revision clause, which increases the level of ambition compared to efforts required to meet the 2020 targets (European Commission, 2020c). Both directives confirm the prominent role of the building sector in achieving the EU’s energy efficiency target. Their effective implementation is, therefore, crucial to assist the accomplishment of 2030 energy efficiency goals and put the EU countries on track for the total decarbonization of the dwelling stock by 2050. **Figure 8** gives the big picture of the main achievements of efficiency energy programs in the EU.

Figure 8: Main achievements of EU energy efficiency programs

(Source: Belaïd et al., 2021a)



Yet, energy efficiency investments in the residential sector seem to lag behind public policy objectives set in several European countries, including France. The issue of understanding why investments in energy efficiency in the building sector remain low, despite the cost-effectiveness and availability of energy efficiency solutions, has received growing interest in the international academic literature. As an explanation, some scholars argue that energy efficiency investments may not be as attractive as they have been theoretically predicted to be because of the existence of barriers that prevent their large-scale diffusion. In the literature, academics refer to this phenomenon as the "energy efficiency gap", or "energy efficiency paradox" (Jaffe and Stavins, 1994).

Theoretical background

1. The energy efficiency paradox: from theory to practice

The implementation of energy efficiency solutions in residential housing is a key lever for reducing the sector's energy consumption. However, investment in these innovative technologies is currently low, an observation easily expanded beyond the French context. Accordingly, scholars have paid growing attention to what deters households, at the micro-scale, and countries, at the macro-scale from adopting energy-efficient technologies. The energy economics literature highlights the potential existence of an energy efficiency gap, or paradox, in the residential sector (Jaffe and Stavins, 1994), justified by the prevalence of barriers to energy efficiency investment (Sutherland, 1991). Sorrell et al. (2004) defines the energy efficiency gap as "the gap between what appears to be an attainable cost-effective level of energy efficiency and the level of energy efficiency actually observed in practice". What causes this discrepancy is called a "barrier to energy efficiency", consisting in "a mechanism that inhibits investment in technologies that are both energy-efficient and apparently cost-effective for the potential investor in such technologies" (Sorrell et al., 2004).

Initially, the barriers to energy efficiency received particular attention in the literature, seeking to understand, describe and categorize them into a taxonomy. Sorrell et al. (2004) write that energy efficiency barriers vary depending on sectoral and regional conditions, which justifies the large number of existing classifications. Indeed, Hirst and Brown (1990) were the first to suggest a qualitative classification of barriers, stating that there are two types: behavioral and structural. First, behavioral barriers are obstacles occurring during the end user's decision-making process, at the most disaggregated scale, such as attitudes toward energy efficiency, perceived risk of energy efficiency investments, information gaps, and misplaced incentives. Second, structural barriers, fueled by structural market failures, are beyond the individual end-user's control, including distortion in and uncertainty about future fuel prices, limited access to capital, government fiscal and regulatory policies, codes and standards, and supply infrastructure limitations. This is the classification adopted in this thesis, and each of the two typologies will be studied (in **Chapters 1** and **2**, respectively).

Later, the international academic literature investigated the behavioral and structural barriers that prevent the extensive diffusion of energy efficiency investments. **Table 2** surveys this literature, to which this thesis aligns, and provides a definition of each barrier.

Table 2: Literature review of the barriers to energy efficiency investment

Barriers	References
Behavioral barriers	
Attitudes toward energy efficiency: refer to the intrinsic disposition of individuals to save energy in their everyday life, *e.g.*, related to preferences for comfort, implying a rebound effect, and preferences for environmental protection.	Bakaloglou and Charlier, 2019, 2021; Schleich et al., 2019; Fischbacher et al., 2021
Perceived risk of energy efficiency investments: eventually due to the innovation status of energy efficiency technologies, which implies the inaccuracy of measures of performance, and limited access to robust feedback; also linked to the portfolio theory since energy efficiency investments tie up a large share of the investment portfolio.	Sutherland, 1991; Qiu et al., 2014; Volland, 2017; Heutel, 2019; Schleich et al., 2019; Fischbacher et al., 2021; Bakaloglou and Belaïd, 2022
Information gaps: refer to asymmetric information around the quality of renovation operations for households wishing to invest in energy renovation, due to the “experience good” nature of energy efficiency investments (non-accurately-predictable energy savings).	Sutherland, 1991; Fowlie et al., 2015, 2018; McCoy and Kotsch, 2018; Myers, 2020
Misplaced incentives: split incentives, *e.g.*, between owners and renters.	Charlier, 2015, 2018
Structural barriers	
Distortion in fuel prices: when comparing the current prices of different energy sources hinders the investment to change the primary energy source.	Alberini et al., 2013; Bakaloglou and Belaïd, 2022
Distortion in uncertainty about future fuel prices: when short-term uncertainty about future energy prices, which agents cannot fully anticipate, hinders investment.	Sutherland, 1991; Alberini et al., 2013; Bakaloglou and Belaïd, 2022
Limited access to capital: when the high energy efficiency investment upfront costs deter the investment itself; may be linked to agent’s myopia, *i.e.*, they give too much weight to the upfront cost.	Blumstein et al., 1980; Gillingham et al., 2009; Blumstein, 2010; Cohen et al., 2017
Government fiscal and regulatory policies: support provided by authorities (tax policies or research and development subsidies) to foster energy efficiency investments.	Dubin and Henson, 1988; Fowlie et al., 2015, 2018; Risch, 2020
Codes and standards: compliance with the (environmental) social norm, imitation effect of peers.	Allcott, 2011; Trotta, 2018a
Supply infrastructure limitations: when particular regional geographic characteristics limit the availability of new energy-saving technologies.	

In practice, despite the success of MaPrimeRénov', one of the seven French financial schemes aimed at fostering energy renovation work, only 0.1% of the projects subsidized were so-called “global” renovations, *i.e.*, total insulation work, while the overwhelming majority of projects consisted of minor work, such as changing a boiler (in 72% of cases) or window insulation (26%) (France Stratégie, 2021). Yet, these small renovation projects only have a limited effect on a dwelling’s energy intensity. Moreover, the number of global renovations (as opposed to minor work) is still very likely to be below the targets. The HCC recommends a sharp acceleration of the rate of energy efficiency renovations to reach 1% per year after 2022, and 1.9% per year by 2030, to reach the French low carbon strategy objectives. For comparison, this rate was equal to 0.2% between 2015 and 2018 (France Stratégie, 2021). This aligns with a recent European instruction encouraging efforts to at least double the renovation rate by 2030 (European Council of the EU, 2021).

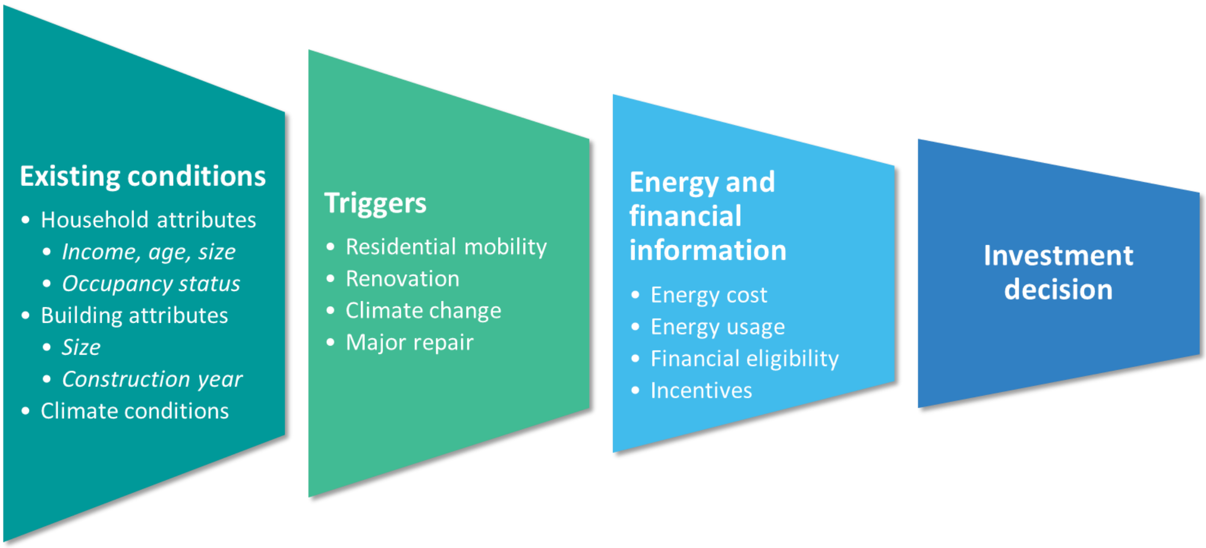
On this basis, the French government has launched new incentive programs, *e.g.*, the FAIRe program introduced in September 2018, to subsidize energy renovation work but also the intervention of energy experts assessing the quality of renovation work before, during, and after their implementation, in order to avoid scams. Indeed, the energy renovation market today is a very competitive market where many actors come into play: households wishing to reduce their energy bills, unscrupulous craftsmen taking advantage of the ignorance and naivety of households regarding the proposed solutions, or the State trying to catch up by stimulating the rate of renovation in the housing stock.

All this shows the importance of behavioral aspects in the residential energy efficiency investment decision process, in which households are the rulers. Then, the issue of behavioral change is central here, and the selected responses must focus on actions to raise awareness of eco-responsible practices. The next section presents the importance of the underlying behavioral dimension and of household and dwelling heterogeneity in the management of residential energy consumption and energy-saving behaviors.

2. The role of dwelling and household heterogeneity in the energy demand and energy-saving behaviors

In the residential sector, households are the main actors in the decision-making process regarding the implementation of energy-efficient technologies, as schematized in **Figure 9**. The role of the consumer is then central to understanding energy consumption. Indeed, in the context of environmental protection through energy management, reducing residential energy consumption raises a major question. Knowing the primary drivers of such consumption then represents an important step towards addressing the challenges of rising energy demand.

Figure 9: Residential energy efficiency investment decision process
(Source: updated from Belaïd et al. (2021a))



Globally, the literature agrees that income, age of the reference person, the size and composition of the family, the occupancy status, individual preferences, and dwelling technical attributes have a strong ability to explain energy consumption variability.

The effect of income on energy consumption is widely recognized. In France, the income elasticity is positive and low, hence a weak income response of residential energy demand, which echoes with the normal good nature of energy consumption. Precisely, Belaïd et al. (2021b) report an income elasticity of French residential electricity demand of 0.22. Income elasticities for energy demand greater than unity, which would suggest that energy consumption responds to an increase in income in a proportion greater than the increase in income itself, have already been found by scholars, for Pakistan notably (Alter and Syed, 2011; Jamil and Ahmad, 2011), but, to our knowledge, the literature on the French case has never led to such conclusions. The energy price in France is one of the lowest in Europe. Thus, the energy bill of French households represents a smaller part of their income and expenditures than that of their European neighbors. Therefore, their energy consumption is less sensitive to variations in their own income.

The influence of family size and composition and the reference person's age on residential energy consumption is linked to the life cycle theory, often invoked by research on the determinants of energy consumption. This theory, undoubtedly related to family dynamics, states that residential energy consumption follows a normal distribution as a function of the household reference person’s age (Fritzsche, 1981). In other words, total energy consumption increases with succeeding life cycle stages, up to the point when children leave the family, *i.e.*, when the family is its largest size. Then, households at the mid-point of their life-cycle are relatively the largest energy consumers. The presence of children is associated with greater energy consumption.

Previous research has shown that occupancy status, particularly homeownership, is a relevant predictor of energy conservation (Painter et al., 1983; Black et al., 1985; Charlier, 2018), as homeowners are more energy conscious (Barr et al., 2005). On this point, Rehdanz (2007) reckons that "owners are more likely to invest in energy-efficient construction, appliances or insulation".

Moreover, habits and individual preferences for energy-saving behavior and energy-efficient solutions have a crucial role in explaining the energy efficiency paradox and, ultimately, energy consumption fluctuations. Indeed, Kendel and Lazaric (2015) study the potential energy savings induced by the implementation of smart meters in order to test behavioral change and show how much households can change their habits, making individual preferences one of the aspects to account for in the implementation of energy-efficient solutions. Kendel et al. (2017) observe that consumers tend to reduce their electricity consumption when they are given feedback on this consumption, should it be learned directly from feedback or indirectly through self-monitoring. Belaïd and Joumni (2020) underline, in particular, the fluctuations of household energy-saving behavior throughout time. Bakaloglou and Charlier (2021) state that up to 12% of the gap between theoretical energy consumption predicted by engineering calculations and real energy consumption in France is explained by individual preferences. Additionally, the roles of environmental concerns and comfort expectations in the decision to retrofit a dwelling are investigated by Galassi and Madlener (2017), who suggest that thermal comfort preferences are heterogeneous and matter in the decision of retrofitting.

Finally, many scholars have already documented empirical evidence of the impact of dwelling technical attributes on energy consumption and energy-saving behaviors. Beforehand, it should be borne in mind that the intrinsic energy performance of the dwelling and its already installed heating system are arguments that can drive the choice of heating energy, whose consumption and carbon emission levels can undeniably greatly differ from one energy to another (Belaïd and Massié, 2022). Housing type (individual house vs. other types of housing), size (large vs. small), and age (old vs. recent) are factors that contribute to increases in the energy use of residential units (Vaage, 2000; Rehdanz, 2007; Huebner and Shipworth, 2017; Belaïd et al., 2021a). The geographical location of the dwelling and its climate also play a role in energy consumption variations: cold departments located in northeastern France consume more energy for heating purposes, while the Mediterranean Sea's hottest departments consume the least energy (Belaïd and Massié, 2022).

It is then necessary to distinguish the effects of variables that households can control, *i.e.*, their individual preferences, *e.g.*, for savings or comfort, from those that they cannot voluntarily modify, such as their installed heating system, which is often difficult to change because co-ownership regulations might enforce it, or the place where they live. Therefore, efforts to change energy consumption and energy-saving behaviors must focus on the easily modifiable households' determinants of their energy use. Indeed, certain attitudes and preferences, notably for comfort, can compromise the virtuous effects of energy renovation. Consequently, the next section explores to what extent these paradoxical behaviors represent a threat.

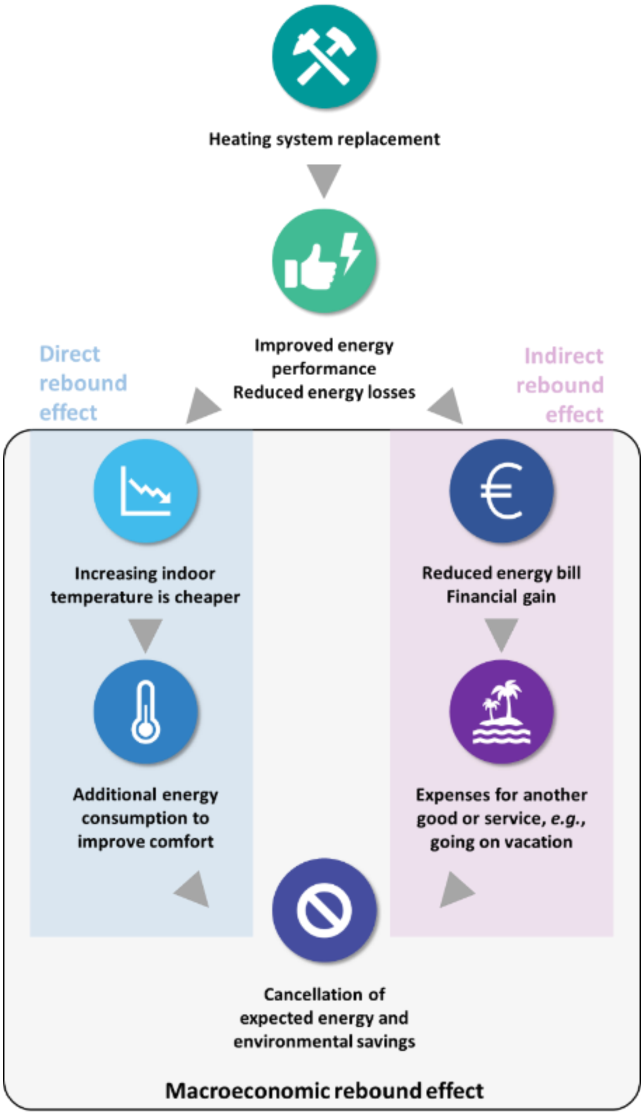
3. The rebound effect of residential energy consumption

As it has just been shown that individual preferences, among many other determinants, influence energy consumption and energy-saving behaviors, they should be accounted for in designing energy efficiency policies, especially when they prejudice their efficacy. Thus, the last part of the literature suggests that potential individual barriers deter residential energy-saving behavior and is deeply linked to the "rebound effect". Indeed, the question also arises why, after the implementation of energy-efficient techniques, energy savings eventually remain lower than those expected by theoretical consumption. The underlying mechanism corresponds to an overall increase in energy consumption induced by the energy efficiency improvement of an energy item. The "rebound effect" expression was popularized by Jevons, in 1865, who noted that, after the introduction of James Watt's steam engine, which was more efficient than its predecessor, the consumption of coal had risen sharply instead of falling. In fact, this new steam engine's energetic and financial gains had the effect of generalizing its use and therefore increasing the total coal consumption in England. Thus, a rebound effect implies that consumers do not miss out on their savings but rather decide to re-optimize their consumption.

Two sub-effects and a global effect occur. Concretely adapted to the context of energy efficiency renovation in the residential sector, the *direct* rebound effect consists in augmenting energy consumption, *e.g.*, for comfort reasons, after renovating a dwelling, of which energy performance is then better, while energy savings were expected. They are then cancelled out and offset by an extra-consumption mechanism. An *indirect* effect occurs when the demand for another good is increased. At last, the *macroeconomic* rebound effect combines the direct and indirect effects. From a macroeconomic perspective, the hypothesis is that improving energy efficiency by stimulating economic growth can lead to increased national energy demand.

Figure 10 summarizes the two concepts considering, for instance, a heating system replacement. Thanks to technical progress, it enables the household to raise the indoor temperature at a lower cost, since less energy is needed for the same energy service – this is the direct rebound effect, or to spend the money saved from the reduced energy bill by going on vacation – this is the indirect rebound effect. In either case, it, unfortunately, yields increased energy consumption.

Figure 10: Illustrated example of the rebound effect after heating system replacement (Source: own elaboration)



Theoretically, a wide range of methodologies exist to measure the rebound effect, extensively reviewed by Sorrell and Dimotropoulos (2008). The first strand of research, named the quasi-experimental approach, relies on a comparison of energy consumption before and after an energy efficiency improvement. However, the feasibility of this approach strongly depends on the availability of panel data (at least two observation periods) and control variables. The second strand, named the econometric approach, consists in assessing the energy efficiency elasticity, *i.e.*, the way energy service demand reacts to energy efficiency improvement. This approach has significant advantages over the first since it applies to cross-sectional analysis, time series, or panel data. Yet, it requires a variable representative of the energy efficiency level of the equipment, which is not often the case. Thus, scholars mostly turn to another option, that is the estimation of the energy service cost elasticity, or energy price elasticity.

Following Khazzom's (1980) original concept deducted for the single commodity case, the rebound effect based on the energy service elasticity can directly be estimated by assessing the energy price elasticity, provided that: (i) the reaction of consumers to an energy efficiency improvement and a fall in energy prices is identical; and (ii) energy prices do not affect energy efficiency. Denoting $\eta_X(Y)$ as the elasticity of Y with respect to X, it follows from these two assumptions that the efficiency elasticity of demand for energy is equal to minus the price elasticity of demand for the energy service minus one:

$$\eta_\varepsilon(e) = -\eta_P(\nu) - 1$$

where e is the demand for energy, whose price is P_e; ν is the demand for the energy service, whose price is $P = \frac{P_e}{\varepsilon}$, where ε is the energy efficiency of the equipment. This relationship signifies that a high energy price elasticity implies a high rebound effect. The direct rebound effect of electricity consumption of some European countries, proxied by the energy price elasticity in time series data, will then be the focus of **Chapter 3**. The microeconomic foundations of the rebound effect shall also be further discussed.

The empirical literature on the rebound effect brings mixed results, since estimates strongly depend on the quality and type of the employed data (panel, time series, cross-sectional data), and on the econometric methodology adopted to assess its magnitude. In their large literature review on the topic, Sorrell and Dimitropoulos (2008) find that the rebound effect of heating use could vary from 10 to 58% in the short-run, and from 1.4 to 60% in the long-run, with an average of 30%, *i.e.*, 30% of the energy savings induced by an energy efficiency improvement are lost because of an increase in energy demand.

From a different perspective, an impactful econometric study by Blaise and Glachant (2019) revealed the importance of the post-renovation rebound effect in France. They found that the average energy renovation investment does have a statistically significant negative impact on the energy bill in the residential sector, but it is small: a decrease of 8.39€ per year in the energy bill for 1,000€ invested, *i.e.*, -0.64%. It is much lower than theoretical models' predictions. This work provoked debate and controversy in well-informed circles, among whom much more optimistic beliefs about the effects of energy retrofits were circulating. The rebound effect was simply not accounted for in theoretical calculations.

These observations are just common practical examples to illustrate the energy paradox and the rebound effect in France, though it exists in other economies. Understanding the rebound effect, mitigating the barriers hampering the massive adoption of energy-efficient technologies in the residential sector, and deploying awareness-raising solutions is therefore necessary to benefit from energy efficiency progress in reducing CO2 emissions. Then, the residential sector is a key player in the energy transition and the fight against climate change, and this is why the scope of analysis of this thesis is narrowed down to this sector, its energy demand and energy-saving behaviors.

Structure of the thesis

This predominantly empirical thesis is organized into three chapters. In **Chapter 1**, we explore the ins and outs of the energy efficiency paradox by focusing on behavioral barriers to energy efficiency investments in the French residential sector, with particular attention to the role of environmental concerns and energy context perception. Employing an original survey conducted in 2018, containing sociodemographic variables, dwelling characteristics, and information about the eventual energy efficiency improvement work done in the current dwelling for 3,000 French homeowners, a Nested Logit model is developed to investigate the determinants of energy renovation behavior, considering different energy renovation work. Results indicate that environmentally sensitive homeowners (sorting waste, paying attention to environmental labels when buying appliances, being mindful about their intensity of use, and taking public transportation and carpooling for ecological reasons) are significantly more likely to renovate their home. Second, consistent with the literature, the analysis supports the hypothesis that risk aversion reduces the likelihood of investing in energy efficiency measures. Third, sociodemographic and dwelling characteristics are also found to impact energy renovation behavior. Overall, results offer implications for policymakers and underline the need to reduce the risk burdened by households to foster energy efficiency investments for a low-carbon economy.

In **Chapter 2**, in search of a deeper understanding of the energy efficiency paradox, we pursue the analysis of the determinants of energy renovation behavior by, this time, putting emphasis on structural barriers hindering the massive adoption of energy efficiency investments. A focus is made on financial incentives for energy-efficient retrofit work, which take the form of direct subsidies. By use of the same dataset exploited in **Chapter 1**, a Logit model is developed to estimate the probability of French households of renovating their homes. Accounting for dwelling and household heterogeneity, results suggest the existence of a threshold effect in the impact of financial incentives: under a certain amount of financial aid, households do not feel encouraged to undertake renovation work and simply give up, which constitutes money and efforts in vain from the French government. Further insights, provided by the estimation of a Classification And Regression Tree model (CART), indicate that this threshold effect occurs around 3,000 euros of aid. In the context of a rare increase in the budget of the French Ministry of ecological transition in 2022, this has implications for the design of future effective energy policies.

In **Chapter 3**, we investigate the direct rebound effect of some selected European countries' residential electricity consumption, both in the short- and long-run. We use annual panel data covering the period 1996-2018, extracted from multiple sources, including Eurostat and the World Bank. By applying the energy service elasticity concept, using the energy price elasticity in a demand model as a proxy of the rebound effect, we develop instrumental variable techniques to tackle the reverse causality of the electricity price, and then opt for lagged electricity prices. We present two different models to estimate the direct rebound effect in residential electricity consumption: (i) a General Method of

Moments (GMM) model for the long-run direct rebound effect; and (ii) a first-difference model for the short-run direct rebound effect. Estimates of the direct rebound effect in residential electricity use are 18% in the short-run and 43% in the long-run. Our findings reject the hypothesis of a backfire effect in residential electricity demand and have important implications for policymakers, suggesting the need for smart policies which consider energy consumption behaviors and decision-making processes among a variety of households.

At last, in light of the results obtained in the three chapters, the General conclusion will synthetize them, and offer energy policy recommendations and insights into the discovered key levers for climate change mitigation. Then, before presenting the different venues for future research that this thesis calls for, and how to change behaviors, it will discuss its challenges and limits.

Further detailed information on each chapter of this thesis and on miscellaneous work carried out since January 2020 is presented in **Table 3** below.

Table 3: Chapters details

Title - Authors	**Publication - Presentation**
Chapter 1: Residential energy efficiency behavior in France: the role of energy context perception and environmental concerns	Submitted to Energy Policy. Presented at: • The 3rd International Conference on Energy Research & Social Science "Energy and Climate Transformations" of the University of Manchester, UK, in June 2022 (poster presentation); • The 8th Doctoral Day of the Université Le Havre Normandie, in November 2021.
Chapter 2: Financial incentives and their impact on energy renovation behavior: evidence from the French residential sector	Submitted to The Energy Journal. Presented at: • The 19th edition of the Augustin Cournot Doctoral Days of the Université de Strasbourg, in May 2022. Accepted for future presentation at: • The Workshop on Environmental Policy Evaluation of the University of Saint Gallen, Switzerland, in January 2023. Accepted for presentation at (though I did not go): • The 8th Conference "Évaluation des politiques publiques" of the Association Française de Sciences Economiques and Direction Générale du Trésor, in Paris, in December 2022.
Chapter 3: Direct rebound effect for residential electricity use in selected European countries	Submitted to Energy Economics. Accepted for presentation at (though I did not go): • The Slovak Economic Association Meeting 2022 in Bratislava, Slovakia, in September 2022.

Miscellaneous	
What are the salient factors determining the usage of heating energy sources in France? Evidence from a Discrete Choice Model * Fateh Belaïd[a] and Camille Massié	Published in Energy & Buildings: https://doi.org/10.1016/j.enbuild.2022.112386. Referred to as "Belaïd and Massié, 2022".
A life-cycle theory analysis of French household electricity demand * Fateh Belaïd[a], Christophe Rault[b] and Camille Massié	Published in Journal of Evolutionary Economics: https://doi.org/10.1007/s00191-021-00730-x. Referred to as "Belaïd et al., 2021b". Presented at: • The 3rd Conference-Debate "Ecological transition and climate and environmental issues" of the Smart and Sustainable Cities research unit of the Université Catholique de Lille, in April 2021.
Exploring the cost-effectiveness of energy efficiency implementation measures in the residential sector * Fateh Belaïd[a], Zeinab Ranjbar[c] and Camille Massié	Published in Energy Policy: https://doi.org/10.1016/j.enpol.2020.112122. Referred to as "Belaïd et al., 2021a". Presented at: • The 3rd Annual International Conference of the Smart and Sustainable Cities research unit of the Université Catholique de Lille, in May 2021.
Exploring the impact of COVID-19 on electricity consumption and CO2 emissions in France Camille Massié and Fateh Belaïd[a]	Submitted to Economics of Energy & Environmental Policy. Presented at: • "Le COVID-19 au prisme des Sciences Humaines et Sociales : regards croisés et mises en perspectives", Maison Française d'Oxford, MESHS of Lille, and MSH of the Université Libre de Bruxelles, in Lille, in December 2022.
Smart cities initiatives and perspectives in the MENA region * Fateh Belaïd[a], Razan Amine and Camille Massié	In book "Smart city: Energy Transition, Environmental Challenges, and Opportunities for Local Authorities".
What role does energy efficiency play in climate mitigation in Saudi Arabia? Time series quantile and out-of-sample forecast approaches Camille Massié and Fateh Belaïd[a]	Ongoing work. Accepted for future presentation at: • The 44th IAEE International Conference "Pathways to a Clean, Stable and Sustainable Energy Future" in Riyadh, Saudi Arabia, in February 2023.

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* I participated in the finalization of this work only

Chapter 1: Residential energy efficiency behavior in France: The role of energy context perception and environmental concerns

*This article was submitted to Energy Policy. I presented it at the 8th Doctoral Day of Université Le Havre Normandie in November 2021, and at the 3rd International Conference on Energy Research & Social Science "Energy and Climate Transformations" of the University of Manchester, UK, in June 2022 (poster presentation, see **Appendix A.a**).*

Keywords: Energy efficiency; Environmental concerns; Energy efficiency paradox; Risk perception; Renovation; France.

1. Introduction

In the urgent context of the fight against global warming and environment protection through energy management, encouraging energy transition has highlighted the importance of the residential sector and placed it at the very center of the energy efficiency debate. France's final energy consumption in 2019 amounted to 142 Mtoe, of which 29% was due to the residential sector, making it the country's second-largest consumer, after transport (Ministère de la Transition Ecologique et Solidaire, 2020a). Therefore, it is crucial to foster energy efficiency investments, considering that (i) energy renovation is not a goal in itself, but a means to reduce energy use and carbon emissions (Sutherland, 1994); and that (ii) there is remarkable consensus on the cost-benefit of energy efficiency as a climate change mitigation strategy (Borenstein, 2014).

Recently, a new strand of literature has emerged examining the main drivers of residential energy use (Huebner et al., 2015; Longhi, 2015; Belaïd, 2016, 2017; Belaïd et al., 2020b, 2021b; Belaïd and Joumni, 2020) and showing the importance of residential renovation in achieving the EU's objectives for energy consumption reduction. Enhancing the energy performance of households to reduce energy demand is a cornerstone for energy policymakers in many countries (Brounen, 2012; Olaniyan and Evans, 2014). In fact, the residential sector offers a substantial low-cost potential for energy savings and reduction of related carbon gas emissions. A recent study by Belaïd et al. (2021a) shows that renovating the entire French building stock would cut energy consumption by 18% and CO2 emissions by 32%. Furthermore, energy efficiency measures are expected to contribute to 44% of the carbon dioxide emissions reduction by 2035 in the International Energy Agency countries (Ryan and Campbell, 2012). Promoting and disseminating energy renovation on a massive scale would provide numerous benefits such as reducing energy dependence and local environmental impacts, reinforcing energy security, as well as driving down fossil fuel usage (Ryan and Campbell, 2012; Patiño-Cambeiro et al., 2019).

However, despite the empirical evidence of the economic and environmental benefits of energy efficiency investments provided by the literature (Liu et al., 2018; Luddeni et al., 2018; Belaïd et al., 2021a), these investments are not sufficiently adopted by households in many countries, which significantly compromises the ability to achieve the energy and climate goals set by the EU. The intractable contradiction between the slow diffusion of energy-efficient technologies and the profitability of these measures is called the "energy paradox" and has become a critical issue in the recent debate on energy transition and climate change (Jaffe and Stavins, 1994; Fowlie et al., 2015, 2018; Gerarden et al., 2015).

Scholars have paid growing attention to causes of this discrepancy, which has been shown to be fueled by systematic behavioral biases in households' decision-making processes along with market barriers and failures (Tietenberg, 2009; Allcott and Greenstone, 2012; Allcott et al., 2012; Gillingham and Palmer, 2014). Hirst and Brown (1990) suggest a classification of these barriers, stating that there are two types: structural and behavioral. On the one hand, structural barriers are the result of the actions of public or private organizations that are beyond the control of the individual end-user. These can be distortions in fuel prices which generate uncertainty about their future values, governmental fiscal and regulatory policies which tend to foster energy consumption and not energy efficiency, or supply infrastructure limitations due to geographical restrictions which can slow the implementation of energy efficiency technologies. On the other hand, behavioral barriers deal with problems occurring during the end-user's decision-making process, such as attitudes toward energy efficiency, consumption behavior, environmental concerns, or the perceived risk of energy efficiency investments. Both these market failures preventing society from closing the energy efficiency gap are critical to understanding and analyzing how to close the gap.

Accordingly, the present study focuses on understanding behavioral barriers. This paper investigates the determinants of the decision to renovate a dwelling and the choice of the type of energy efficiency renovation in the French residential sector using a Nested Logit model. Particular attention is paid to the role of environmental concerns and energy context perception in terms of risk and uncertainty. An original survey conducted in 2018 including cross-sectional data on 3,000 French homeowners is employed. To our knowledge, this is the first work investigating the role of environmental concerns and risk perception on the decision to implement energy efficiency measures in France using a Nested Logit model. However, this is a legitimate new line of study because adopting energy efficiency improvement measures is risky by nature. These measures fall in the category of experience goods which are risky because it is difficult to assess their quality before purchasing and implementing them. There is also uncertainty related to comfort and energy savings. On top of that, most people only invest in such measures once in a lifetime, generating a greater degree of risk-aversion than standard products that are more widely used (Farsi, 2010). Therefore, this paper contributes new insights about the drivers of household energy-saving behavior by empirically examining the effects of household sociodemographic characteristics, dwelling attributes, environmental concerns, and energy context perception.

We find that homeowners who adopt pro-environmental behaviors (sorting waste, paying attention to environmental labels when buying appliances, being mindful about their intensity of use, and taking public transportation and carpooling for ecological reasons) are more likely to renovate their home. We also provide empirical evidence that risk-aversion reduces the households' likelihood of investing in energy efficiency improvement measures, a result in line with the literature and the portfolio theory. Sociodemographic and dwelling characteristics are also found to impact energy renovation behavior significantly. Overall, results offer implications for policymakers and highlight the need to reduce the risk burdened by households in order to foster energy efficiency investments for a low-carbon economy.

The remainder of this paper is organized as follows: Section 2 explores the existing literature about the energy efficiency paradox and its barriers; Section 3 introduces the survey data and the econometric methodology applied for the analysis; Section 4 inspects the barriers to energy efficiency investments; Section 5 discusses empirical results; Section 6 presents robustness checks to test the sensitivity of our results; Section 7 offers some policy implications; finally, Section 8 concludes.

2. Literature review

The motivation for this research stems from the nascent literature focusing on the barriers to investing in energy efficient measures, the role of individual preferences in explaining the adoption of energy-efficient technology, and the so-called energy efficiency gap or energy paradox (Sutherland, 1991; Jaffe and Stavins, 1994; Gerarden et al., 2015; Bakaloglou and Belaïd, 2022). Recently, it has been shown that systematic behavioral biases in households' decision-making process along with market barriers and failures may influence the energy efficiency gap (Tietenberg, 2009; Allcott and Greenstone, 2012; Allcott et al., 2012; Gillingham and Palmer, 2014). Thus, this article is part of the literature atempting to identify and better understand the barriers to energy efficiency investments and is also in line with the area of research focusing on factors that influence the choice to retrofit.

There is abundant literature analyzing household energy use (Huebner et al., 2015; Longhi, 2015; Belaïd, 2016, 2017; Belaïd et al., 2020b; Belaïd and Joumni, 2020). Some studies combine energy demand analysis with life cycle theory (Fritzsche, 1981; Estiri and Zagheni, 2019; Belaïd et al., 2021b). Nevertheless, few studies focus on the adoption of energy-efficient renovation solutions. Ferguson's (1993) pioneer work in Canada emphasizes the importance of houses' technical characteristics, such as type and location, in the decision-making process that leads homeowners to engage in renovation work. The effect of these dwelling-specific variables is even more potent than that of sociodemographic variables. These results are consistent with the findings of Trotta (2018b), who analyzes the determinants of residential energy efficient retrofit investments in the UK. Employing a standard discrete choice probit model framework, he also finds that dwelling-related attributes have a higher explanatory power than sociodemographic characteristics. Similarly, by estimating the renovation probability using Logit and Probit models in Canada, Gamtessa (2013) finds that the year of construction of a house greatly impacts retrofit decisions, which confirms this tendency.

The role of environmental preferences on energy-saving behavior is at the core of a growing number of articles, but they provide mixed evidence. On the one hand, (i) using a discrete choice experiment on German data, Galassi and Madlener (2017) find that "environmentally concerned occupants are not more prone than others to living in retrofitted dwellings"; (ii) Aravena et al. (2016) find no positive relation between environmental benefits of energy efficiency measures and the intention for and adoption of such measures in Ireland; and (iii) also by conducting a choice experiment among homeowners in Germany, Achtnicht (2011) suggests that environmental benefits resulting from a renovation significantly impact the choice of heating systems but not the choice of insulations. On the other hand, (i) Schleich et al. (2019) find a positive relation between pro-environmental identity (a score constructed as the average of answers to questions about self-perception towards environmental protection and other green living practices) and house renovation in eight EU countries; and (ii) Fischbacher et al. (2021) suggest that Swiss pro-environmental renovators live in homes with higher energy efficiency. To sum up, results seem to depend on data quality, econometric approaches, and measures adopted to assess environmental concerns and behaviors. Thus, the present research will fuel this debate by examining the impact of environmental concerns on energy efficiency renovation decisions.

Klöckner and Nayum (2017) study psychological barriers to energy upgrades in Norway and find that not being sure if it is the best time for a rehabilitation project and being unsure about the saving potentials are the most critical barriers to energy efficiency investment. Impending relocation also has a negative impact on the likelihood of renovating. Achtnicht and Madlener (2014) investigate the factors that influence German homeowners' preferences on energy retrofits and suggest that those who can afford it, and who perceive this kind of investment as profitable in terms of payback period and energy cost savings, are more likely to implement energy efficiency retrofits. All these elements are related to the perception of risk and uncertainty, which plays a role in the adoption and diffusion of energy-efficient solutions (Baker, 2012). Homeowners can perceive investments in energy efficiency measures as risky for many reasons such as loss of capital, unprofitability, uncertainty of energy-saving potential, high upfront costs, or lack of valuation of the property at resale. In this regard, the profitability of various energy efficiency solutions is estimated by Belaïd et al. (2021a) based on a Cost-Benefit Analysis on French data which considered both household and dwelling heterogeneity. This analysis showed energy gain to be the most significant driver of uncertainty in the profitability of energy efficiency solutions, followed by energy price. Using a discrete choice experiment conducted in Switzerland, Alberini et al. (2013) stress that homeowners who indicate that they are uncertain about future energy prices are less likely to invest in energy efficiency investments, which highlights the importance of this parameter in household's decision-making process as well. Likewise, empirical evidence of the impact of perceived risk of energy efficiency investments is demonstrated by Qiu et al. (2014) in the US: they find that “more risk-averse consumers are less likely to adopt energy-efficient technologies”. All in all, many scholars have reached a consensus regarding the negative relationship between risk aversion and the adoption of energy efficiency techniques in the residential sector. Further evidence that risk aversion is an obstacle to energy efficiency investments is also documented by Farsi (2010) for Switzerland, Volland (2017) for the UK, Heutel (2019) for the US, and Schleich et al. (2019) for eight EU countries. Lastly, theoretical background about prospect and portfolio theories, intimately related to the topic on hand, can be found in Kahneman and Tversky (1979) and Elton and Gruber (1981), respectively.

3. Data and methodology

Based on a Nested Logit model, the present article seeks to examine the determinants of the decision to renovate and the choice of work type. This section describes the survey data used to perform this analysis and introduces the methodology of the selected estimation approach.

3.1 Data source and description

The dataset used in this study comes from an online survey carried out between December 2017 and January 2018 which contains cross-sectional data on a representative sample consisting of 3,000 French homeowners (see **Appendix B.a**). Previous research has shown that there is a significant difference between rented and owner-occupied housing in retrofit behavior. Indeed, renters are less likely to invest than owners because they anticipate that their rental period may not be sufficient to make such investment profitable (Davis, 2010; Meier and Rehdanz, 2010; Charlier, 2018). Thus, as we focus on individuals who really can make decisions on the energy efficiency performance of their dwelling, only owner-occupiers are surveyed.

This study collects data on household characteristics (age, income, family composition) and on dwelling attributes (surface, construction date, energy performance, dwelling type, location). Additionally, respondents were asked questions about their perception of the energy context, how risky it is, and the impact of their environmental concerns on their attitude towards purchasing and using equipment, purchasing food, and using public transportation. Finally, the survey gathers information about any energy efficiency renovation work carried out in the dwelling since moving in, including external or internal wall insulation, roof or attic insulation, double-glazed windows installation, and heating system replacement.

Data about the climatic zone where each dwelling is located come from Météo France and were matched to the original dataset using postal code.

As it is common in stated preference surveys, the sensitive information about net monthly income is not perfectly exploitable as some respondents may refuse to answer. Therefore, after discretizing the stated net monthly income variable, in order to reduce the bias coming from inconsistent extreme values and outliers, the final regression sample is made of 2,712 observations.

Table 4 displays descriptive statistics of variables used in the estimation process for the retained sample. Respondents range in age from 21 to 76, with an average of 49 years old. 43% live with at least one dependent child at home. 83% of our sample is made of individual houses and 17% of apartments or other housing types. The surface area of the housing sample varies from 33 to 400 square meters, with an average dwelling surface of 122 square meters. Nearly one third of the dwellings were constructed between 1975 and 1999. This corresponds to the post-oil-shock construction period during which, as an answer to this economic crisis, the first thermic regulation was implemented in France, setting an objective of 25% reduction in residential heating consumption. Finally, 29% of homeowners live in a rural area (less than 5,000 habitants) and 37% in an urban area (more than 100,000 habitants).

The retained sample is perfectly balanced between retrofitters and non-retrofitters. Installing double-glazed windows is by far the most favored energy efficiency solution carried out by retrofitters (70%). It is followed by replacing the heating system (56%), insulating the roof and attic (50%), and insulating walls (32%). This ranking is not surprising, knowing that installing double-glazed windows was ranked as the 4th most cost-effective solution among a panel of 12 solutions considered in 2013 in France (Belaïd et al., 2021a). Replacing the heating system, insulating walls and roof have also been found to be economically profitable in terms of net present value, but less than installing double-glazed windows. Note that cumulated frequencies for the four types of renovation do not sum to 100% in **Table 5** simply because several renovation works may have been carried out in the same dwelling. The share of non-retrofitters (50%) also underlines the energy efficiency paradox in France.

Surveyed homeowners are rather pessimistic about investing in energy efficiency since 71% of them reckon that this type of investment is a “risky investment”, *i.e.*, there is a risk of losing money or not making the project profitable when investing. Moreover, respondents were asked to give a score from 0 to 10 to evaluate the risk of defects in retrofit works in general to assess their personal perceived quality of energy retrofits. The average score reaches 6.5/10, which is above the mean, revealing that defects are likely to be a concern. A great majority (91%) of respondents pay attention to environmental labels when buying appliances. Regarding environmental concerns and their role on individual habits, 95% of respondents declare that their environmental awareness impacts their behavior about sorting their waste, 57% about food purchasing, 44% about their intensity of use of household appliances, and 31% about taking public transportation and carpooling.

Table 4: Variable definitions and descriptive statistics for the retained sample (2,712 observations)

Variable	**Mean or frequency**
Energy retrofit	
Retrofit (1: yes; 0: no)	50%
Nature of retrofit	
Wall insulation	32%
Roof insulation	50%
Double-glazed windows installation	70%
Heating system replacement	56%
Sociodemographic characteristics	
Age of respondent (years)	48.8 (13.3)
21-38 years old *	25%
39-48 years old	25%
49-60 years old	25%
61-76 years old	25%
Household net monthly income (euros)	
< 2,400€/month *	25%
2,400-3,200€/month	25%
3,200-4,500€/month	25%
≥ 4,500€/month	25%
Children in the household (1: yes; 0: no)	43%
Perception of the energy context and environmental concerns	
Risk-averse individual (1: yes; 0: no)	71%
Perception of quality of retrofit works (0: non-conformity never happens; 10: non-conformity is always an issue)	6.5
Environmental label is a significant criterion when buying appliances (1: yes; 0: no)	91%
Waste separation (1: yes; 0: no)	95%
"Green" food purchases (1: yes; 0: no)	57%
Intensity of use of household appliances (1: yes; 0: no)	44%
Public transportation and carpooling (1: yes; 0: no)	31%
Dwelling characteristics	
Surface of the dwelling (square meters)	121.9 (50.7)
Owners living in an individual house (1: yes; 0: no)	83%
Energy Performance Diagnosis (A: best category; G: worst category)	
No diagnosis	45%
A-B	10%
C	15%

D	21%
E-F	8%
G	1%
Building construction period	
Before 1949 *	25%
Between 1949 and 1974	25%
Between 1975 and 1999	32%
After 1999	18%
Climate zone	
H1 (the coldest winter temperatures)	58%
H2 (more temperate winters)	33%
H3 (under the influence of the Mediterranean climate) *	8%
Rural area ($<$ 5,000 habitants) (1: yes; 0: no)	29%
Urban area ($>$ 100,000 habitants) (1: yes; 0: no)	37%
Note: * stands for the reference category; standard error in parenthesis	

3.2 Empirical strategy

This paper investigates the determinants of the decision to renovate a dwelling and of the nature of renovation. It gives particular attention to environmental concerns and the uncertainty in the decision-making process. The hypothesized decision-making process to renovate a dwelling that homeowners face is presented in **Figure 12**. First, homeowners wonder if they want to renovate their residence and thus meet a binary choice: yes or no – this is the upper nest of the decision-making process. Second, if homeowners have decided to retrofit their dwelling, they choose the type of work they want to implement among a set of four alternatives: wall insulation, roof insulation, double-glazed windows installation, or heating system replacement – this is the lower nest of the decision-making process. In this framework, a Nested Logit model of energy retrofit behavior is developed as it allows to simultaneously model the choice to retrofit and the type of retrofit. This econometric specification is often used in the context of residential energy renovation, as in Cameron (1985), Ferguson (1993), and Jakob (2007).

There are many pros and cons to using a Nested Logit model. On the one hand, one of the advantages of this approach is that it does not require the Independence of Irrelative Alternatives (IIA) hypothesis to hold, inherent to discrete choice models. Roughly, the IIA assumption means that adding or deleting alternative outcome categories does not affect the odds among the remaining outcomes. The Nested Logit approach actually accounts for the correlation of alternatives within the same nest. It thus relaxes this assumption, solving the issue of counterintuitive predictions that could arise from the violation of this property (Ben-Akiva and Lerman, 1985). On the other hand, as the Nested Logit model uses a Maximum Likelihood Estimation method (MLE), it requires a large sample size. However, our sample of more than 2,700 French homeowners is large enough to perform this regression. By consequence, the Nested Logit is appropriated to our research question.

Belonging to the family of discrete choice models, the Nested Logit stems from random utility theory maximization models (McFadden, 1978; Train, 2002). This theory assigns a utility level U_{ij} to each alternative $j = 1, \dots, J$ for each decision-maker $i = 1, \dots, I$, the latter being assumed to choose the alternative offering him/her the highest level of utility. This utility is split into a deterministic part V_{ij} known by the researcher, and a stochastic part ε_{ij} which ensures the uncertainty of this utility, so that it writes as:

$$U_{ij} = V_{ij} + \varepsilon_{ij} \tag{1}$$

In this framework, a general version of the distribution of the error term ε_{ij} in equation (1) is assumed, thus allowing the alternatives within a nest to have mutually correlated error terms and then relaxing the IIA assumption. Besides, V_{ij}, the predicted utility that individual i derives from choosing alternative j in equation (1), is estimated with a linear combination of variables X_{ik}, $k = 1, \dots, K$, and their associated parameters β_k:

$$V_{ij} = \beta_0 + \sum_{k=1}^{K} \beta_k X_{ik} \tag{2}$$

The probability P_{ij} that individual i chooses the alternative j is equal to the probability of U_{ij} being the largest of all the other J utilities:

$$P_{ij} = \Pr(U_{ij} > U_{il} \; \forall j, l = 1, \dots, J : l \neq j) \tag{3}$$

Considering the hypothesized decision-making process for retrofitting behavior presented in **Figure 11** and the Nested Logit specification, the choice probability of individual i of retrofitting measure j from the J possible improvements is (Ferguson, 1993):

$$P_{ij} = \Pr(R) \times \Pr(j|R) \tag{4}$$

where R means retrofit (and R^{-} no retrofit). Equation (4) can be estimated sequentially: a Logit estimation for $\Pr(R)$, the probability of retrofitting, and a Multinomial Logit estimation for $\Pr(j|R)$, the choice probability of the nature of the retrofit work, *i.e.*, the conditional part. This sequential estimation is feasible in this study because the households' decision-making process has only two levels (Wrigley et al., 1988).

As mentioned earlier, homeowners' choice set when deciding how to renovate their dwelling is made of four alternatives: wall insulation, roof insulation, double-glazed windows installation, or heating system replacement. Similar to Achtnicht and Madlener (2014), this choice set is expanded by a status-quo option which will act as the base alternative. This enables us to investigate what makes one energy efficiency solution preferable to doing nothing, *i.e.*, the status-quo, rather than studying what makes it preferable to another. In other words, we can really assess the key drivers and barriers for the adoption of energy efficiency solutions. Technically, it accounts for adding a fifth alternative "Status-quo" to the "Retrofit" branch of the decision-making process illustrated in **Figure 11**.

The various factors influencing energy retrofit behavior considered in this study are displayed in **Figure 12**.

Figure 11: Decision-making process for retrofitting behavior

(Source: own elaboration)

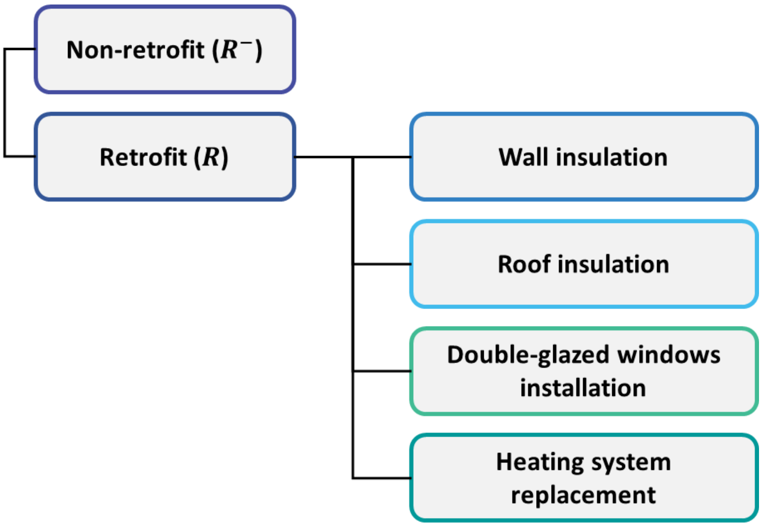
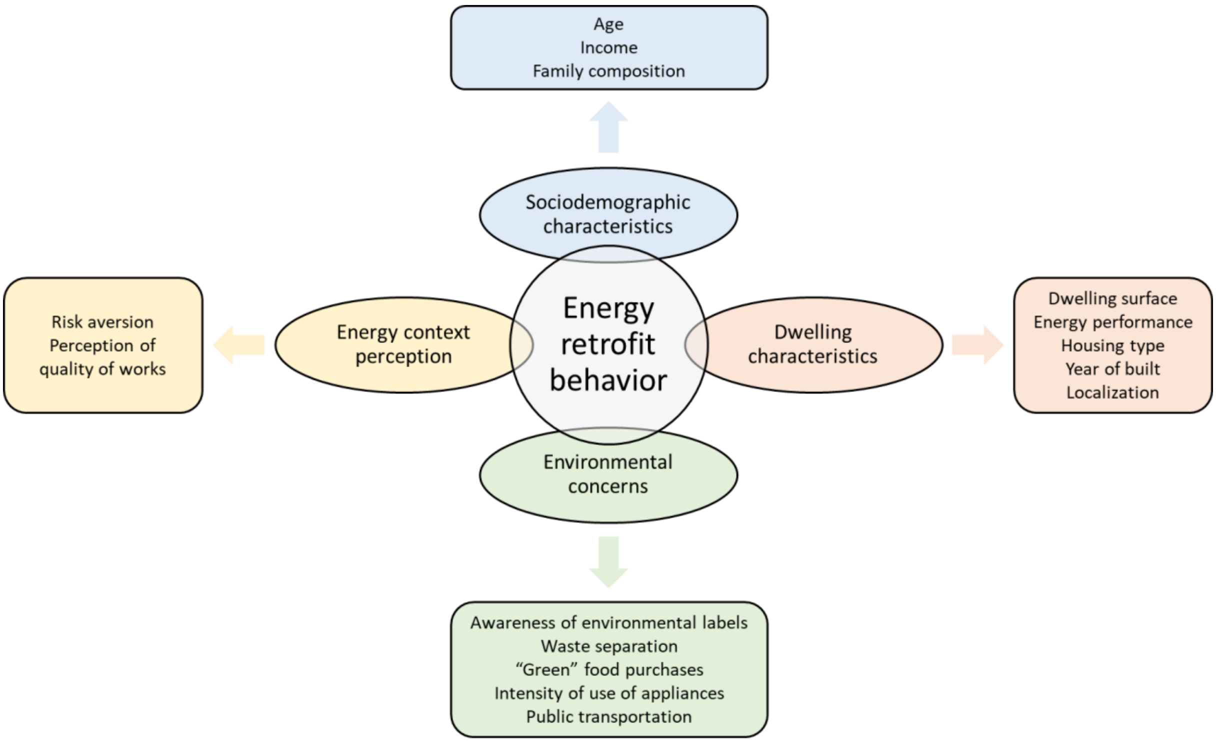


Figure 12: Conceptual framework for energy retrofit behavior

(Source: own elaboration)



4. Descriptive results

Before starting the econometric analysis, it is interesting to inspect the barriers to energy efficiency measures as respondents themselves identify them. In this regard, **Tables 5** and **6** display some descriptive results. First, the surveyed homeowners who did not renovate were asked if they were planning any renovation work in the next two years. Second, those who said they were not planning any renovation work (505 respondents) were provided with a list of possible reasons, and multiple answers were allowed. Therefore, **Table 5** lists the general reasons respondents identified. The four most frequently stated barriers to energy efficiency investments are the satisfaction with the current state of the dwelling (65%), the recency of the dwelling (24%), the too high level of investment required (22%), and the prioritization of investments (21%). Risk-related reasons (being insecure about the financial profitability of the project, the quality of work, or the revaluation of the value of the property) are identified as a barrier to energy efficiency investments in 25% of cases, which, if considered as such, places the notion of risk in second place in the podium. To be moving soon is also quoted as a reason for not implementing energy efficiency improvement measures in 9.5% of cases. This is consistent with Charlier (2014), who argues that individuals in an energy paradox situation (*i.e.,* households deciding not to renovate when there is evidence that it would be profitable) have a strong desire for mobility, while to be moving soon decreases the probability of renovating (Klöckner and Nayum, 2017).

Additionally, non-retrofitters were presented with a list of elements that could potentially change their minds about retrofitting their dwelling. Again, multiple answers were allowed. **Table 6** shows the details listed by respondents. Unsurprisingly, the most frequently stated element is the ease in obtaining public aids (31%). A retrofit work funding system change is also a decisive factor (13%). These two elements are linked to the third stated barrier to investment identified by non-retrofitters (**Table 5**): the too high level of investment required. Indeed, respondents implicitly indicate that the necessary investment is too high considering the risk involved in such a project. Thus, more easily accessible public aids that would reduce the household's economic burden would be welcome. This would increase the proportion of owners who undertake renovation work. This is consistent with Gamtessa’s findings (2013), stating that financial incentives play a critical role in the energy efficiency retrofitting behavior in Canada, so that the larger the government rebates are, the more likely households are to undertake retrofit investments.

Finally, it is interesting to note the high proportion of non-retrofitters that would never change their investment decision (23%), despite the profitability of energy efficiency investments (Belaïd et al., 2021a). This provides partial evidence of the existence of the energy efficiency paradox in France.

Based on **Tables 5** and **6**, there is evidence that homeowners perceive energy efficiency investments as risky. As descriptive results are not self-sufficient, we further analyze the choice of renovating in the next section in order to gain some insights into its determinants and barriers.

Table 5: General reasons for not deciding to implement energy efficiency improvement measures

Reason	**Percentage ($N = 505$)**
I am satisfied with the current state of my dwelling	64.4%
My dwelling is new	24.0%
The necessary investment is too high	22.2%
This type of investment is not in my priorities and preferences	21.2%
I am not sure that the financial gains will follow	14.9%
I will be moving soon	9.5%
I am not sure that the energy renovation of my home will be valued in the case of a sale	6.9%
It is impossible given the legal context (co-ownership, town planning code, *etc.*)	5.0%
The inconvenience caused is too great	4.0%
I do not trust the quality of the work done	3.0%
The subject is technically too complex, I am afraid of making a mistake	2.8%
I did not find any offers/craftsmen	0.4%
Other reason	4.2%

Table 6: Main elements that could change non-retrofitters' minds and make them retrofit their dwelling

Element	**Percentage ($N = 505$)**
More easily accessible public aid	30.7%
The guarantee of the realization of the economic gains expected at the time of the decision of energy renovation	16.4%
A more flexible retrofit work funding system: for example, loan and third-party financing which is reimbursed on the energy savings made	13.1%
The significant increase in the price of energy in the coming years	11.5%
When carrying out other types of work, I could consider energy renovation works (cost sharing and inconvenience)	9.9%
The better recognition of the patrimonial value of the energy performance of my dwelling	9.1%
Personalized information: for example, the advice of an objective expert for the realization of my work	5.9%
Nothing	22.6%
Other reason	26.7%

5. Empirical results

For clarification purposes, estimation results are displayed by nest of the decision-making process. Thus, we discuss results obtained for the binary choice of retrofitting below: Column (1) of **Table 7** gives parameter estimates while Column (2) gives odds ratios. Results obtained for the choice of the nature of retrofit works selected by retrofitters will actually be discussed as robustness checks in Section 6.2.

Prior to the analysis, a battery of tests was performed in order to assess the validity of the estimation method. Firstly, a Hosmer-Lemeshow goodness-of-fit test (1980) was conducted to check the goodness-of-fit of the model. As the statistical power of tests increases with sample size, which can be undesirable for goodness of fit tests, we opt for a standardized version of the Hosmer-Lemeshow test, enabling us to account for sample size and offset the increase in power (Paul et al., 2013). After choosing the adequate number of groups of observations, the test fails to reject the null hypothesis that the model fits the data, indicating the robustness of the model. Secondly, the model correctly classifies 67.6% of observations, which is satisfactory. Thirdly, the area under the Receiver Operating Characteristic (ROC) curve is equal to 0.743. Basically, ranging from 0 to 1, the higher this area, the better the model is at distinguishing between the two outcomes of the dependent variable (Fawcett, 2006). **Figure 13**, showing the ROC curve itself, constructed by plotting the true positive rate against the false positive, confirms that the model correctly distinguishes between retrofitters and non-retrofitters, as the curve is far from the 45-degree line. Lastly, a Wald test of overall significance (1943) yields to reject the null hypothesis that all coefficients of the model are simultaneously equal to zero. All in all, in the light of the various tests implemented, the model is correctly specified.

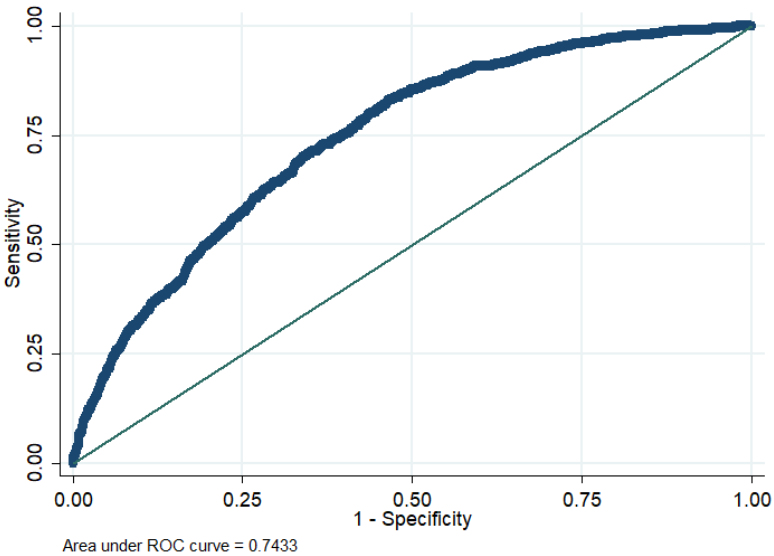
Table 7: Estimation results of the upper nest (binary choice to retrofit or not), coefficients and odds ratio

Dependent variable: retrofit or not		
Variables	**(1)** **Coefficient**	**(2)** **Odds ratio**
Sociodemographic characteristics		
Age (vs. 21-38 years old)		
39-48 years old	0.138	1.148
	(0.122)	(0.140)
49-60 years old	0.584***	1.793***
	(0.127)	(0.227)
60-76 years old	0.957***	2.604***
	(0.141)	(0.367)
Household net monthly income (vs. < 2,400€/month)		
2,400-3,200€/month	0.207*	1.230*
	(0.124)	(0.153)
3,200-4,500€/month	0.229*	1.257*
	(0.124)	(0.156)
≥ 4,500€/month	0.265*	1.303*
	(0.136)	(0.177)
Children in the household	0.190*	1.209*

	(0.104)	(0.126)
Perception of energy context and environmental concerns		
Risk-averse individual	-0.412***	0.662***
	(0.0967)	(0.064)
Perception of quality of retrofit works	0.0189	1.019
	(0.0233)	(0.024)
Environmental label is a significant criterion	0.561***	1.752***
	(0.152)	(0.266)
Waste separation	0.560***	1.750***
	(0.205)	(0.358)
"Green" food purchases	0.139	1.149
	(0.0895)	(0.103)
Intensity of use of household appliances	0.207**	1.230**
	(0.0897)	(0.110)
Public transportation and carpooling	0.326***	1.386***
	(0.0976)	(0.135)
Dwelling characteristics		
Log of dwelling surface	0.293**	1.341**
	(0.136)	(0.183)
Owners living in an individual house	0.438***	1.549***
	(0.137)	(0.213)
Energy performance diagnosis	-0.0176	0.983
	(0.0238)	(0.023)
Building construction period (vs. Before 1949)		
Between 1949 and 1974	0.103	1.109
	(0.124)	(0.137)
Between 1975 and 1999	-0.449***	0.638***
	(0.112)	(0.071)
After 1999	-1.960***	0.141***
	(0.157)	(0.022)
Climatic zone (vs. H3)		
H1 (the coldest winter temperatures)	-0.0181	0.982
	(0.152)	(0.149)
H2 (more temperate winters)	0.133	1.142
	(0.162)	(0.185)
Rural area	-0.0368	0.964
	(0.114)	(0.110)
Urban area	-0.159	0.853
	(0.110)	(0.094)
Constant	-3.009***	0.049***

	(0.667)	(0.033)
Observations	2,712	
R-squared	0.142	
AIC	3,276.574	
BIC	3,424.210	
Percentage of correct prediction	67.63%	
Area under the ROC curve	0.743	
Hosmer–Lemeshow goodness-of-fit test: p-value	0.544	
Wald test of overall significance: p-value	0.000	
Note: robust standard errors in parenthesis; *** $p < 1\%$; ** $p < 5\%$; * $p < 10\%$		

Figure 13: ROC curve of the upper nest modeling



5.1 The effect of sociodemographic variables

Sociodemographic variables seem to have good explanatory power in the adoption of energy-efficient retrofit investments. As **income** increases, the probability of renovating increases too: by 23% for families belonging to the second quartile, by 26% for families belonging to the third quartile, and by 30% for families belonging to the fourth quartile, compared to families belonging to the first quartile. Wealthier households simply can afford such costly investments. This relationship is statistically significantly different from zero and corroborated by Trotta (2018a) notably.

The **presence of children** in the house is also found to significantly increase the probability of renovating (by 21%). This conclusion has already been documented by Ferguson (1993), who argues that households with children are immobile and therefore have a longer expected tenure in their current dwelling, making them more keen to renovate. This variable also implicitly captures household size, which has been shown to positively affect energy retrofit behavior (Poortinga et al., 2004).

Results about **age** are clear and, despite the non-significance of the parameter estimate for the first quartile, it appears that growing old increases the probability of renovating. Households that are most likely to renovate are those headed by people over 60: they are more than twice as likely to do so compared to younger households (21-38 years old). Trotta (2018a) and Qiu et al. (2014) also reckon that elderly households are the most likely to invest in energy-efficient retrofit. Yet, our findings refute those of Poortinga et al. (2003) and Nair et al. (2010), who argue that older household heads are less likely to renovate because "the expected rate of return is lower than for households with younger heads".

5.2 The effect of dwelling characteristics

We do not find a significant impact of location on energy efficiency investments, *i.e.*, the **climatic zone**, being located in a **rural area** or in an **urban area**. The **energy performance diagnosis** does not significantly alter the decision of investing either. However, **housing type** strongly affects the probability of renovating: living in an individual house rather than an apartment or a different kind of dwelling increases the likelihood of households renovating by 55%. Interestingly, the **dwelling surface** also plays a role in the decision to renovate: the larger the dwelling, the more likely households are to renovate (chances increase by 34%). These last two outcomes are linked: the type and size of a dwelling are highly correlated (0.52, $p < 0.01$). Indeed, individual houses are often larger than detached or semi-detached houses and even larger than apartments – this holds for our sample and for France in general (INSEE, 2017). This implies a higher energy consumption in individual houses. As a result, owners of these types of dwellings are more likely to renovate to reduce their energy consumption.

Lastly, the **building construction period** appears as an influential factor in energy retrofitting behavior. Compared to occupants of dwellings completed before 1949, occupants of dwellings built between 1975 and 1999 and after 1999 are 36% and 86% respectively less likely to invest in energy efficiency measures. As dwellings built before 1949 act as the reference category for this variable, this negative relation was expected: it merely means that the older the dwelling, the more likely its occupants are to renovate it. This relation is statistically significant at a 1%-significance level for dwellings built after 1975. This date corresponds to the first thermic regulation implemented in France, as an answer to the 1973 oil shock. This measure set an objective of a 25%-reduction in residential heating consumption, achievable via external wall insulations and better air exchange systems that were imposed on owners. Thus, from that moment on, dwellings became less energy-intensive than older ones. Today, this is reflected in households' energy efficiency retrofitting behavior: occupants of newer dwellings are less likely to invest simply because their dwellings consume less energy. These results about the relation between dwelling age and the choice of renovating are notably supported by Ferguson (1993) and Gamtessa (2013), and confirm the strong explanatory power of dwelling attributes in energy renovation behavior.

5.3 The effect of risk perception

Firstly, as intuitively expected, **risk-averse households** are 33% less likely to invest in energy efficiency for their dwelling, a statistically significant result in line with the literature (Farsi, 2010; Qiu et al., 2014; Heutel, 2019; Schleich et al., 2019). Part of the theory behind the risky nature of energy efficiency investments stems from Sutherland's work (1991), who claims that "investments in energy efficiency are risky because the actual savings of a particular investment cannot be predicted accurately", which results in a gap between the actual energy savings post-renovation and the *a priori* energy savings. Thus, the inability to accurately predict energy savings discourages energy efficiency investments and violates the perfect knowledge and foresights underlying conditions of perfectly competitive markets. This ambiguity effect, yielding ambiguity aversion, negatively affects investment decisions (Ellsberg, 1961). Furthermore, from a portfolio theory perspective, owning and renovating a house is a major capital asset in household's portfolio due to the high initial cost required by such investment, thus preventing households from diversifying their investment risk (Elton and Gruber, 1981). As a result, because of households' risk-aversion, energy efficiency investments are curtailed compared to what they would be in a more certain world (Carlsmith et al., 1990; Sutherland, 1991), which undoubtedly contributes to the energy paradox.

Secondly, the parameter estimate associated to the **perception of retrofit works quality** variable is positive, which is surprising. Indeed, as it is coded (0: non-conformity never happens; 10: non-conformity is always an issue), a negative coefficient estimate (or a below unity odds ratio) would have indicated that being pessimistic about the quality of retrofit decreases the probability of renovating. In this case, it would have provided another measure of the perceived risk of energy efficiency investments and thus its impact on their adoption. However, this result is not significant and thereby not reliable.

5.4 The effect of environmental concerns

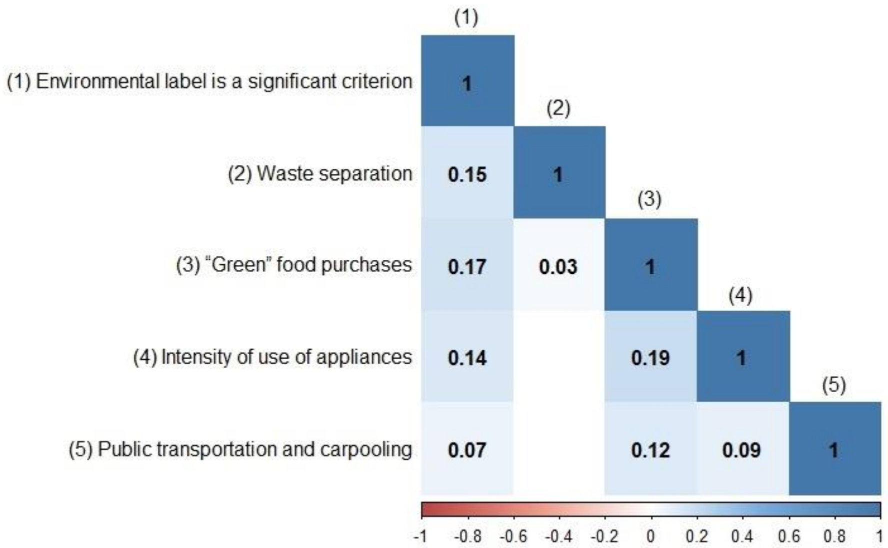
Of the five explanatory variables capturing environmental beliefs and related behaviors, four are significant. All of them increase the probability of homeowners undertaking energy efficiency retrofit. **Paying attention to environmental labels when buying appliances** is associated with a 75%-increase in the likelihood of renovating. Besides, **sorting waste**, **being mindful of the intensity of appliances use**, and **taking public transportation and carpooling** for environmental reasons increase the likelihood of homeowners renovating by 75, 23, and 39%, respectively. These last results about environmental concerns and related behaviors are consistent with those of Schleich et al. (2019), who find that households with higher environmental identity are more likely to implement renovation measures, but also with those of Fischbacher et al. (2021), suggesting that pro-environmental renovators live in more energy-efficient homes. However, our results stand out from those of Achtnicht (2011), Aravena et al. (2016), Galassi and Madlener (2017), and Trotta (2018a), who fail to find a significant and positive relation between environmental beliefs and energy efficiency retrofitting behavior.

Conclusions seem to depend on the contextual framework, the empirical approach, data quality, and above all, on the measure used to capture environmental perception and behavior.

The fact that all variables capturing environmental concerns positively affect the probability of renovating may be due to cross-situational environmental motivations and spillover effects, *i.e.*, the notion that the adoption of a new behavior can lead to the adoption of other pro-environmental behaviors. In our context, investing in energy efficiency retrofit could be considered as a pro-environmental behavior. As in Thøgersen and Ölander (2006) and Whitmarsh and O'Neill (2010), we present in **Figure 14** pairwise correlations between variables capturing environmental concerns and related behaviors as they can provide empirical evidence of spillover effects. The positive and significant correlations indicate that households are consistent within similar categories of behavior: buying "green" food and paying attention to intensity of appliances use (0.19, $p < 0.01$); buying "green" food and using public transportation and carpooling (0.12, $p < 0.01$); paying attention to environmental label when buying appliances and sorting waste (0.15, $p < 0.01$). The scant literature on the empirical impact of spillover effects on energy retrofit behavior leaves open possibilities for future academic advances. Nevertheless, theoretical support from models of behavior can be found in Lidenberg and Steg (2007).

Figure 14: Pairwise correlations between variables capturing environmental concerns and related behaviors

Note: blank space is for non-significant correlations ($p > 0.01$)



6. Robustness checks

This section develops two robustness checks to verify the stability and reliability of our empirical results. In a first subsection, the estimated method is changed in order to tackle the sensitivity of our results to the selected econometric approach so far. In a second subsection, we present estimation results for the lower nest of the decision-making process, that is, once the decision to renovate has been made, to choose which alternative energy efficiency improvement works to implement.

6.1 Sensitivity of results to a change in the estimation method

The Nested Logit approach developed in this article implicitly amounts to estimating the binary choice of renovating or not, *i.e.*, the upper nest of the decision-making process schematized in **Figure 11**, via a Logit model. We elaborate an alternative empirical specification to estimate this binary choice for a Probit model and a Linear Probability Model (LPM) as a robustness analysis. **Table 8** displays estimation results obtained by these two regressions: Column (1) for the Probit model and Column (2) for the LPM.

Although parameter estimates resulting from the LPM are always strictly smaller than those obtained from the Logit (Column (1) of **Table 7**) and the Probit models, signs and significance agree across the three specifications. This underlines the robustness of our empirical results to a change in the estimation method. Moreover, studying the value of the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) for the three models enables us to know which best fits our data. Indeed, the Logit specification's lowest values of AIC and BIC are jointly reached, making the Probit model and the LPM less accurate. The suitability of the Logit model over the Probit model and the LPM to tackle energy efficiency retrofit behavior has already been proven by Gamtessa (2013).

Therefore, we can assert that the Logit specification is the best empirical approach to estimating our sample's probability of renovating. As the Nested Logit implicitly induces this Logit model for the upper nest of the decision-making process, it also confirms the suitability of this original method to explore our research question.

Table 8: Estimation results of the upper nest (binary choice to retrofit or not), Probit model and LPM coefficients

Dependent variable: retrofit or not		
Variables	**(1)** **Probit**	**(2)** **LPM**
Sociodemographic characteristics		
Age (vs. 21-38 years old)		
39-48 years old	0.0879	0.0253
	(0.0738)	(0.0252)
49-60 years old	0.358***	0.122***
	(0.0763)	(0.0266)
60-76 years old	0.588***	0.203***
	(0.0849)	(0.0292)
Household net monthly income (vs. < 2,400€/month)		
2,400-3,200€/month	0.126*	0.0405
	(0.0752)	(0.0259)
3,200-4,500€/month	0.139*	0.0456*

	(0.0751)	(0.0257)
≥ 4,500€/month	0.164**	0.0554**
	(0.0821)	(0.0282)
Children in the household	0.110*	0.0352*
	(0.0624)	(0.0214)
Perception of energy context and environmental concerns		
Risk-averse individual	-0.249***	-0.0849***
	(0.0579)	(0.0195)
Perception of quality of retrofit works	0.0125	0.00432
	(0.0139)	(0.00477)
Environmental label is a significant criterion	0.335***	0.112***
	(0.0904)	(0.0300)
Waste separation	0.301**	0.106***
	(0.120)	(0.0371)
"Green" food purchases	0.0858	0.0285
	(0.0541)	(0.0187)
Intensity of use of household appliances	0.130**	0.0432**
	(0.0542)	(0.0186)
Public transportation and carpooling	0.197***	0.0663***
	(0.0588)	(0.0199)
Dwelling characteristics		
Log of dwelling surface	0.179**	0.0579**
	(0.0822)	(0.0281)
Owners living in an individual house	0.261***	0.0923***
	(0.0828)	(0.0284)
Energy performance diagnosis	-0.0108	-0.00297
	(0.0144)	(0.00480)
Building construction period (vs. Before 1949)		
Between 1949 and 1974	0.0565	0.0163
	(0.0751)	(0.0268)
Between 1975 and 1999	-0.278***	-0.102***
	(0.0686)	(0.0247)
After 1999	-1.167***	-0.390***
	(0.0902)	(0.0269)
Climatic zone (vs. H3)		
H1 (the coldest winter temperatures)	-0.0117	-0.00295
	(0.0924)	(0.0312)
H2 (more temperate winters)	0.0796	0.0278
	(0.0984)	(0.0331)
Rural area	-0.0238	-0.00762

	(0.0689)	(0.0236)
Urban area	-0.0943	-0.0313
	(0.0665)	(0.0229)
Constant	-1.790***	-0.0887
	(0.401)	(0.134)
Observations	2,712	2,712
R-squared	0.141	0.177
AIC	3,278.422	3,457.069
BIC	3,426.058	3,604.705
Wald test of overall significance: p-value	0.000	0.000
Note: robust standard errors in parenthesis; *** $p < 1\%$; ** $p < 5\%$; * $p < 10\%$		

6.2 Lower nest modeling

This sub-section presents estimation results for the lower nest of homeowners' decision-making process, it is the choice of the renovation's type. Thus, the lower nest contains four alternatives: wall insulation, roof insulation, double-glazed windows installation, and heating system replacement, plus a status-quo alternative which is the base alternative in this analysis. The utility derived from the four other alternatives is then lower or higher than the utility derived from the status quo, *i.e.*, doing nothing. Focusing on the lower nest actually acts as robustness check of results obtained for the upper nest. **Table 9** and **Figure 15** display log odds ratios, since the coefficient estimates value cannot be directly interpreted.

A Hosmer-Lemeshow goodness-of-fit test (1980) was performed to check the goodness of fit of the model. Still accounting for sample size when defining the adequate number of groups of observations (Paul et al., 2013), the large p-value associated with this test indicates that there is not enough evidence to reject the null hypothesis that the model fits the data. Therefore, the estimated model is a good fit. Additionally, the Wald test (1943) confirms the overall significance of results (p-value of zero). To sum up, these two tests conclude that the model is correctly specified.

Comparing odds ratios from Column (2), **Table 7,** and **Table 9** stresses the stability of our results: although magnitudes may slightly differ, signs and significance always agree between the two specifications. Risk-aversion is still found to negatively impact the adoption of energy efficiency techniques, whatever their nature. Identical conclusions about the effect of environmental concerns and related behaviors are reached: pro-environmental households increase their likelihood of adopting one of the four energy efficiency solutions considered.

Table 9: Estimation results of the lower nest (choice of nature of retrofit), status-quo as base alternative, odds ratios

Dependent variable: nature of retrofit				
Variables	**Odds ratio**			
	(1) **Wall insulation**	**(2)** **Roof insulation**	**(3)** **Double-glazed windows installation**	**(4)** **Heating system replacement**
Sociodemographic characteristics				
Age (vs. 21-38 years old)				
39-48 years old	0.775	1.158	1.140	1.364**
	(0.134)	(0.185)	(0.160)	(0.203)
49-60 years old	1.204	1.937***	2.031***	2.168***
	(0.208)	(0.306)	(0.286)	(0.327)
60-76 years old	1.954***	3.410***	3.168***	3.128***
	(0.373)	(0.593)	(0.491)	(0.521)
Household net monthly income (vs. < 2,400€/month)				
2,400-3,200€/month	1.261	1.283*	1.212	1.102
	(0.221)	(0.194)	(0.165)	(0.159)
3,200-4,500€/month	1.481**	1.187	1.257*	1.125
	(0.257)	(0.182)	(0.171)	(0.161)
≥ 4,500€/month	1.498**	1.243	1.281*	1.199
	(0.287)	(0.208)	(0.189)	(0.186)
Children living in the household	1.338**	1.278*	1.246*	1.160
	(0.195)	(0.166)	(0.143)	(0.142)
Perception of energy context and environmental concerns				
Risk-averse individuals	0.704***	0.616***	0.665***	0.713***

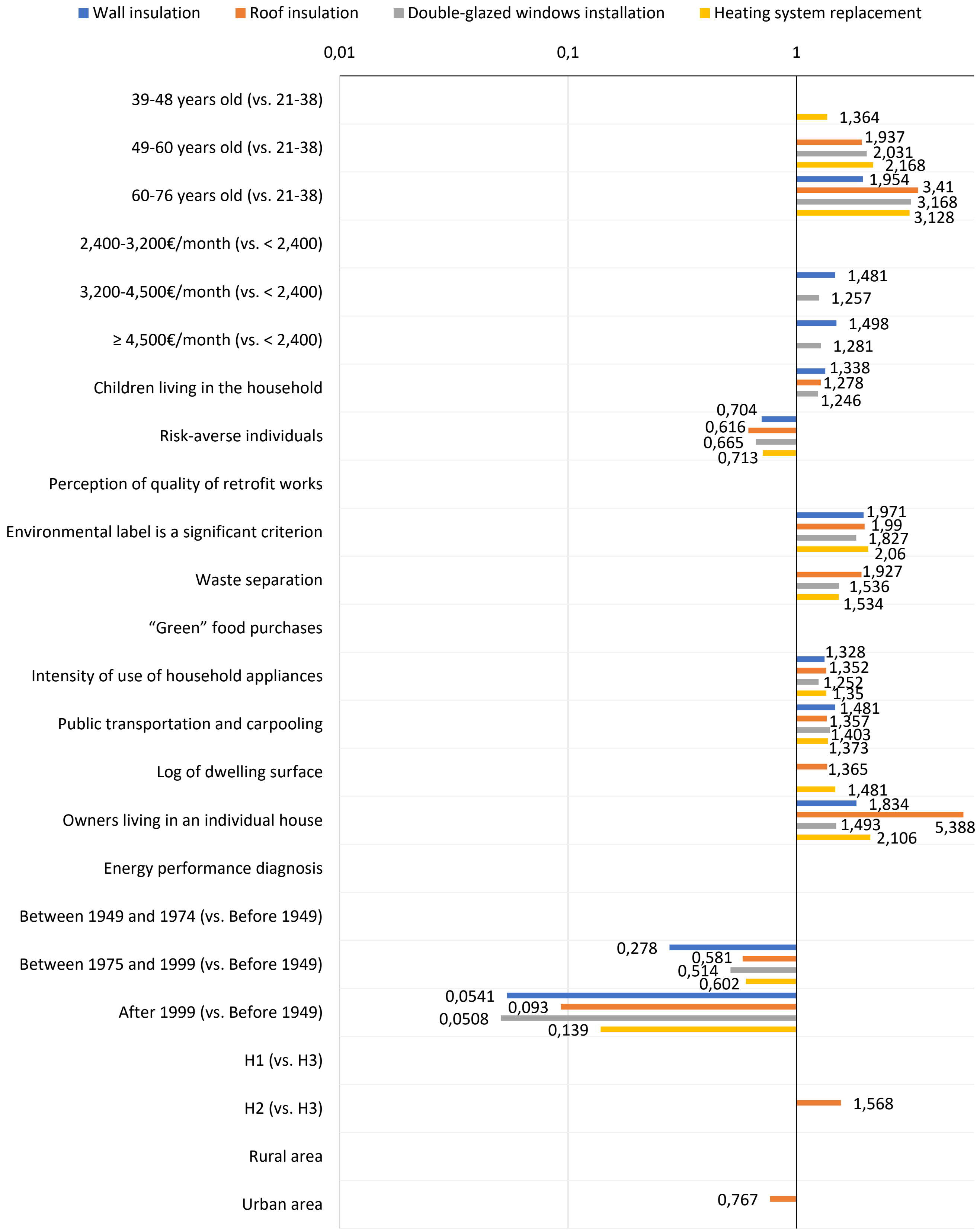
	(0.0938)	(0.0714)	(0.0700)	(0.0794)
Perception of quality of retrofit works	1.038	1.014	1.018	1.030
	(0.0336)	(0.0281)	(0.0256)	(0.0266)
Environmental label is a significant criterion	1.971***	1.990***	1.827***	2.060***
	(0.445)	(0.388)	(0.307)	(0.378)
Waste separation	1.589	1.927**	1.536*	1.534*
	(0.467)	(0.560)	(0.358)	(0.386)
“Green” food purchases	1.063	1.000	1.111	1.005
	(0.133)	(0.109)	(0.110)	(0.103)
Intensity of use of household appliances	1.328**	1.352***	1.252**	1.350***
	(0.167)	(0.147)	(0.123)	(0.139)
Public transportation and carpooling	1.481***	1.357***	1.403***	1.373***
	(0.195)	(0.161)	(0.148)	(0.154)
Dwelling characteristics				
Log of dwelling surface	1.241	1.365*	1.261	1.481**
	(0.234)	(0.228)	(0.194)	(0.237)
Owners living in an individual house	1.834***	5.388***	1.493***	2.106***
	(0.365)	(1.212)	(0.227)	(0.363)
Energy performance diagnosis	1.021	1.014	0.975	0.985
	(0.0345)	(0.0291)	(0.0252)	(0.0268)
Building construction period (vs. Before 1949)				
Between 1949 and 1974	0.816	1.176	1.034	1.078
	(0.128)	(0.171)	(0.133)	(0.151)
Between 1975 and 1999	0.278***	0.581***	0.514***	0.602***
	(0.0446)	(0.0785)	(0.0619)	(0.0773)
After 1999	0.0541***	0.0930***	0.0508***	0.139***

	(0.0156)	(0.0210)	(0.0124)	(0.0268)
Climatic zone (vs. H3)				
H1 (the coldest winter temperature)	1.207	1.155	0.937	0.964
	(0.290)	(0.229)	(0.157)	(0.172)
H2 (more temperate winters)	1.471	1.568**	1.067	1.094
	(0.366)	(0.322)	(0.188)	(0.207)
Rural area	1.251	0.939	0.975	0.974
	(0.192)	(0.124)	(0.122)	(0.127)
Urban area	0.877	0.767**	0.838	0.888
	(0.138)	(0.101)	(0.100)	(0.113)
Constant	0.0180***	0.00493***	0.0574***	0.0115***
	(0.0161)	(0.00420)	(0.0429)	(0.00916)
Observations	4,165			
R-squared	0.089			
Hosmer–Lemeshow goodness-of-fit test: p-value	1.000			
Wald test of overall significance: p-value	0.000			

Note: robust standard errors in parenthesis; *** $p < 1\%$; ** $p < 5\%$; * $p < 10\%$

Figure 15: Variation of the probability of choosing a type of retrofit rather than staying in a status quo situation (reference), logarithmic scale for odds ratio, significant results only

Reading key: everything else being equal, the probability of risk-averse individuals of choosing to insulate their walls rather than doing nothing is 1/0.704=1.42 less than that of non-risk-averse individuals.



7. Policy implications

Our findings highlight the necessity to lower the risk burdened by households to help reduce perceived risk. There are several options for policymakers to foster energy efficiency investments for a low-carbon economy.

First, labels that would provide the accurate level of energy costs and savings of energy efficiency solutions, and not only average values as it is currently the case, may be of interest. Indeed, these labels are only informative and fail to alleviate the demonstrated negative effects of risk perception. By clearly giving the uncertainty of energy savings on ecological labels, such as expected savings rather than averages, risk-averse homeowners would get an idea of the distribution of expected savings.

Second, the creation of company labels or certificates, at a national scale, could reassure and give confidence to households who are mainly looking for a quality guarantee. As a matter of fact, the French RGE label (Recognized Environmental Guarantor) was established in 2011 to allow individuals wishing to make energy savings work in their homes to call on competent and qualified professionals recognized by the State. Calling on a professional who holds the RGE label is actually mandatory to obtain public aids. This is the first step towards the recognition of energy renovation professionals in order to guarantee the quality of their work, thus reducing the risk of defects.

Third, better support for households in carrying out work could also encourage them to undertake a renovation. On this point, in France, a public information and advisory service on home energy renovation, the FAIRe program, was set up in September 2018 by the ADEME (the French environment and energy management agency), the ANAH (the national housing agency), and local authorities. To help them carry out the most suitable work or to estimate the necessary budget and the financial aid from which they can benefit, households can be accompanied by a FAIRe consultant. Accompanying households in their energy renovation process could prevent them from giving up and also help them minimize the inconvenience caused by better planning the various technical interventions.

Fourth, more readily available public subsidies and more aggressive financial incentives would be effective in reducing the economic burden on households and mitigating the risk of unsustainability.

8. Conclusions

This paper seeks to analyze behavioral barriers to energy efficiency investments in the French residential sector with particular attention to the role of environmental concerns and energy context perception. A Nested Logit model is developed to investigate the determinants of energy renovation behavior in France based on a stated preference survey conducted in 2018, including cross-section data on 3,000 French homeowners.

First, results indicate that adopting pro-environmental behaviors (sorting waste, paying attention to environmental labels when buying appliances, being mindful of their intensity of use, and taking public transportation and carpooling for environmental reasons) increases households' probability of renovating their home. The existence of spillover effects among pro-environmental behaviors shows that households are behave consistently. In light of the various contributions of the literature, which does not reach a consensus on the topic, it seems that results are sensitive to (i) data quality, (ii) the conceptual and econometric framework, and (iii) the measure adopted to assess pro-environmental behaviors.

Second, according to the portfolio theory, risk-aversion is found to be a deterrent factor to households investing in energy efficiency improvement measures since it significantly decreases the probability of households to invest in energy efficiency improvement measures (up to a 33%-decrease).

Third, sociodemographic characteristics also hold some importance in the decision to renovate. The probability of undertaking renovation work significantly increases with aging and rising income. Also, the presence of children, a deterrent factor to residential mobility, encourages households to renovate.

Fourth, dwelling attributes are significant drivers of the households' decision to renovate as well. Owning a large and old individual house is associated with a greater likelihood of adopting energy-efficient technologies.

As is always the case with self-reported data, estimates ought to be interpreted cautiously. Due to factors such as social desirability, wording, response scales, and other types of response bias, respondents may misreport their actual behaviors, consciously or unconsciously (Podsakoff et al., 2003), which may ultimately alter the quality of our results.

Conclusion and transition to Chapter 2

This first chapter investigates the determinants of residential energy efficiency renovation behavior in France by developing a two-level discrete choice model. Results highlight the strong explanatory power of sociodemographic and housing characteristics, which is a further affirmation of what the empirical literature on the topic already suggests. Findings also point out that adopting pro-environmental behaviors increases the likelihood of households to renovate their dwelling, and that spillover and cross-situational environmental motivations effects may occur. Finally, focusing on the behavioral barriers hampering the diffusion of energy-efficient technologies, the analysis of the effect of the perception of the energy renovation market on the decision to renovate indicates that risk-averse households are less likely to implement energy efficiency measures. All in all, this chapter provides interesting policy implications, such as the need for policymakers to consider household and dwelling heterogeneity in designing energy policies. Emphasis should be placed on guaranteed post-retrofit energy gains, to limit the risk of non-profitability, which is a source of uncertainty for households willing to renovate their home, but still hesitant to do so.

The descriptive results also highlighted financial aid as a key criterion in the decision-making process. Therefore, using the same rich micro-data as in **Chapter 1**, **Chapter 2** turns to the effect of structural barriers to energy efficiency, that are independent from the will of the households.

Chapter 2: Financial incentives and their impact on energy renovation behavior: evidence from the French residential sector

This article was submitted to The Energy Journal. I presented it at the 19th edition of the Augustin Cournot Doctoral Days of Université de Strasbourg in May 2022, and will present it at the Workshop on Environmental Policy Evaluation of the University of Saint Gallen, Switzerland, in January 2023. It was accepted for presentation at the 8th Conference "Évaluation des politiques publiques" of the Association Française de Sciences Economiques and Direction Générale du Trésor, in Paris, in December 2022, though I did not go.

Keywords: Financial incentives; Policy evaluation; Energy efficiency renovation behavior; Energy efficiency paradox; France.

1. Introduction

Reducing GHG emissions has become over the last decades a key priority of the EU. Actions to combat climate change are multiplying, as confirmed by the 2015 Paris Agreement reached by the EU, its Member States and other parties. In order to limit global warming to below 2°C and pursue efforts to limit it to 1.5°C, the EU committed to (i) reduce GHG emissions by at least 40% by 2030 compared to 1990 levels; (ii) increase the share of renewable energy to at least 32%; and (iii) improve energy efficiency by at least 32.5%. Recently, the European Green Deal, presented in December 2019, revised the 2030 targets which now consist in cutting GHG emissions by 55% compared to 1990 levels.

Thus, energy efficiency appears crucial for the EU to meet these climate objectives. It is estimated that it would require a "reduction of 60% of emissions in the building sector alone" (Agir pour le climat, 2021). In France precisely, renovating the entire building stock would cut energy consumption by 18% and GHG emissions by 32%, according to a recent study by Belaïd et al. (2021a). Knowing that, in 2020, the French residential sector was the country's first-largest final energy consumer (accounting for 31% of total final energy consumption)[2], it offers a substantial low-cost potential for energy savings and reduction of related carbon gas emissions (Ministère de la Transition Ecologique et Solidaire, 2021a).

Therefore, buildings have a tremendous potential to deliver cost-effective GHG emissions reductions in both developed and developing countries. In the last decade, many experts and international institutions such as the International Energy Agency highlighted the highest untapped

[2] Energy consumption for transportation purposes was strongly affected by the traffic restrictions related to the 2020 sanitary crisis, allowing the usual second largest residential sector to move up to first place.

energy savings potential achievable from building design and the renovation of existing and aging dwellings. According to the IEA's 2019 study, about 80% of the economic potential of energy efficiency in buildings remains untapped, primarily due to non-technical barriers.

Arguably, the most obvious potential benefits of energy efficiency deployment in buildings are the environmental ones. Indeed, it contributes to the 13th SDG of the UN by reducing carbon emissions, improving environmental quality and mitigating climate change impacts. Although the 17 SDGs are wide-ranging, from eradicating hunger to promoting peaceful and inclusive societies, there are several goals to which a decarbonized building sector could, and already does, contribute significantly: it can ensure healthy lives and promote well-being (SDG3); reduce consumer energy bills, and secure access to affordable, reliable, sustainable and modern energy (SDG7); increase competitiveness of industries and services, promote inclusive and sustainable economic growth, and create green jobs (SDG8); stimulate innovation and support the development of climate-resilient infrastructures (SDG9); promote the design of sustainable communities, resilient, and inclusive cities (SDG11); stimulate resource reuse and promote sustainable consumption (SDG12); save water resources, preserve forests and biodiversity (SDG15); and save energy and water resources, preserve forests and biodiversity (SDG17).

For all these reasons, it is essential to focus on the energy efficiency of buildings while defining the energy transition and the path to sustainability. Today, the achievement of binding national commitments related to energy consumption depends on a willingness to invest or not in the energy efficiency of millions of private actors, individuals, who are making a decision at the most disaggregated scale. Thus, considering the slow rate of energy efficiency investments in the building sector, there is an urgent need to go further in the understanding of the decision-making process behind energy efficiency investments to design effective public policies.

This study is part of the literature examining the determinants of residential energy demand (Vaage, 2000; Rehdanz, 2007; Leahy and Lyons, 2010; Belaïd, 2016, 2017; Belaïd et al., 2020b; Belaïd and Joumni, 2020) and residential energy efficiency behavior (Cameron, 1985; Ferguson, 1993; Gamtessa, 2013, Achtnicht and Madlener, 2014; Galassi and Madlener, 2017; Trotta, 2018a, 2018b). It is also linked to the understanding of the barriers that stand in the way of large-scale deployment of energy efficiency in the sector, pointing at the so-called energy efficiency paradox, or energy efficiency gap (Jaffe and Stavins, 1994; Fowlie et al., 2015, 2018; Gerarden et al., 2015). Accordingly, Hirst and Brown (1990) suggest a classification of barriers to energy efficiency: behavioral barriers, dealing with internal problems occurring during the end-users decision-making process; and structural barriers, that are external to individuals, and then linked to the actions of organizations, such as governmental fiscal and regulatory policies, or supply and geographical restrictions.

Starting from this conjecture, this article focuses on the impact of structural barriers on the energy renovation behavior in the French residential sector, in particular the role of financial aid. Financial incentives studied hereby take the form of direct subsidies granted from the French governments to retrofitters. They are simulated for non-retrofitters and non-beneficiary retrofitters using an original approach, in compliance with the official financial aid simulator Simul'aides provided by the French government. By use of a rich online survey conducted in 2018 including cross-section data on 3,000 French homeowners, a Logit model is developed to estimate households' likelihood to renovate their housing. A CART model is also performed, to gain more insights about the most potent drivers of energy renovation behavior. Studying the impact of financial schemes on the deployment and adoption of energy efficiency improvement measures is legitimate since it provides policymakers with key information on the accurate effectiveness of the various incentive programs implemented in the country. More broadly, this article offers insights that can help mitigate structural barriers to energy efficiency investments, and ultimately narrow the persistent energy efficiency gap.

We find evidence of a significant non-linear effect of financial aid on the renovation probability, suggesting a threshold effect. In parallel, the age of the household's head and the construction period of the dwelling are found to be the most influent factors. Considering household and dwelling heterogeneity, and the existence of the demonstrated threshold effect, better adapting the amount of aid to the renovation project of each household can enable governments to improve the return on investment of energy policy measures, and speed-up the energy efficiency implementation process in the private residential sector.

This paper proceeds as follows: Section 2 provides an overview of French energy efficiency policies and energy renovation subsidies; Section 3 explores the existing literature about the energy efficiency gap and energy efficiency behavior; Section 4 introduces the survey data and the econometric methodology applied for the analysis; Section 5 discusses empirical results; Section 6 presents robustness checks to test the sensitivity of our results; finally, Section 7 draws concluding remarks and policy implications.

2. Overview of French energy efficiency policies and energy renovation subsidies

Until the 1970s, the economic development of the "Glorious Thirty" intensified the use of fossil fuels in France to run industries. However, the first oil shock of 1973 called oil and energy consumption into question. France became aware of the importance of reducing its overall energy consumption, following the dramatic fluctuations in hydrocarbon prices. This is in this context that the first thermal regulation, the RT 1974, was implemented. The main objective of this measure was to reduce energy losses in new housing, particularly at the level of internal and external wall insulations. A 25%-reduction in energy consumption of new housing was also targeted, compared to the standards of the 1950s. Eight years later, after the second oil shock in 1979, the RT 1982 was set up with growing requirements about energy consumption reduction in new housing: it consisted in reducing residential energy consumption by 20% more than the objectives of the previous RT. Thereafter, the RT 1988 extended the policies to tertiary buildings, which had not been concerned until then. In 2000, the RT 2000 was introduced, with the obligation to reduce the maximum consumption of residential and non-residential buildings by 20% and 40% respectively. Emphasis was also placed on summer comfort and GHG emissions reduction, in compliance with the 1997 Kyoto Protocol. The RT 2005 was designed five years later, and continued the efforts to account for comfort and energy performance in the construction of residential and tertiary buildings. Labels such as HPE (high energy performance) and BBC (low consumption building) were also defined.

The 2007 Grenelle Environment Forum became one of the cornerstones of France's energy policy, as it launched a national debate on the issue of energy efficiency. Essentially, it led to a draft bill adopted in May 2015, called the Law on the Energy Transition for Green Growth, or Energy Transition Law. Along with a 40%-reduction in GHG emissions in 2030 compared to 1990, the principles of this law were based on six main axes: (i) the energy renovation of existing buildings and the energy performance of new buildings, via encouraging the use of renewable energies notably; (ii) the fight against energy insecurity and poverty, by expanding financial assistance for paying energy bills for low-income households; (iii) the development of clean mobility, by fostering the purchase and use of cleaner vehicles; (iv) the abandon of nuclear power and the development of renewable energies, to reach energy independence and encourage the development of green electricity suppliers; (v) the simplification of the energy regulation framework, via the adoption of new calculation methods of regulated electricity prices for instance; and (vi) the fight against waste and the development of circular energy, by promoting waste sorting and recycling.

Taking advantage of the impetus generated by the 2007 Grenelle Environment Forum, the RT 2012 was implemented and remains today the biggest change in the French energy policy, with stricter requirements in terms of GHG emissions and energy consumption reductions in new buildings. In parallel, it introduced the Bepos label (positive energy buildings): buildings producing more energy than they consume. This concept was relayed by the next RT 2018, which aimed at (i) better considering GHG emissions, via calculating energy and resource consumption over the entire life cycle of households and of the building itself; and (ii) encouraging the use of renewable energy, to cover the needs of buildings. The latest RT 2020 (or RE 2020, environmental regulation) also relies on the Bepos concept and focuses on the deployment of this type of buildings. To sum up, **Figure 16** shows the evolution of the different RTs in the form of a timeline.

These numerous RTs that make up France’s energy policy seek to foster energy efficiency in the construction of residential, and later tertiary buildings, but none of them address the energy efficiency renovation of the existing stock of buildings, at the micro-level. Therefore, in order to encourage French households to carry out energy renovation work, which is often quite expensive, the public authorities and institutions have set up financial aid. The amounts allocated depend on the households’ projects, income, and can be cumulated in some cases. There are currently seven national financial schemes aimed at French households wishing to carry out energy renovation work. **Table 10** presents their main characteristics. There are also regional, departmental and local schemes, *e.g.*, the temporary exemption of the property tax granted by certain localities. Finally, some financial schemes are intended to enhance energy security, such as the energy cheque. This nominative voucher for energy bills is dedicated to households with modest resources and its value, ranging between 48 and 277 euros per year, is proportional to income.

Figure 16: Timeline of the introduction of thermal regulations in France

(Source: own elaboration)

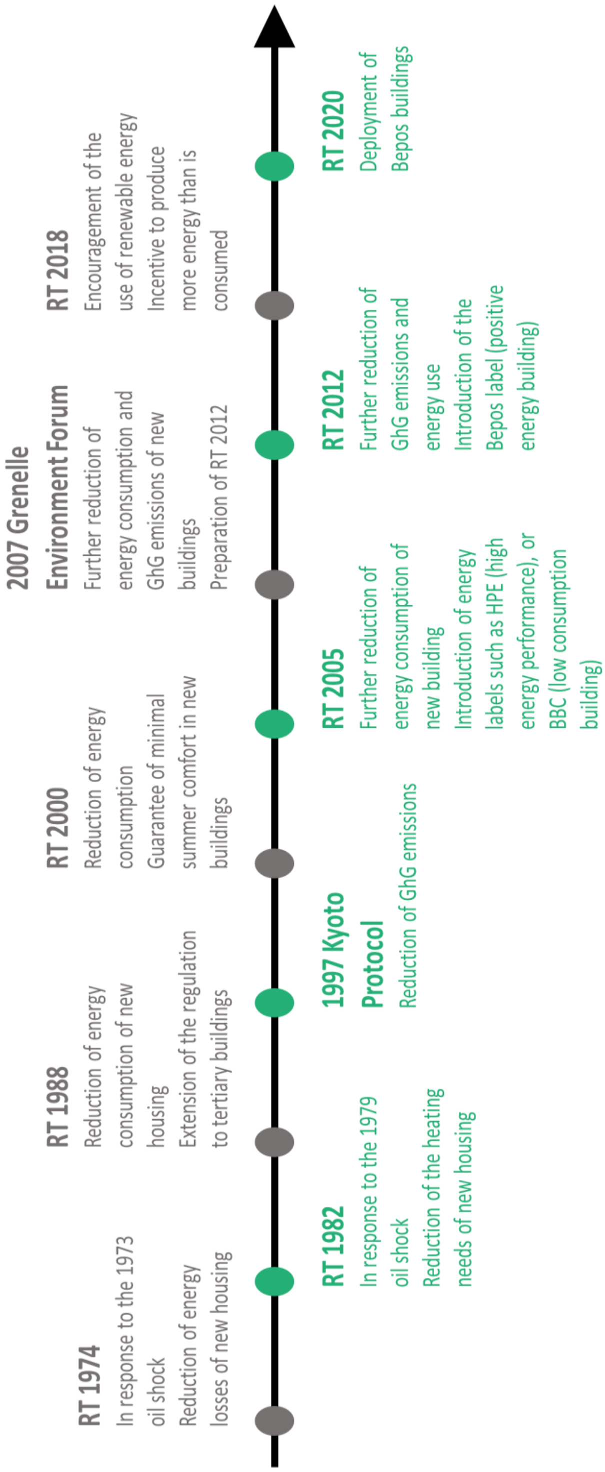


Table 10: The main financial schemes for energy renovation in France
(Source: own elaboration based on Ministère de l'Economie, des Finances et la Relance (2021))

Financial aid	Beneficiary households	Principle	Amount
MaPrimeRénov' (formerly the Energy Transition Tax Credit, CITE)	All households	Bonus payment	Proportional to income and the ecological gain of the renovation work
"Habiter mieux sérénité" aid from the National Housing Agency (ANAH)	Households with modest and very modest resources, owner-occupants of individual dwelling, landlords, condominiums	Bonus payment after completion of the renovation work	Proportional to the amount of work, up to 18,000€
Zero-rate eco-loan	Owner-occupants, landlords, condominiums	No cash advance and no interest when financing the renovation work	Only one loan per dwelling, up to 30,000€ over a 10-year period
"Coup de pouce économies d'énergie"	All households	Bonus payment	Proportional to income
Energy Efficiency Certificates	Owners, tenants	Financial assistance offered by energy suppliers to carry out renovation work	Depends on the energy supplier
5.5%-VAT for energy efficiency renovation work	All households	VAT reduction on the amount of renovation work	5.5% or 10%-VAT instead of 20%
Denormandie tax reduction	Landlords carrying out work representing at least 25% of the price of the property purchased, located in one of the 222 cities benefiting from the "Action cœur de ville" program	Tax reduction	Calculated by applying a percentage to the net cost price of the property, which varies according to the length of the rental period

Note: VAT stands for Value-Added Tax

3. Literature review

Considering the low rate of new building construction in Europe and the insufficient rate of existing building renovation (Odyssee-Mure, 2021), it is necessary to accelerate the pace of building renovation, while keeping in mind the EU's CO2 emission reduction objectives by 2050. Energy efficiency appears a solution and then, boosting the adoption of energy-efficient technologies in the residential sector becomes crucial. However, the drivers of residential energy use must be identified beforehand. Consequently, this article belongs to the rich branch of literature studying this topic. The determinants of residential energy consumption are now largely known thanks to numerous empirical studies (Vaage, 2000; Rehdanz, 2007; Leahy and Lyons, 2010; Belaïd, 2016, 2017; Belaïd et al., 2020b; Belaïd and Joumni, 2020), which even sometimes adopt a life cycle approach (Fritzsche, 1981; Estiri and Zagheni, 2019; Belaïd et al., 2021b). These determinants are either (i) sociodemographic, *i.e.*, related to households' characteristics such as the age and gender of the household's head, the size and composition of the family, the income level, or the occupancy status; (ii) dwelling-specific, *i.e.*, dealing with dwellings' technical attributes such as the size, age, type, location and energy performance of the building; or (iii) attitudinal, *i.e.*, linked to behavioral beliefs such as risk-aversion or pro-environmental identity. Columns (1) and (2) of **Table 11** scrutinize the existing literature and give the effect direction of explanatory variables on residential energy consumption.

Afterwards, based on this solid literature, a nascent line of thought focusing on the drivers of energy efficiency behavior emerged. Either theoretically or by the use of field experiments, or discrete choice experiments, scholars try and understand what determines the adoption of energy-efficient technologies. Columns (3) and (4) of **Table 11** list the effect direction of the main determinants of energy renovation behavior identified by the empirical literature. **Figure 17** also clarifies the underlying conceptual framework for both energy consumption and energy efficiency renovation behaviors in the residential sector.

All the studies listed in **Table 11** are intertwined with the energy efficiency paradox (Sutherland, 1991; Jaffe and Stavins, 1994; Gerarden et al., 2015). Indeed, despite considerable promises and multiple benefits that energy efficiency investments can offer, there are many barriers that stand in the way of their large-scale deployment in the residential sector. What causes this discrepancy between the slow diffusion of energy-efficient technologies and the profitability of these measures, yet widely demonstrated by scholars (Liu et al., 2018; Luddeni et al., 2018; Belaïd et al., 2021a), points to the so-called energy efficiency paradox. This phenomenon is linked to the fact that individuals seem to under-invest in energy efficiency improvements that have the potential to be more than worthwhile in terms of energy savings.

Indeed, the energy efficiency gap seems to be fueled by systematic behavioral biases in households decision-making process, and market barriers and failures (Tietenberg, 2009; Allcott and Greenstone, 2012; Allcott et al., 2012; Gillingham and Palmer, 2014; Bakaloglou and Belaïd, 2022). In other words, both behavioral and structural barriers influence energy renovation behavior. Regarding the latter, which are the focus of this article, Gillingham et al. (2009) write that liquidity constraints are a commonly cited market failure relevant to energy efficiency. The pioneer work of Blumstein et al. (1980) describes liquidity constraints as a deterrent factor of energy-efficient investments since a lack of access to credit can result in underinvesting, an outcome also discussed in the development economics literature (Ray, 1998). The IEA (2011) also reckons that a lack of finance is a key barrier to investment in energy efficiency projects.

A potential policy option aimed at mitigating the effect of liquidity constraints on energy renovation behavior is then financing or loan programs. Blumstein (2010) reports that increasing the likelihood of households to undertake energy efficiency improvement measures can be achieved by raising their awareness about the existence of various incentive schemes. Interestingly, economic and fiscal incentives can hit two targets with one bullet by (i) addressing an asymmetric information problem, due to the inherent gap between the actual energy savings post-renovation and the *a priori* energy savings (Sutherland, 1991); and by (ii) lowering the upfront costs of an investment and improving affordability of retrofits, which is particularly relevant for risk-averse individuals, known to be less likely to invest in energy efficiency (Baker, 2012; Alberini et al., 2013; Achtnicht and Madlener, 2014; Qiu et al., 2014; Bakaloglou and Belaïd, 2022). Therefore, financial support constitutes a key lever for residential renovation.

However, the empirical literature investigating the direct effect of financial incentives on the adoption of energy efficiency measures remains scant. The majority of works about energy efficiency-oriented financial schemes are only descriptive and roughly consist in an overview of public and private schemes in the EU Member States, as in a 2019 European Commission report by Economidou et al., in a discussion on the barriers and challenges in a deep building renovation in Europe, as in D'Oca et al. (2018), or in a review of the literature about the advantages and weaknesses of fiscal policies, as in Sarker et al. (2020) for the industrial sector. In addition, the scarce empirical literature on the topic fails to reach a consensus. On the one hand, using a sharp discontinuity design and matching methods on French data, Risch's valuable work (2020) indicates that the energy transition tax credit (*cf.* first line of **Table 10**) has little but significant effect on the decision to renovate, increasing the renovation rate by 1.09%, ceteris paribus. On the other hand, (i) using a Tobit model on American data, Dubin and Henson (1988) do not find evidence that tax credits provide an incentive to home renovation; and (ii) Fowlie et al. (2015) write that "individuals and households bypass opportunities to improve energy efficiency that require zero out-of-pocket expenditures", after evaluating the effect of a free energy-efficiency program, in which more than 30,000 households in Michigan enrolled.

Thus, there exists few empirical works investigating the direct effect of financial schemes on energy renovation behavior, while a better understanding of the ins and outs of this relation is still needed. In that regard, the present study fills in this gap and takes initial steps towards the estimation of the explanatory power of financial aid on energy efficiency behavior, also accounting for household and dwelling heterogeneity. In view of the plurality of financial schemes for energy efficiency renovation (*cf.* **Table 10**), both in terms of amount, principle, and eligible public, it is interesting to estimate their impact on residential renovation behavior. Besides, considering that 3.1 million households, *i.e.*, 20% of households living in an individual house in mainland France, completed at least one renovation action in 2019 (Ministère de la Transition Ecologique et Solidaire, 2021a), understanding how financial aid directly affect the adoption of energy-efficient technologies can help policymakers increase the share of retrofitters in the French population.

Table 11: Literature review about the main determinants of energy consumption and energy renovation behaviors

Variable	Effect on residential energy consumption behavior (1)	References (2)	Effect on residential energy renovation behavior (3)	References (4)
Sociodemographic variables				
Age of head of household	+ then -	Fritzsche, 1981; Estiri and Zagheni, 2019; Belaïd et al., 2021b	+ then -	Poortinga et al., 2003; Nair et al., 2010
			+	Trotta, 2018a
Gender (men vs. women)	+	Carlsson-Kanyama and Lindén, 2007; Räti and Carlsson-Kanyama, 2010	No effect	Ameli and Brandt, 2014; Trotta, 2018a
	No effect	Martinsson et al., 2011; Trotta, 2018a		
Income level	+	Wiedenhofer et al., 2011; Belaïd et al., 2020a, 2020b, 2021b	+	Achtnicht and Madlener, 2014; Trotta, 2018a
			-	Gamtessa, 2013
Family size	+	Vaage, 2000; Leahy and Lyons, 2010	+	Ferguson, 1993; Poortinga et al., 2003; Trotta, 2018b
Occupancy status (owner vs. tenant)	+	Yohanis et al., 2008; Belaïd, 2016	+	Davis, 2010; Meier and Rehdanz, 2010; Charlier, 2018; Trotta, 2018b
	-	Ndiaye and Gabriel, 2011; Jones et al., 2015		
Financial incentives	-	Fowlie et al., 2015	+	Risch, 2020

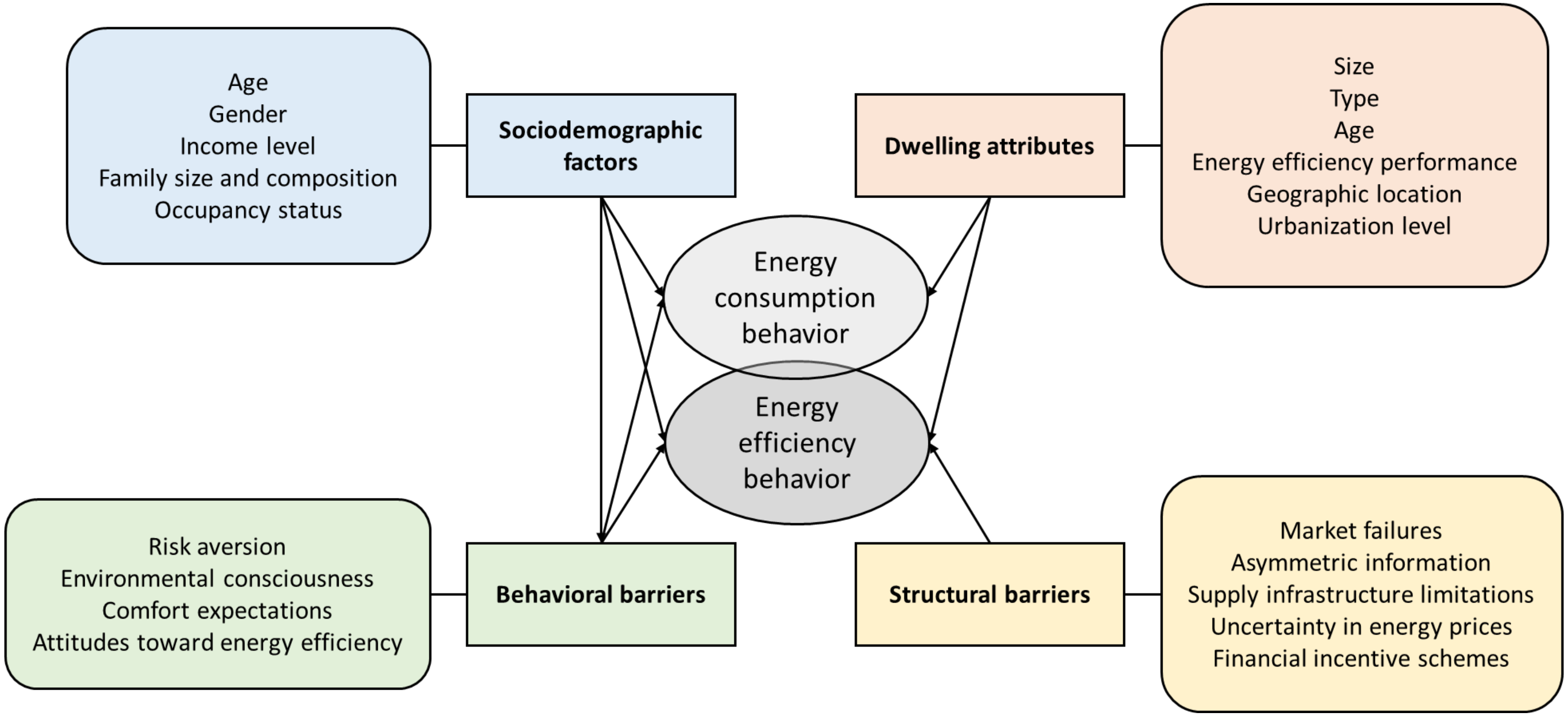
			No effect	Dubin and Henson, 1988; Fowlie et al., 2015, 2018
Dwelling characteristics				
Size	+	Belaïd et al., 2020a, 2021a; Huebner and Shipworth, 2017	+	Ferguson, 1993
Dwelling age	+	Vaage, 2000; Rehdanz, 2007; Belaïd et al., 2021a	+	Ferguson, 1993; Gamtessa, 2013
Housing type (individual house vs. other)	+	Vaage, 2000; Rehdanz, 2007; Belaïd et al., 2021a	+	Ferguson, 1993; Gamtessa, 2013; Trotta, 2018a, 2018b
Local climate and temperatures (hot vs. cold temperatures)	-	Wiedenhofer et al., 2011; Belaïd, 2017	No empirical literature	
Urbanization level (urban zone vs. rural zone)	+	Sheng et al., 2017	+	Ferguson, 1993; Belaïd, 2016
			-	Trotta, 2018b
Energy performance diagnosis (good vs. poor performance)	-	Hamilton et al., 2013; Belaïd et al., 2020a, 2021a	-	Belaïd et al., 2021a
Attitudinal variables				
Risk aversion	Not relevant		-	Baker, 2012; Alberini et al., 2013; Achtnicht and Madlener, 2014; Qiu et al., 2014; Bakaloglou and Belaïd, 2022

Pro-environmental identity	-	Lindenberg and Steg, 2007; Hamilton et al., 2013	+	Whitmarsh and O'Neill, 2010; Schleich et al., 2019; Fischbacher et al., 2021
			No effect	Aravena, 2016; Galassi and Madlener, 2017

Note: + stands for a positive effect; - stands for a negative effect

Figure 17: Conceptual framework for energy consumption and energy efficiency renovation behaviors in the residential sector

(Source: own elaboration)



4. Data and methodology

Based on a Logit specification, this paper investigates the determinants of energy efficiency renovation in the residential sector, with an emphasis on governmental financial aid. This section presents the cross-sectional data used to perform this analysis, along with descriptive results already stressing out certain behavior patterns. Then, it details the methodology of the selected estimation approach.

4.1 Data source and description

This study employs a dataset coming from an online survey carried out between December 2017 and January 2018 (see **Appendix B.a**). It provides cross-section data for 3,000 French homeowners about their sociodemographic characteristics (age, income, family size and composition, the existence of an outstanding loan) and dwelling attributes (surface, construction date, dwelling type, heating energy). The survey also gathers information about any energy efficiency renovation work carried out in the dwelling since moving in, including external or internal wall insulation, roof or attic insulation, double-glazed windows installation, and heating system replacement. The amount in euros of financial aid that the renovators may have received is also known. The employed dataset is representative of the stock of French homeowners.

Previous research has shown that the energy renovation behavior of tenants and owner-occupants significantly differs (Davis, 2010; Meier and Rehdanz, 2010; Charlier, 2018). Indeed, tenants are more reluctant to renovate than owners because they anticipate that their rental period may not be sufficient to make such investment profitable. Thus, in order to assess the impact of financial aid on the energy renovation behavior, only individuals who really can make decisions about the energy efficiency performance of their dwelling must be considered, *i.e.*, owner-occupants.

Most variables are discretized in order to avoid the bias coming from inconsistent extreme values, a well-known issue in stated preference surveys, sometimes revealing a refusal to answer. Therefore, after cleaning some aberrant observations, the retained sample contains 2,638 households.

Table 12 displays summary statistics for the retained sample, and for retrofitters and non-retrofitters. They are perfectly balanced. Incidentally, this provides evidence of the energy efficiency paradox: still half of the households do not renovate their dwelling even though it has been proven to be cost-effective. Non-retrofitters are more than 6 years younger than retrofitters, with an average age of 49 years for the whole sample. The share of retrofitters also increases with age, as shown in **Figure 18**, which already highlights a potential positive relation between ageing and home renovation.

Back to **Table 12**, 45% of respondents (48% of non-retrofitters and 41% of retrofitters) live with at least one dependent child at home. The sample is made at 79% of individual houses, and 21% of apartments or other housing types. The difference between retrofitters and non-retrofitters is striking here: retrofitters live more often in individual houses than non-retrofitters (84% and 74% respectively).

They also live in larger dwellings (around 10 additional square meters which represents 9% more space). Half of the dwellings were built before 1975, and almost one third between 1975 and 1999. A very small minority of retrofitters (6%) live in recent dwellings, *i.e.*, completed after 1999. This date corresponds to a new thermal regulation implemented in France, the RT 2000, to control the thermal design of new buildings. As a result, dwellings completed after this date became less energy-intensive which is reflected today in the energy renovation behavior: few of these houses are renovated. Finally, nearly one in two retrofitters (47%) received financial aid, that were on average of 2,345 euros, ranging from 200 to 12,000 euros.

Supplementary survey questions were asked to households about their energy efficiency renovation behavior. Precisely, retrofitters who received financial aid (610 households) were asked to answer the following question: "Would you have carried out this energy renovation work without financial aid?". **Figure 19** presents answers. Obtaining financial aid enabled households to carry out energy renovation work in 23% of the cases. Plus, 44% of retrofitters admit that, without financial support, (i) they would not have asked a professional to carry out work and would have rather do it themselves; (ii) they would not have undertaken as muck work; or (iii) they would have postponed the work in time.

To deepen the analysis, non-retrofitters were asked if they were planning any renovation work in the next two years. First, those who said they were not (500 households) were provided with a list of possible reasons. The too high necessary investment was listed as a reason not to renovate by 22% of respondents. Financial aid seek in particular to mitigate the economic burden born by households by offering tax reductions, zero-interest loans or bonus payments for instance, which would ultimately reduce the final bill. Second, non-retrofitters were presented with a list of elements that could potentially change their minds about retrofitting their dwelling. 31% of non-retrofitters stated that more easily accessible public aid would encourage them to do so. Moreover, 13% of non-retrofitters would welcome a more flexible retrofit work funding system: for instance, loan and third-party financing which is reimbursed on the energy savings made.

All in all, the hereby descriptive results reveal that households are willing to be financially assisted in their energy renovation efforts. As descriptive results are not self-sufficient, we further analyze the impact of financial aid on renovating in order to gain some empirical insights into the determinants of this behavior.

Table 12: Variable definitions and descriptive statistics for the retained sample (2,638 observations)

Variable	**Mean or frequency (standard deviation)**		
	Non-retrofitters	**Retrofitters**	**Total**
Dependent variable			
Retrofit (1: yes; 0: no)	-	-	49%
Sociodemographic characteristics			
Age of respondent (years)	45.8 (12.8)	52.0 (13.0)	48.8 (13.3)
21-38 years old *	-	-	25%
39-48 years old	-	-	25%
49-60 years old	-	-	25%
61-76 years old	-	-	25%
Household net monthly income (euros)			
< 2,400 euros/month *	-	-	25%
2,400-3,200€/month	-	-	25%
3,200-4,500€/month	-	-	25%
> 4,500€/month	-	-	25%
Financial aid (euros)			2,344.9 (2,218.4)
< 1,300€ *	-	-	25%
1,300-1,900€	-	-	25%
1,900-2,400€	-	-	25%
> 2,400€	-	-	25%
Children in the household (1: yes; 0:no)	48%	41%	45%
Dwelling characteristics			
Dwelling surface (square meters)	112.3 (49.3)	122.8 (49.4)	117.4 (49.6)
Owners living in an individual house (1: yes; 0: no)	74%	84%	79%
Building construction period			
Before 1949 *	19%	31%	25%
Between 1949 and 1974	21%	29%	25%
Between 1975 and 1999	31%	33%	32%
After 1999	30%	6%	18%
Note: * stands for the reference category			

Figure 18: Distribution of retrofitters and non-retrofitters by quartile of age

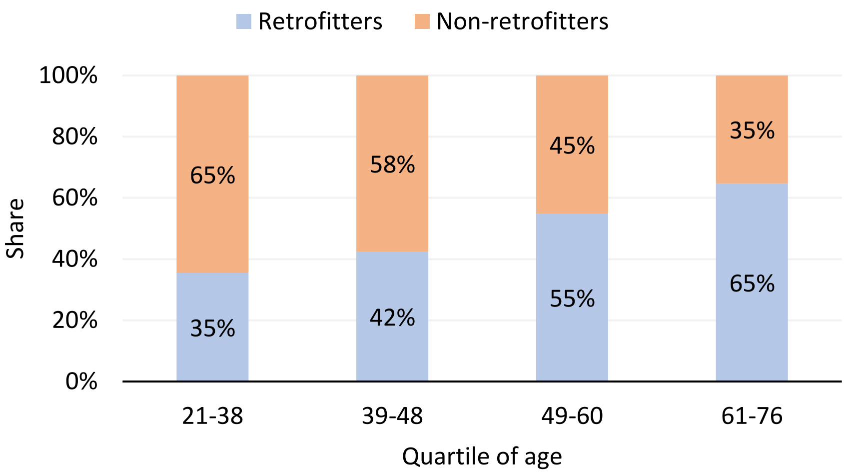
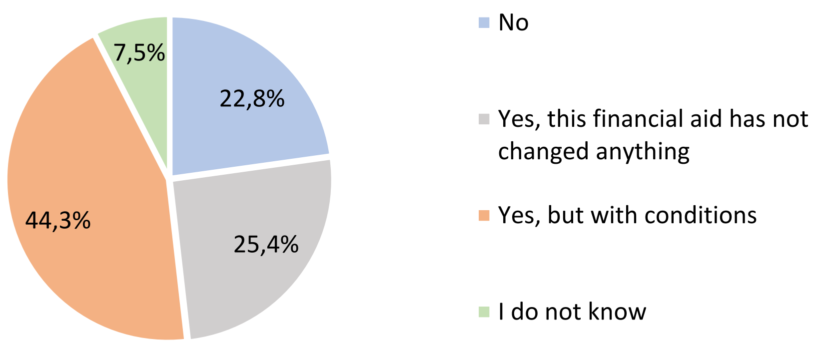


Figure 19: Retrofitters' answers to "Would you have carried out this energy renovation work without financial aid?"

Note: the answer "Yes, but with conditions" encompasses "Yes, but I would not have asked a professional", "Yes, but the volume of work would have been less", and "Yes, but the work would have been postponed in time".



4.2 Empirical strategy

This paper investigates the determinants of residential energy efficiency behavior with a focus on the impact of financial aid. Households meet a binary choice: renovate or not renovate their housing. In this framework, a Logit model for the choice of renovating is developed, which allows estimation of probabilities. The Logit regression estimates the odds outcome of the binary dependent variable given a set of quantitative or categorical independent variables, using MLE methods. As a supervised machine learning algorithm, it requires a large sample size. This also ensures that the maximum likelihood estimator is consistent and normally distributed. Hopefully, our sample of nearly 2,700 French homeowners is large enough to ensure the feasibility and accuracy of this estimation process.

Thus, using the notation $\Lambda(.)$ to indicate the logistic cumulative distribution function, the Logit regression function for the binary dependent variable Y, with multiple regressors, estimated for the whole sample (2,638 observations), writes as:

$$\Pr(Y = 1|X_1, X_2, \dots, X_k) = \Lambda(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k)$$
$$= \frac{1}{1 + \exp(-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k))} \quad (1)$$

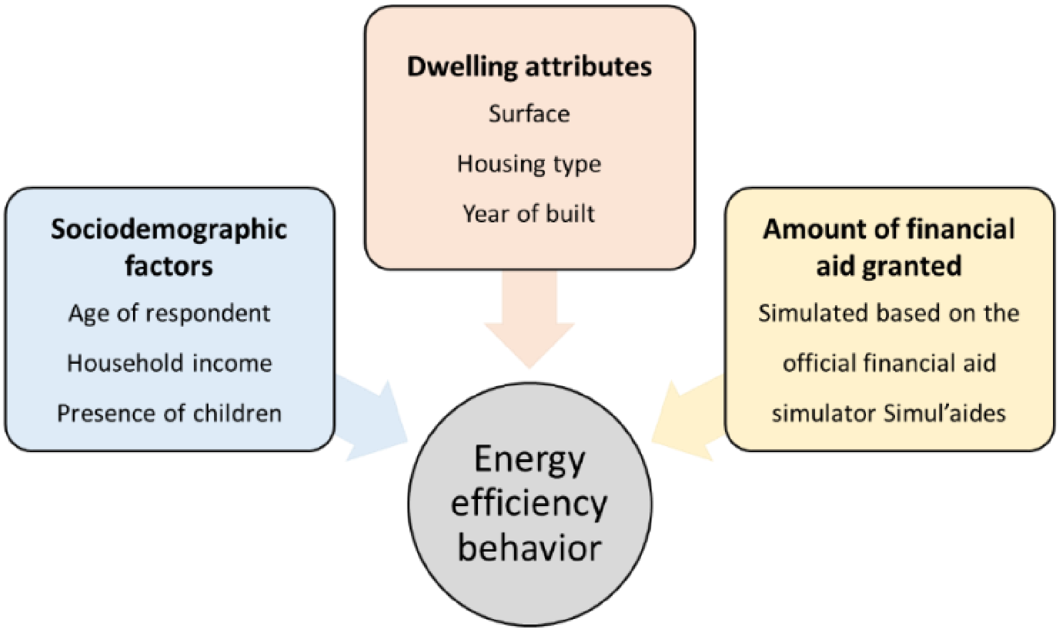
Based on empirical evidence provided by the literature previously discussed, the covariates included in equation (1) contain sociodemographic variables (age of respondent, household net monthly income, the presence of children in the house, and the amount of financial aid received) and dwelling characteristics (dwelling surface in log, housing type, and the dwelling building period).

In the employed dataset, information about the amount of financial aid is only available for the retrofitters who received it from the French government (610 households). Therefore, to tackle the issue of missing data for non-retrofitters and non-beneficiary retrofitters, we complete our dataset by simulating the amount of financial aid. To do so, we opt for an Ordinary Least Square (OLS) estimation where the dependent variable is the amount of financial aid when known. The independent variables of the model contain: (i) sociodemographic characteristics, such as household monthly net income, family size, and if the household has an outstanding loan; (ii) dwelling characteristics, such as heating energy, dwelling surface, housing type (house or other), the year the dwelling was built, and the energy performance diagnosis; and (iii) renovation-related variables, such as the nature of work implemented (heating system replacement, double-glazed windows installation, internal or external wall insulation, and roof and attic insulation). The explanatory variables included in the financial aid OLS simulation model are those employed by the official financial aid simulator Simul'aides[3] provided by the French government in collaboration with the French Agency for ecological transition (ADEME), the National Housing Agency (ANAH) and the National Housing Information Agency (ANIL).

Once the amount of financial aid is predicted, this information is matched to the known amount of financial aid, which then becomes the regressor of interest in our main econometric specification. This variable, like some others, is discretized in order to avoid the bias coming from outliers. After these preliminary steps, the estimation process is ready to be launched. The simplified conceptual framework hereby adopted is presented in **Figure 20**.

[3] For more information, visit https://www.faire.gouv.fr/aides-de-financement/simulaides.

Figure 20: Simplified conceptual framework for residential energy renovation behavior (Source: own elaboration)



5. Empirical results

This section presents the estimation results from the Logit model for the choice of renovating, on the whole sample. Column (1) of **Table 13** gives parameter estimates while Column (2) gives odds ratios.

Prior to the analysis, three statistical tests were implemented to evaluate the validity and accuracy of the selected Logit model. First, a Wald test of overall significance (1943) yields to the rejection of the null hypothesis that all coefficients in the model are jointly equal to zero. Second, the area under the ROC curve is computed for the Logit model with and without the variable of interest, namely the amount of financial aid received. It is respectively equal to 0.8017 and 0.7175, indicating that (i) the model performs relatively well at distinguishing between the two outcomes of the dependent variable (Fawcett, 2006), *i.e.*, between retrofitters and non-retrofitters; and that (ii) the model performs better with financial aid included as a regressor, suggesting their strong explanatory power. The ROC curves, plotted in **Figure 21**, are also far from the 45-degree line. Last, the model correctly classifies 73.73% of observations, which is a very satisfactory score.

On the whole, the estimated Logit model is correctly specified and ready for interpretation.

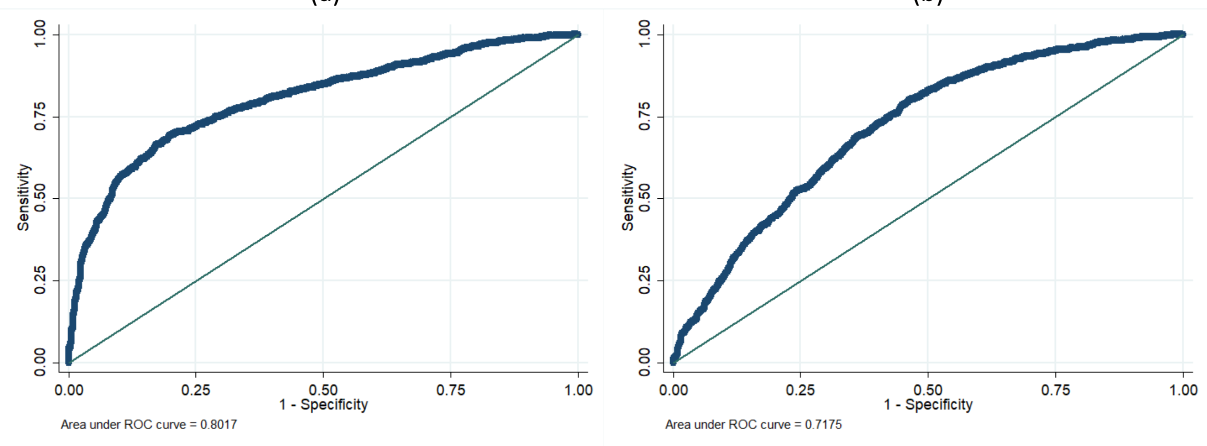
Table 13: Logit estimation results of the binary choice to retrofit or not, coefficients and odds ratios

Dependent variable: retrofit or not		
Variables	**(1) Coefficient**	**(2) Odds ratio**
Sociodemographic characteristics		
Age of respondent (vs. 21-38 years old)		
39-48 years old	0.249*	1.283*
	(0.130)	(0.167)
49-60 years old	0.673***	1.961***
	(0.135)	(0.264)
61-76 years old	1.109***	3.030***
	(0.147)	(0.446)
Household net monthly income (vs. < 2,400 euros/month)		
2,400-3,200€/month	0.321**	1.378**
	(0.127)	(0.175)
3,200-4,500€/month	0.376***	1.456***
	(0.129)	(0.188)
> 4,500€/month	0.435***	1.544***
	(0.139)	(0.214)
Financial aid (vs. < 1,300€)		
1,300-1,900€	-1.641***	0.194***
	(0.184)	(0.0356)
1,900-2,400€	-0.625***	0.536***
	(0.158)	(0.0847)
> 2,400€	0.873***	2.394***
	(0.161)	(0.387)
Children in the household (1: yes; 0:no)	0.186*	1.204*
	(0.111)	(0.134)
Dwelling characteristics		
Log of dwelling surface	-0.378**	0.685**
	(0.158)	(0.108)
Owners living in an individual house (1: yes; 0: no)	1.024***	2.784***
	(0.191)	(0.530)
Building construction period (vs. Before 1949)		
Between 1949 and 1974	0.130	1.138
	(0.129)	(0.147)
Between 1975 and 1999	-0.273**	0.761**
	(0.120)	(0.0913)
After 1999	-1.762***	0.172***
	(0.169)	(0.0290)

Constant	0.762 (0.670)	2.142 (1.435)
Observations	2,638	
Pseudo R-squared	0.216	
AIC	2,898.837	
BIC	2,992.881	
Percentage of correct prediction	73.73%	
Area under the ROC curve	0.802	
Wald test of overall significance: p-value	0.000	
Note: robust standard errors in parenthesis; *** $p < 1\%$; ** $p < 5\%$; * $p < 10\%$		

Figure 21: ROC curves of the Logit model estimates, with (a) and without financial aid (b)

(a) (b)



5.1 The effect of financial aid

Empirical results provide mixed evidence about the effect of **financial aid** on households' likelihood to undertake energy efficiency improvement measures. The relation between the amount of financial aid granted by the government and the renovation probability is indeed not simple: we observe a significant decrease in the probability of renovating for the second and third quartiles of the amount received (81% and 46%, respectively), and a significant increase for the fourth quartile only, compared to the first quartile of the distribution. Precisely, the chances of renovating explode for families who received more than 2,400 euros: they are 2.4 times more likely to renovate than families who received less than 1,300 euros. By lowering the upfront cost via an external financing, the considered investment becomes more attractive, and especially more profitable, making households keener to take action.

This jump in the probability of renovating can be explained by a threshold effect in the amount of financial aid received. Once the amount of aid granted is known, if it is too low, households are no longer willing to undertake renovation work because they do not feel encouraged or financially supported enough. In other words, renovating is not worth it, and households simply drop out. From the perspective of policymakers, the money offered is then lost, which considerably reduces the effectiveness of governmental financial incentive programs. Nevertheless, if the amount received is high enough, the financial incentive is effective and chances of renovating considerably increase.

The significant impact of financial aid on households' decision to renovate their housing was expected. In fact, as already discussed in Section 4.1, retrofitters confessed that obtaining financial aid enabled them to carry out energy renovation work in 23% of cases (*cf.* **Figure 19**). Moreover, through questions about why they did not renovate their housing, households admitted that such investments were unaffordable in 22% of cases. Finally, 31% and 13% of non-retrofitters would renovate their dwelling if financial aid were more easily accessible, and would welcome a more flexible retrofit work funding system, respectively. By consequence, the key players themselves indicate that financial support is an essential lever to activate in order to boost home renovation.

In light of the empirical results suggesting a threshold effect of financial aid on renovation behavior, it is relevant to estimate the amount at which households feel encouraged to renovate and supported enough. Therefore, a CART model is developed in Section 6.1 to identify this threshold value, and by extension, the most potent factors of energy renovation behavior. Knowing that the budget of the French Ministry of ecological transition, in charge of promoting energy renovation of the housing stock, will increase in 2022 (+1.3 billion euros compared to 2021, thus increasing from 48.6 to 49.9 billion euros, *i.e.*, an increase of almost 3%), it is necessary to optimize spending (Ministère de la Transition Ecologique et Solidaire, 2021b). Two billion euros will even be allocated to finance the MaPrimeRénov' renovation aid scheme (*cf.* first row of **Table 10**), a funding envelope that should not be wasted.

5.2 The effect of sociodemographic factors

Results show that household characteristics have a significant influence on the likelihood to renovate a dwelling. **The age of the household's head** positively impacts the decision to renovate: compared to the youngest households (headed by a person between the ages of 21 and 38), those headed by a person between the ages of 39 and 48 are 28% more likely to invest in energy efficiency improvement measures, everything else being equal. Chances even double (triple) for household heads between 49 and 60 years old (between 61 and 76 years old). Therefore, getting old considerably increases the probability of households to renovate, a result already predicted by **Figure 18** representing the distribution of retrofitters and non-retrofitters by quartile of age. However, some scholars studying the link between age and energy efficiency behavior do not reach the same conclusion, as they often find mixed results suggesting a non-linear effect of age. Indeed, Poortinga et al. (2003) and Nair et al. (2010) argue that older household heads tend to invest less in energy efficiency because their expected rate of return on investment is lower than for households with younger heads, due to their lower expected tenure in their current dwelling. This line of reasoning is then contradicted in the present study, as in Trotta (2018a) on British data.

The presence of children in the household, implicitly capturing family size, is found to have a positive and significant effect on residential energy efficiency investments, which agrees with the literature (Ferguson, 1993; Poortinga et al., 2003). Interestingly, families with children are less mobile than couples, and therefore have a longer expected tenure in their current dwelling, which makes energy efficiency investment more financially attractive.

Now turning to **income** effects, results show a direct positive and significant relation between households' income and their probability of investing in energy-efficient technologies: households belonging to the second, third and fourth quartiles of income appear to be (38%, 46% and 54%, respectively) more likely to invest than households belonging to the first quartile. Wealthier households are merely better able to afford energy efficiency investments. Besides, as they are known to consume more energy than low-income households (Wiedenhofer et al., 2011; Belaïd et al., 2020b, 2021b), they simply want to improve their home's energy efficiency to reduce their energy expenditures. These results tie in nicely with the work of Achtnicht and Madlener (2014) in Germany, and Trotta (2018a) in the UK, but go against those of Gamtessa (2013) in Canada. By developing two Logit and Probit models to estimate the renovation probability, the author finds that "high-income households are less likely to undertake retrofit investment, possibly because energy expenditure accounts for a very small share of their income such that they may not care much".

5.3 The effect of dwelling attributes

There is a negative and significant relation between **dwelling size** and energy efficiency renovation behavior, meaning that the larger the home, the less likely its occupants are to renovate it. In fact, the large surface of their home seems to discourage them from undertaking renovation works, as it necessarily increases the upfront costs they support. The literature, and notably Ferguson (1993), disagrees, since dwelling size is usually found to be a motivating factor in household' decision-making process. Indeed, larger houses are highly energy-intensive, and, as a result, owners are willing to improve their house's energy efficiency in order to reduce their energy consumption. Plus, households can more easily achieve economies of scale by renovating their entire house at once rather than by renovating several small areas sequentially. In the present case, upfront costs seem to be a more potent decision factor than potential economies of scale, perhaps highlighting a certain myopia among households.

The type of dwelling has a strong explanatory power in residential energy-saving behavior. Owners living in an individual house are almost three times more likely to invest in energy efficiency measures compared to owners living in an apartment. Again, apartments generally consume less than individual and detached houses because of their smaller heat loss surface (Vaage, 2000; Rehdanz, 2007). By consequence, apartment-occupants have less incentives to renovate their dwelling in order to reduce their energy consumption, since they already consume little.

Lastly, results reveal a negative relation between the renovation probability of households and dwelling age, implicitly accounted for by the **building construction period** variable. Indeed, compared to buildings completed before 1949, *i.e.*, the oldest dwellings, buildings completed between 1975 and 1999 (after 1999) are 24% (83%) less likely to be renovated by their occupants. In this way, the recentness of the dwelling plays a leading role in explaining the residential energy efficiency renovation behavior. This may be due to the intrinsic technical attributes of recent housing. As aforementioned in Section 2, the successive thermal regulations implemented in the country since the mid-1970s have significantly participated in the upgrade of buildings energy efficiency performance, by reducing energy losses and consumption, and improving summer comfort. Then, newer dwellings are simply less energy-intensive than older ones (Vaage, 2000; Rehdanz, 2007; Belaïd et al., 2021a), and more rarely require an energy efficiency renovation. These results agree with those of Ferguson (1993) and Gamtessa (2013).

In overall terms, dwelling characteristics, closely linked to floor area, housing type, and construction period, are factors which may encourage or constrain energy efficiency behavior.

6. Robustness analyses

We deepen the reflection by estimating a CART model, and challenging our empirical specification via a change in the estimation method. This section presents our findings.

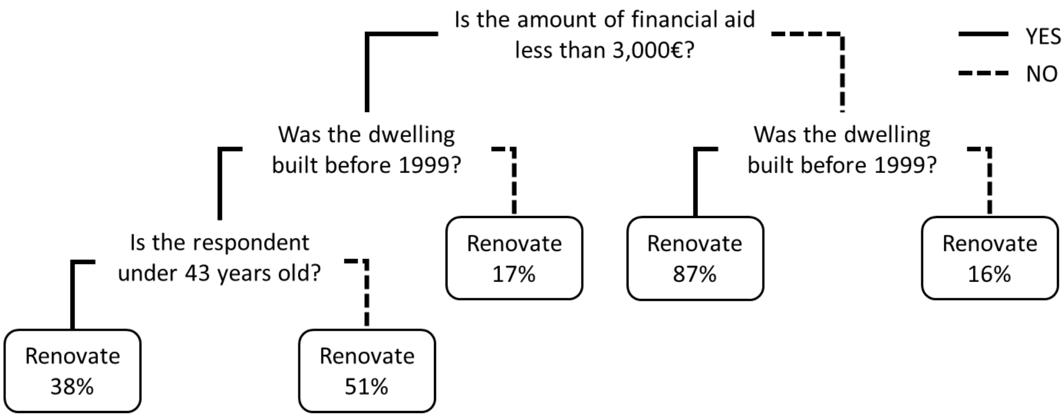
6.1 Decision tree predicting the decision to renovate

The Logit estimation results highlighted the existence of a threshold effect in the impact of financial incentives on the renovation probability. Based on the discretization in quartiles of the variable capturing the amount of financial aid received, results suggested an estimated threshold value of at least 2,400 euros. Therefore, in order to more accurately estimate this cut-off level, we develop a CART model, which, at the same time, allows us to gain more insights on the explanatory power of the determinants of home renovation. This simple machine learning algorithm explains how an outcome variable's values can be predicted based on other values (Breiman et al., 1984). The benefit of the CART approach is to produce a visual representation of the factors that are particularly important in a model in terms of explanatory power.

The obtained decision tree is presented in **Figure 22**. The percentages at the bottom of the terminal branches indicate the mean of the binary dependent variable of the model, *i.e.*, the likelihood of households to renovate their dwelling. The first node confirms the existence of a threshold effect in the impact of financial aid. The cut-off value is indeed estimated around 3,000 euros, in the same range as what the Logit specification provided. Then, conditional on receiving more than 3,000 euros of financial aid, and living in a dwelling completed before 1999, households have 87% chances to renovate. This is the best probability of renovating estimated by the CART model, which identifies the type of households that are most likely to undertake energy efficiency improvement measures. This again demonstrates the strong predictive power of financial support dedicated to households in residential renovation behavior.

In parallel, the second and third nodes of the decision tree underline the ability of the dwelling construction period and the age of the household's head to untangle the probability of renovating. The same conclusions about the effect of these two factors were already drawn by the Logit model. Therefore, the consistency of results between the two approaches, CART and Logit, proves their stability and reliability.

Figure 22: Prediction tree of the decision of households to renovate a dwelling, CART algorithm (Source: own elaboration)



6.2 Sensitivity of results to a change in the estimation method

As a supplementary robustness analysis, the sensitivity of the Logit results for the estimation of the residential renovation behavior is tested by developing two alternative specifications: a Probit model and a LPM. **Table 14** displays estimation results derived from these two regressions: Column (1) for the Probit model and Column (2) for the LPM. **Figure 23** also presents odds ratios obtained from the Logit, Probit and LPM approaches, thus enabling a quick visual inspection.

Although parameter estimates slightly alter, either in magnitudes or in significance, signs always agree across the three specifications. A threshold effect around 2,400 euros of financial aid received is still found. This highlights the robustness of our empirical results derived from the Logit model, since they are stable to a change in the estimation method. Moreover, inspecting the value of the AIC and BIC for the three models shows which one best fits out data. Thus, the Logit specification's lowest values of AIC and BIC are jointly reached, making it more accurate than the Probit model and the LPM. Empirical evidence of the suitability of the Logit model over these alternative econometric specifications has already been documented by Gamtessa (2013), also in the context of energy efficiency renovation behavior.

All in all, this confirms that the Logit specification is the best empirical approach to estimate our sample's probability of renovating.

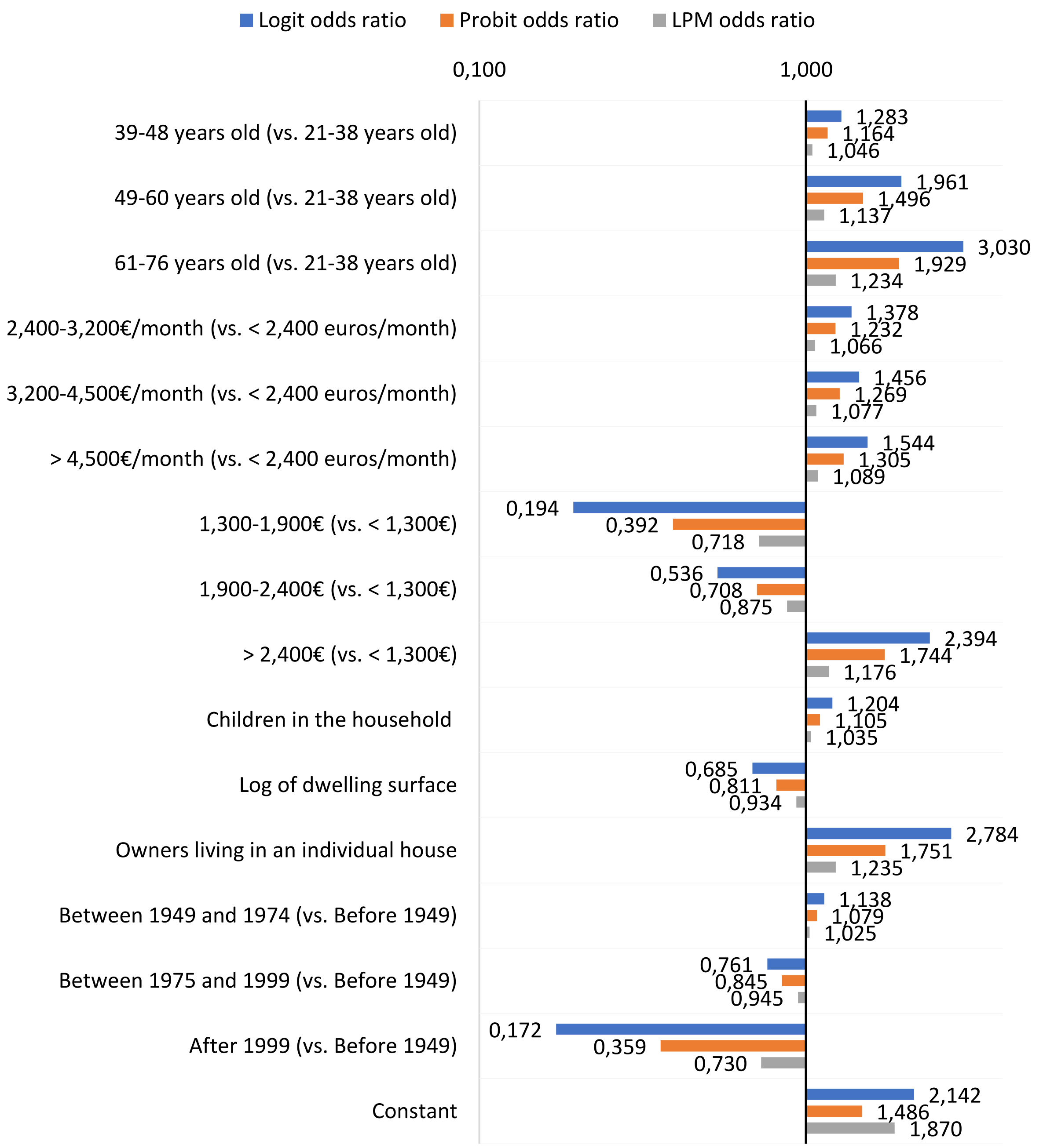
Table 14: Probit and LPM estimation results of the binary choice to retrofit or not

Dependent variable: retrofit or not		
Variables	**(1)** **Probit**	**(2)** **LPM**
Sociodemographic characteristics		
Age of respondent (vs. 21-38 years old)		
39-48 years old	0.152**	0.0451*
	(0.0772)	(0.0240)
49-60 years old	0.403***	0.128***
	(0.0794)	(0.0251)
61-76 years old	0.657***	0.210***
	(0.0870)	(0.0271)
Household net monthly income (vs. < 2,400 euros/month)		
2,400-3,200€/month	0.209***	0.0638***
	(0.0759)	(0.0237)
3,200-4,500€/month	0.238***	0.0738***
	(0.0770)	(0.0237)
> 4,500€/month	0.266***	0.0853***
	(0.0824)	(0.0261)
Financial aid (vs. < 1,300€)		
1,300-1,900€	-0.937***	-0.331***
	(0.0996)	(0.0330)
1,900-2,400€	-0.346***	-0.134***
	(0.0922)	(0.0317)
> 2,400€	0.556***	0.162***
	(0.0940)	(0.0295)
Children in the household (1: yes; 0:no)	0.100	0.0348*
	(0.0660)	(0.0206)
Dwelling characteristics		
Log of dwelling surface	-0.209**	-0.0686**
	(0.0924)	(0.0288)
Owners living in an individual house (1: yes; 0: no)	0.560***	0.211***
	(0.103)	(0.0353)
Building construction period (vs. Before 1949)		
Between 1949 and 1974	0.0762	0.0248
	(0.0770)	(0.0250)
Between 1975 and 1999	-0.168**	-0.0564**
	(0.0718)	(0.0234)
After 1999	-1.024***	-0.315***
	(0.0946)	(0.0266)

Constant	0.396	0.626***
	(0.394)	(0.124)
Observations	2,638	2,638
Pseudo R-squared	0.215	0.264
AIC	2,903.587	3,051.244
BIC	2,997.632	3,145.288
Wald test of overall significance: p-value	0.000	0.000

Note: robust standard errors in parenthesis; *** $p < 1\%$; ** $p < 5\%$; * $p < 10\%$

Figure 23: Variation of the probability of households of renovating their dwelling, logarithmic scale for Logit, Probit and LPM odds ratios



7. Conclusions

The objective of this article is to analyze the structural barriers hindering the massive adoption of energy efficiency investments and fueling the well-known energy efficiency paradox. With an application to the French residential sector, using a rich cross-section dataset surveying 3,000 homeowners in 2018, a Logit model is developed to estimate the probability of households of renovating their homes. Dwelling and household heterogeneity is accounted for by controlling for dwelling technical attributes and household sociodemographic characteristics. A focus is made on financial incentives for energy-efficient retrofit works. As the amount of financial aid is only known for retrofitters who receive it, we come up with an original simulation approach for non-retrofitters and non-beneficiary retrofitters. It is performed in compliance with the French government official financial aid simulator, called Simul'aides. Our results are robust to a change in the estimation method.

To sum up, our research contributes to filling some of the gaps found in the empirical literature in three different ways. First, it confirms the role of sociodemographic factors in energy efficiency renovation behavior in the French residential sector: age, income, and family size and composition are found to significantly stimulate households' decision to renovate their home. Our research suggests a direct effect of both the age of the household head and their income, two results around which the literature does not always reach a consensus (Poortinga et al., 2003; Nair et al., 2010; Gamtessa, 2013; Achtnicht and Madlener, 2014; Trotta, 2018a). Including sociodemographic characteristics as a factor in all energy efficiency regulations and policies is therefore critical to ensure that energy and carbon emission reductions do occur.

Second, it demonstrates that dwelling characteristics, such as dwelling size, type and age, are factors which may encourage or constrain energy efficiency behavior. The developed CART model supports the evidence that the age of the dwelling, here measured by the construction period, is the most influential housing-related attribute. The year 1999 corresponds to a pivotal year for households wishing to renovate, since, beyond this date of construction, dwellings are less likely to be renovated. A line of reasoning supports this finding: housing units built after this date, *i.e.*, in accordance with the various thermal regulations implemented at this time, and in particular the RT 2000, intrinsically have a good energy performance, and therefore rarely need to be renovated. It attests to the effectiveness of the numerous RTs that still constitute the French energy policy today.

Third, it provides new evidence of the importance of financial incentives in the deployment of energy-efficient technologies in France. A threshold effect is estimated around 3,000 euros: below this amount, households do not feel financially supported enough, which ultimately keeps them from renovating their house; above this amount, households are more than twice as likely to renovate their home, compared to receiving less than 1,300 euros. This result serves as a major advance for policymakers in defining energy policies, since it provides a measure of the minimum amount to be allocated to households. Complying with this result should enable energy policies to be more effective in reaching the desired rate of residential renovation, to achieve the EU carbon gas emissions reduction targets. Adopting this optimal minimum allocation can certainly allow the French government to better manage its budget, which has been increased in 2022 (Ministère de la Transition Ecologique et Solidaire, 2021b), but which leaves no room for waste. The cost-effectiveness of energy policies is at stake.

To conclude, an effective energy efficiency program in the building sector should be holistic in order to capture the complexity of the process and different barriers that policymakers face. There needs to be a shift from supply-oriented energy policies (*i.e.*, how do we produce more oil, gas, electricity?) towards demand-oriented energy policies (*i.e.*, how do we consume less energy?). Therefore, a successful energy efficiency program should consider several interconnected dimensions to ensure a substantial transformation, paving the way to sustainability. One the one hand, to tackle structural barriers, (i) incentive and financial measures (*e.g.*, public sector energy efficiency financing, residential and home appliance credit, *etc.*) should be encouraged, as their profitability has just been demonstrated, both at macro and micro level; (ii) a regulatory legal framework should be adopted with energy efficiency policies, defining targets by sector; and (iii) technical capacity improvement should be enhanced, with certification programs and energy audit/manager training, and the development of energy management systems. On the other hand, to mitigate behavioral barriers, (iv) information and awareness campaigns should be launched, including appliance labelling, organization and data analysis.

Further research projects could be launched on the impact of a specific financial incentive on energy renovation or energy-saving behaviors. We can only recommend strengthening energy data collection, storage and processing capabilities.

Conclusion and transition to Chapter 3

With two different approaches, one targeting behavioral obstacles, the other structural obstacles, **Chapters 1** and **2** provide a comprehensive view of barriers to energy efficiency investments. Both chapters offer empirical evidence of the importance of sociodemographic and housing-related characteristics in the decision of households to undertake energy efficiency works. Particular attention was also paid to other parameters that are under or beyond the control of households, namely environmental concerns, risk perception, and financial aid.

Despite the knowledge of the determinants of energy renovation and energy consumption patterns in the residential sector, and the solutions to alleviate the dissuasive power of behavioral and structural barriers, the same observation persists: energy efficiency investments lag behind public policy objectives set in several European countries, resulting in a gap between theoretical and observed energy consumption. The rebound effect holds some importance in the matter. Therefore, **Chapter 3** adopts a more macro-scale of analysis and explores the rebound effect in a panel of European countries for the 1996-2018 period.

Chapter 3: Direct rebound effect for residential electricity use in selected European countries

This article was submitted to Energy Economics. It was accepted for presentation at the Slovak Economic Association Meeting 2022 in Bratislava, Slovakia, in September 2022, though I did not go.

Keywords: Rebound effect; Energy efficiency; Residential electricity consumption; European countries; GMM; First-difference.

1. Introduction

The building sector is one of the cornerstones for achieving the EU's energy and environmental goals. Between 2008 and 2018, household electricity consumption rose by 1.3% in the EU, and in 2019, buildings accounted for nearly 40% of EU energy consumption (Eurostat, 2020b). Significant energy savings can be achieved by renovating existing buildings (Belaïd et al., 2021a), especially knowing that the share of European housing which is deemed energy efficient only amounts to 75%. Given that buildings are responsible for approximately 36% of the European GHG emissions, these energy savings are estimated to be equivalent to a 5-6% reduction in the EU's total energy consumption, and a 5% reduction in CO2 emissions. Because the rate of new construction is only 1% per year, the main challenge is the improvement of existing buildings (European Commission, 2020a).

Several incentive and regulatory mechanisms have been introduced to stimulate energy retrofits, making the EU one of the leading major economies combating climate change. In this context, the European Commission presented the European Green Deal in December 2019. Consistent with the 2015 Paris Climate Conference, this agreement proclaims the implementation of measures which aim to "increase the EU's GHG emission reduction ambition for 2030 and decarbonize the EU's economy by 2050" (European Commission, 2020a). However, in spite of these numerous measures, the energy saving targets are still far below the objectives: in 2018, European GHG emissions had only fallen by 23% since 1990 while the target is a 40% reduction by 2030. The energy savings achieved by improving housing energy efficiency are often lower than thermal calculation models predict (theoretical consumption). One of the explanations for this discrepancy is the long-established phenomenon of the rebound effect.

The rebound effect stems from the seminal work of Jevons (1865) and, limited to its microeconomic meaning, can be of two types: either direct or indirect. According to Khazzoom (1980), the direct effect occurs when the increase in consumption induced by an energy efficiency measure occurs in the same energy item, for instance when more efficient heating equipment is used. The effect is said to be indirect when the resulting energy savings on a service are reinvested in other goods and services consumed by the household. In the context of energy transition in the building sector, the direct rebound effect that we are trying to better quantify generally comes after a thermal renovation of the dwelling, which results in greater energy efficiency and a lower energy cost; thus, the household benefits from this lower cost by increasing its energy demand.

The rebound effect has become the subject of a growing economic literature, especially regarding residential energy consumption. Assessing it can be done using different estimation approaches: either with a quasi-experimental approach or an econometric approach. The latter uses energy efficiency elasticity or energy service elasticity. This article applies the energy service elasticity concept, using the energy price elasticity in a demand model as a proxy of the rebound effect. This is the most widely used method in the literature.

Therefore, based on Eurostat and World Bank annual panel data covering the period 1996-2018, this article focuses on the direct rebound effect in the European residential electricity consumption induced by a drop in electricity prices. Developing a GMM and first-difference approaches, along with instrumental variable techniques, we investigate the direct rebound effect of certain European countries' residential electricity consumption (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Portugal, Slovenia, Spain, Sweden, and the United Kingdom), in the short- and long-run. Results indicate that the direct rebound effect in residential electricity use is approximately 18% in the short-run and 43% in the long-run. The residential electricity use in selected European countries is more price inelastic in the short-run than in the long-run.

The remainder of this paper is organized as follows: Section 2 provides a brief overview of European energy efficiency policies and energy demand patterns; Section 3 defines the theoretical concept of rebound effect and explores the relevant literature; Section 4 introduces the data employed in this analysis; Section 5 details the econometric specifications adopted and provides diagnostic tests prior to the empirical analysis; Section 6 presents results; Section 7 discusses them from a policy perspective; finally, Section 8 concludes.

2. Overview of European energy efficiency policies and residential energy demand

In order to become a world leader in energy efficiency, the EU presented the European Green Deal in December 2019, supervised by the European Commission. More concretely, the established legislative framework includes two measures. Firstly, the Energy Performance of Buildings Directive, implemented in 2010 and revised in 2018, aims at accelerating the rate of building renovation ensuring that all new buildings are nearly zero-energy buildings from December 31, 2020 through the use of intelligent energy management systems (European Commission, 2020d). Secondly, the Directive on Energy Efficiency, designed in 2012 and revised 2018, "sets an energy efficiency target of 32.5% for the EU by 2030, with a clause for upward revision by 2023" (European Commission, 2020c). Together, these policies strive to make buildings more energy efficient in order to contribute to the EU achieving its 2030 energy efficiency and climate goals.

To illustrate, the evolution of the share of each sector of activity in the European total final energy consumption is displayed in **Figure 24** (Odyssee-Mure, 2020d). This figure indicates that transport is generally the largest energy consumer sector in Europe. Moreover, the share of industry decreased by 4 percentage points between 2000 and 2017 for the benefit of the tertiary sector, which is steadily rising. The share of the agricultural sector, although declining, remains stable over the 2007-2017 decade. Finally, the share of the residential sector remains stable at around a quarter of the European total final energy consumption. This level is maintained so that, in 2018, the residential sector accounts for up to 26% of final energy consumption in Europe (Eurostat, 2020a).

Focusing now on the residential sector (**Figure 25**), in 2017, natural gas is the dominant source of energy for households in the EU (36%). Electricity is ranked second, representing 24% of the energy mix. Oil is slowly being phased out by other energy sources, notably wood, at EU average (11% in 2017 compared to 20% in 2000). In the same year, space heating is by far the main usage of electricity since it represents nearly 67% of domestic electricity demand in Europe (Odyssee-Mure, 2020a).

Figure 26 shows the evolution of electricity consumption in kilowatt-hour per dwelling in the countries selected in this study. Between 2000 and 2017, the evolution of electricity demand is not homogenous over European countries. These variations in electricity consumption per dwelling may result from the implementation of thermal retrofits, from an improvement in the energy efficiency of housing equipment, or from a change in households' consumption behavior. Consequently, understanding the role of behavioral issues is crucial in explaining the fluctuations of electricity consumption in the residential sector. As previously mentioned, electricity ranks second in the energy mix of the housing sector; therefore, studying the rebound effect in electricity use is legitimate.

All in all, in the global context as introduced herein, a better understanding of the ins and outs of residential energy consumption is the foundation for identifying the measures necessary to support the EU's objectives and anticipate future energy trajectories. Analyzing the rebound effect and becoming aware of its consequences on the energy behavior of European households will provide politicians with new elements to shape efficient public policies.

Figure 24: Sectoral distribution of total final energy consumption in Europe
(Source: own elaboration based on Odyssee-Mure (2020d))

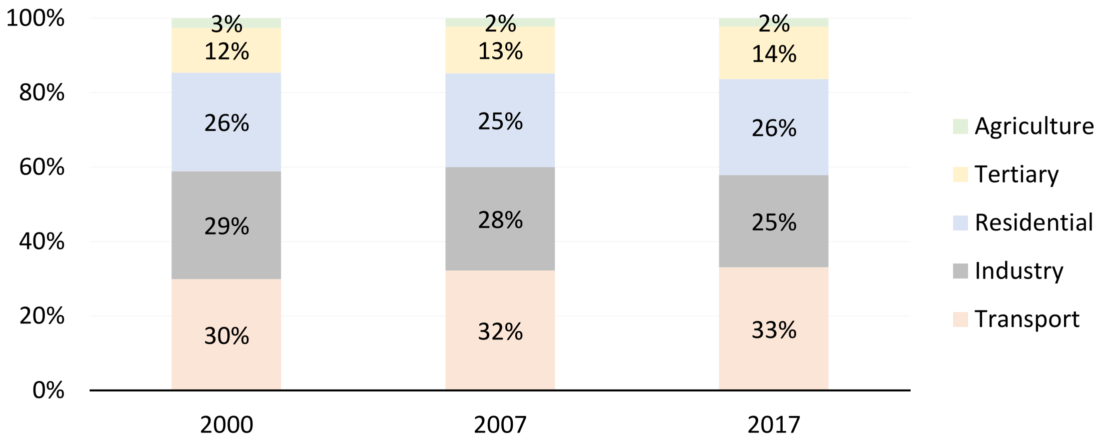


Figure 25: Energy mix in the residential sector in the EU
(Source: own elaboration based on Odyssee-Mure (2020c))

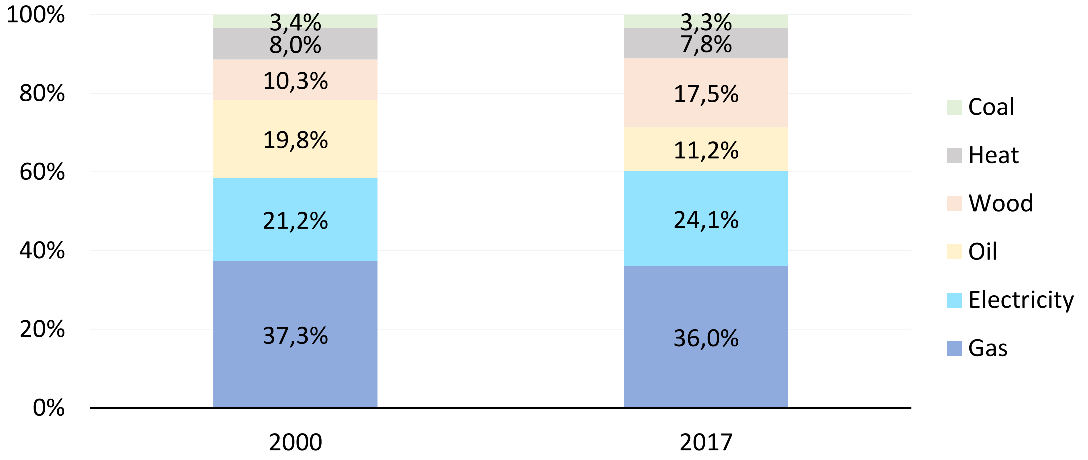
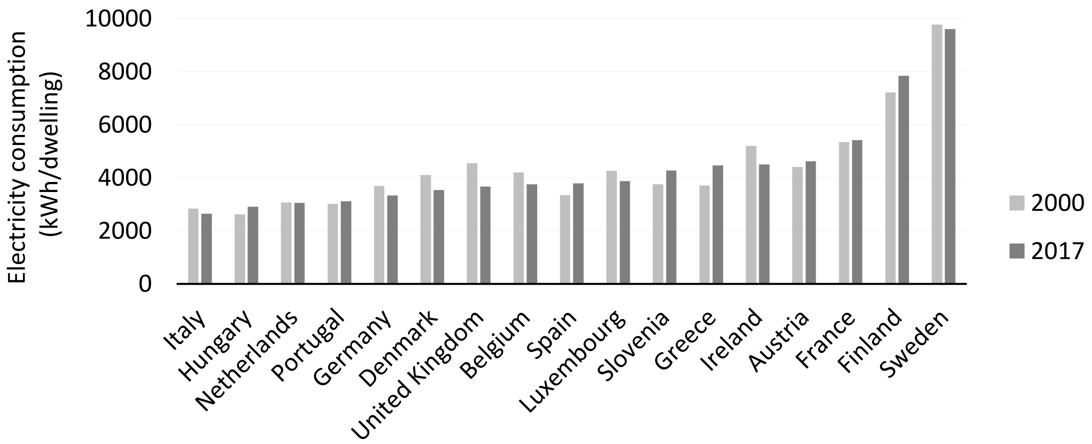


Figure 26: Electricity consumption in kWh per dwelling in Europe
(Source: own elaboration based on Odyssee-Mure (2020b))



3. Theoretical background and empirical evidence in the literature

The main goal of analyzing the rebound effect and the behavioral dimension behind energy consumption patterns in Europe is to increase the effectiveness of environmental policies, as this is crucial to achieving the European Commission's CO2 emission reduction targets. The objective of this third section is to define and theoretically introduce the notion of rebound effect in energy economics, and to discuss previous works examining it.

3.1 Definition of the rebound effect

The economic literature identifies three categories of rebound effects: the direct rebound effect, the indirect rebound effect, and the economy-wide effect (Sorrell, 2007; Thomas and Azevedo, 2013; Freire-González, 2017), respectively defined as follows:

- Direct rebound effect: an improved energy efficiency service uses less energy to provide the same service, hence a decrease in the effective price of that service, which will potentially yield an increase in the demand of that service. This higher consumption will eventually offset the reduction in energy consumption provided by the efficiency improvement itself.
- Indirect rebound effect: the lower effective price of the energy service that was energy-efficiently improved can create additional income for the consumer. This can result in a change in the demand for other goods and energy services. Two sub-effects occur (Borenstein, 2015):
    - if the additional income for the consumer is larger than the cost of the energy efficiency improvement of the energy service, consumers might purchase more of the improved energy service, or purchase something else that also uses energy – this is the income effect;
    - if the additional income does not offset the cost of the energy efficiency improvement of the energy service, the effective cost of this improved service remains relatively lower than it was before; consumers might also purchase more of the improved energy service but less of other goods. The net impact on energy demand depends on the relative energy intensity of what consumers no longer purchase, relative to using more of the more efficient service – this is the substitution effect.
- Economy-wide effect: a fall in the effective price of energy services may reduce the price of intermediate and final goods throughout the economy, leading to the rebalancing of the economic system through prices and quantities, and innovation and market adjustment channels[4].

[4] Empirical research seeking to estimate the economy-wide rebound effect is limited. In that regard, the recent study by Berner et al. (2022) constitutes a good introduction.

Figure 27, loosely adapted from Borenstein (2015), summarizes the rebound concept by stating that the final effect on energy usage is the sum of three distinct components. **Table 15** also shows the different rebound effects that can be found in empirical applications (Adetutu et al., 2016; Zhang et al., 2017). The super conservation effect (a negative rebound effect) is the ultimate aim of energy efficiency improvement in terms of energy conservation and emission reductions, but the most common case is actually the partial rebound effect (a rebound effect between 0 and 1).

Figure 27: Summary of the rebound effect
(Source: own elaboration based on Borenstein (2015))

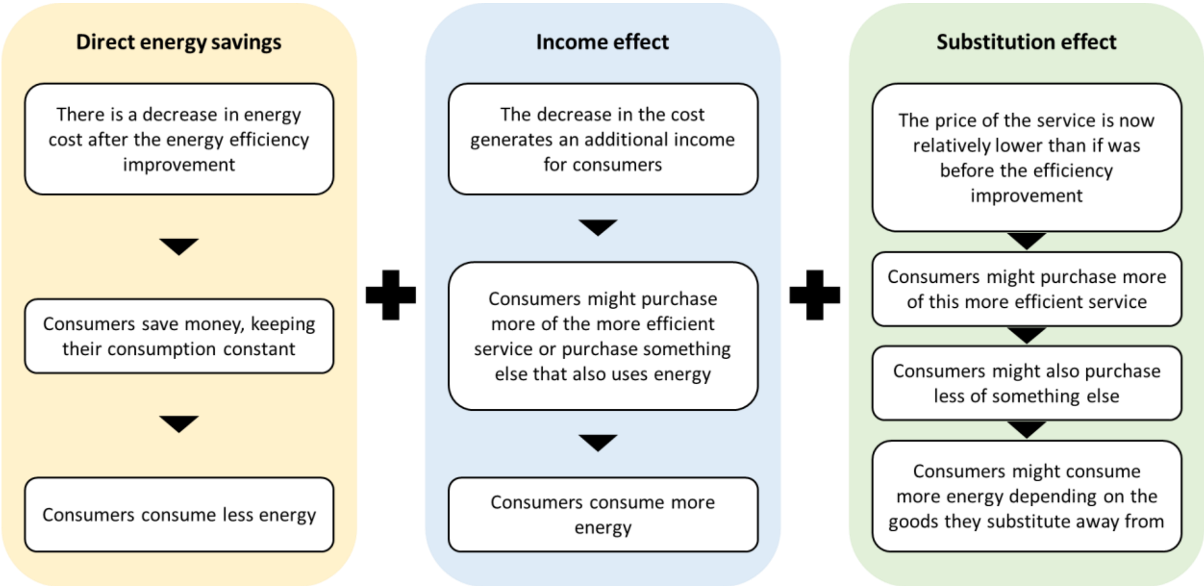


Table 15: The different rebound effects according to their size
(Source: own elaboration based on Adetutu et al. (2016) and Zhang et al. (2017))

Size	Type of RE	Implications
$RE > 1$	Backfire effect	Energy consumption increases due to improvements in energy efficiency.
$RE = 1$	Full effect	Energy consumption remains unchanged.
$0 < RE < 1$	Partial effect	Energy consumption falls by a less-than-proportionate rate to efficiency improvements.
$RE = 0$	Zero effect	There is a one-to-one or unit relationship between energy consumption and efficiency improvements.
$RE < 0$	Super conservation effect	Energy consumption decreases by a more-than-proportionate rate with respect to efficiency gains.

Note: RE stands for rebound effect

3.2 Theoretical background

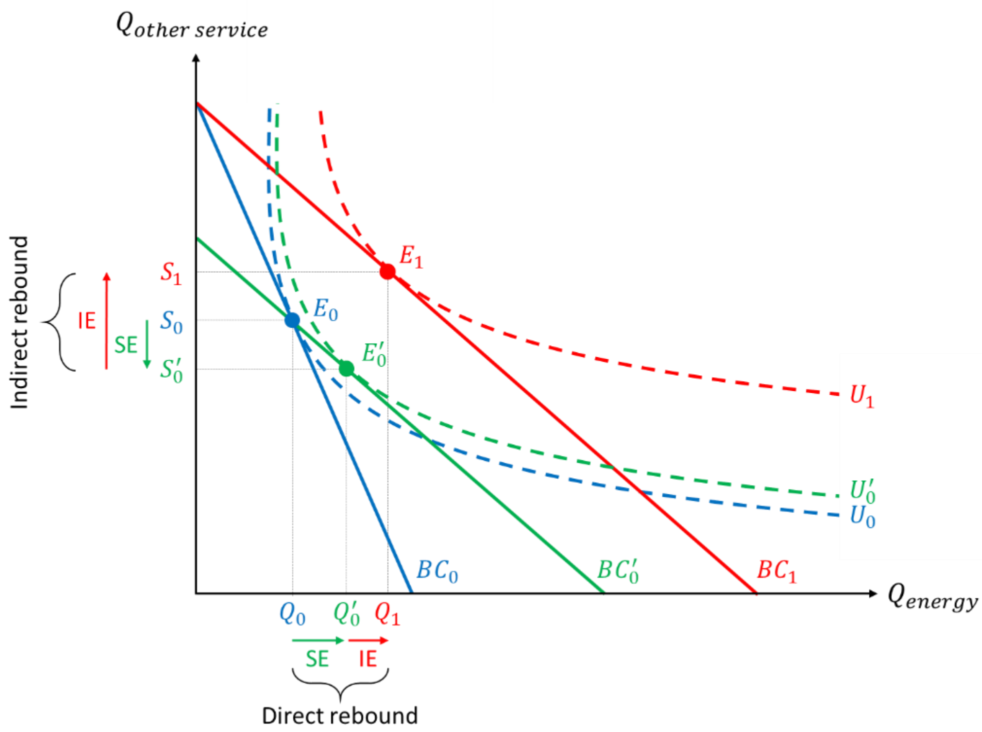
In this article, we focus on the estimation of the direct rebound effect induced by a price reduction of an energy service, itself generated by energy efficiency improvements. As suggested by Borenstein (2015), the direct rebound effect is made of both income and substitution effects, depicted in the Slutsky decomposition. An indirect rebound effect also exists. **Figure 28** presents the situation from a microeconomic perspective.

With a given preference structure (the utility function), we suppose that households maximize their utility function $U(Q,S)$, derived from consuming energy services Q and other goods S, subject to a budget constraint BC. Initially, for a given budget constraint BC_0, households' consumption basket is $E_0(Q_0,S_0)$, providing them with a given utility level of U_0. After an energy price drop, due to energy efficiency improvements, energy services become relatively more preferable, as they are relatively cheaper than other goods. At constant budget, characterized by a flatter budget constraint BC_0', rational households choose the optimal consumption basket $E_0'(Q_0',S_0')$, made of more energy services and less other goods than E_0, but providing them with a higher utility level U_0'. Changes in consumed quantities correspond to the so-called substitution effect (SE): as energy services become cheaper and more preferable, households substitute other goods for energy services.

As things stand, households' purchasing power is constant, while it sensibly increased after the energy price drop. Consequently, households now maximize their utility subject to a new budget constraint BC_1, which rotates anti-clockwise from a fixed point on the vertical axis. They now consume the consumption basket $E_1(Q_1,S_1)$. It is made of more energy services and more other goods than E_0 and E_0', and provides households with a higher utility level U_1. The additional rise in the quantity of energy services consumed, from Q_0' to Q_1, is characterized by the income effect (IE). Another rise occurs for the quantity of other goods consumed, from S_0' to S_1.

Graphically, the direct rebound effect combines the net change in energy services demand (the sum of both substitution and income effects), visible on the x-axis. On the opposite, the indirect rebound effect corresponds to variations in other goods demand, visible on the y-axis.

Figure 28: Slutsky decomposition of the rebound effect after an energy price drop (Source: own elaboration)



3.3 Literature review

In the last a few decades, measuring the rebound effect has become a key issue in research on energy efficiency, and in the understanding of energy consumption patterns. In their literature review, Sorrell and Dimotropoulos (2008) report two distinct methodologies. The first one, the quasi-experimental approach, relies on a comparison of energy consumption and behaviors before and after an energy efficiency improvement. However, the feasibility of this approach strongly depends on the data availability and control variables. A relevant study using a quasi-experimental methodology in this field is that of Aydin et al. (2017), launched in the Netherlands between 2008 and 2011. In 2008, the Dutch government initiated a large retrofit subsidy program to stimulate energy efficiency improvements in the residential sector. Using a first-difference estimator to identify the average rebound effect in space heating for the treated dwellings, and based on energy efficiency elasticity, authors document that the rebound effect is about 41% for tenants and 27% for homeowners.

The second approach identified by Sorrell and Dimotropoulos (2008) is the econometric approach, and its main advantage is that it can be applied to any type of data: cross-section data, time series, or panel data. This approach suggests assessing the rebound effect either by estimating an energy efficiency elasticity or an energy service elasticity. On the one hand, the energy efficiency elasticity is defined as "the way energy service demand reacts to energy efficiency improvement" (Belaïd et al., 2018). Facing the same problems as the research stream using the quasi-experimental approach, studies developing the energy efficiency elasticity to gauge the rebound effect are rare, due to a lack of data and above all the lack of a variable capturing the energy efficiency level of the equipment. Although Aydin et al. (2017) use both energy efficiency elasticity and quasi-experimental approaches, another study stands out. Interestingly, Belaïd et al. (2020a) investigate the French direct rebound effect of residential electricity consumption using an original dataset providing them with a measure of the energy efficiency level of dwellings. Their results are suggestive of a rebound effect between 72% and 86% using efficiency elasticity. Their study also reveals the importance of the choice of measure adopted to estimate the rebound effect since, based on energy price elasticity instead, they find that the rebound effect ranges between 38% and 71%.

This point leads us to the second way of estimating the rebound effect, still within the framework of an econometric approach: the one based on energy service elasticity. Thus, on the other hand, some scholars argue that estimating the rebound effect based on the energy service elasticity can be done directly by assessing the energy price elasticity, provided that these two hypotheses are verified: (i) the reaction of consumers to an energy efficiency improvement and a fall in energy prices is identical; and (ii) energy prices do not affect energy efficiency (Khazzoom, 1980). This approach is the most widely used in the literature. However, with this approach, “price elasticities are the same for rising and falling prices” (Haas and Biermayr, 2000). Some authors (Alvi et al., 2018; Belaïd et al., 2018; Han et al., 2019) tackle this issue by including a non-symmetric energy price using a price decomposition method, introduced by Dargay and Gately (1995). This method decomposes the price into maximum, rise and fall of energy prices, making the coefficient of the fall of price a proxy of the rebound effect. The studies using the energy price elasticity to measure the rebound effect bring diverse results, using a price decomposition or not (Freire-González, 2010, 2017; Zhang and Peng, 2016; Alvi et al., 2018; Belaïd et al., 2018, 2020a; Han et al., 2019).

Finally, it is worth mentioning that an alternative strand of research uses other econometric methods, based in particular on a stochastic frontier analysis approach, or on input-output models, allowing researchers to control for characteristics such as the structure of the economy that might bias the usual energy efficiency indicators. This is notably the case of Oreal et al. (2015), who find a rebound effect ranging from 56% to 80% in the US. **Table 16** summarizes some relevant empirical evidence of the rebound effect in residential energy consumption.

In light of the surveyed literature, the contribution of this article is threefold: (i) it does not analyze the rebound effect in energy consumption in the broad sense, but rather in residential electricity consumption specifically, thus yielding even more accurate estimations; (ii) it provides an international overview of this rebound effect in 17 selected European countries; and (iii) through a distinction between long-run and short-run, it is intended to inform choices in terms of European public policy and can, for example, feed into the modeling of building stock and/or the evaluation of economic instruments.

Table 16: Literature review of the assessment of the rebound effect in energy consumption

Reference	Country, year	Scale of analysis	Methodology	Estimated rebound effect
Freire-González, 2010	Catalan municipalities, 1991-2002	Electricity consumption	Energy price elasticity with fixed effects, error correction model and generalized least squares estimations using panel data.	Short term: 35%; Long term: 49%
Orea et al., 2015	US states, 1995-2011	Aggregate energy demand	Stochastic frontier analysis approach of an aggregate energy demand frontier with panel data.	Between 56 and 80%
Zhang and Peng, 2016	Chinese provinces, 2000-2013	Electricity consumption	Energy price elasticity with Ordinary Least Squares (OLS) and panel threshold models using panel data.	72% on average; 68% in the low-income regime; 55% in the high-income regime
Aydin et al., 2017	Netherlands, 2008-2011	Space heating	Energy efficiency elasticity with instrumental variable and fixed effects approaches on panel data. First-difference estimation and propensity score matching after a quasi-experimental analysis using a large retrofit subsidy program.	27% among homeowners; 41% among tenants
Freire-González, 2017	EU-27, 2007	Energy consumption	Energy price elasticity in a demand model for the direct rebound effect and energy input-output and re-spending models for the indirect rebound effect using cross-section data.	Between 74% and 81% for the overall EU-27 (weighted average of the direct and indirect rebound effect estimated using the GDP of all countries)
Alvi et al., 2018	Pakistan, 1973-2016	Electricity consumption	Energy price elasticity and price decomposition with fixed effects and error correction model using time series data.	Short term: 43%; Long term: 70%
Belaïd et al., 2018	France, 1983-2015	Gas consumption	Energy price elasticity and price decomposition with OLS and autoregressive-distributed lag (ARDL) approaches on time series data.	Short term: 53%; Long term: 60%

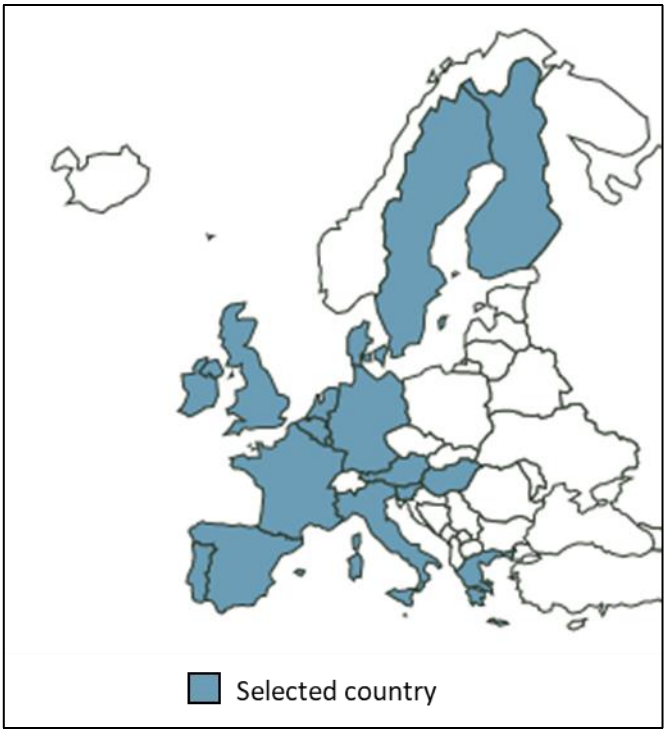
Han et al., 2019	Chinese provinces, 2006-2016	Electricity consumption	Energy price elasticity, price decomposition and spatial spillover effects with a fixed effect model on panel data.	37% with a 13% spillover effect
Belaïd et al., 2020a	France, 2014	Electricity consumption	Energy efficiency elasticity and Granger causality analyses to estimate the rebound effect resulting from technological progress, with time series data.	54.4% on average, though the energy rebound effect each year is different
Yuan et al., 2022	Chinese provinces, 2001-2017	Energy consumption	Energy efficiency elasticity and energy price elasticity with quantile and OLS regressions using cross-section data.	Between 38% and 86% in overall with substantial heterogeneity among consumption quantiles; 72%–86% using efficiency elasticity; 38%–71% using price elasticity

4. Data

Like many studies (Freire-González, 2010; Orea et al., 2015; Zhang and Peng, 2016; Aydin et al., 2017; Han et al., 2019; Berner et al., 2022; Yuan et al., 2022), this article employs annual panel data to assess the rebound effect in residential electricity consumption. Panel data prevail over cross-section or time series data on several aspects (Wooldridge, 2002; Baltagi, 2005). Firstly, observed units, be they households or countries, are usually heterogenous. Time series and cross-section studies fail to control for this heterogeneity, eventually leading to omitted variable bias, while panel data do account for these time-invariant and individual characteristics. Secondly, panel data avoid multicollinearity problems, which are unfortunately fairly common in time series, and offer more variability, resulting in more efficiency and less collinearity among the explanatory variables.

Covering the period from 1996 to 2018, this article studies 17 European countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Portugal, Slovenia, Spain, Sweden, and the United Kingdom (see **Figure 29**). The selected countries and the time period have been determined by the availability of data. Our five core variables are provided by Eurostat and the World Bank. Namely, they are (i) the electricity final consumption of households measured in gigawatt-hour; (ii) annual heating degree days, henceforth HDD; (iii) the GDP per capita in constant 2015 euro; (iv) the population density and (v) bi-annual electricity prices for domestic consumers, averaged by year, expressed in euro per kilowatt-hour. All variables are transformed into their natural logs. Data definition and precise sources are given in **Appendix C.a**.

Figure 29: Selected countries for empirical analysis
(Source: own elaboration)



Bi-annual household electricity price data provided by Eurostat are averaged to form an annual dataset. The methodology of these data changed in the second half of 2007, resulting in massive changes in electricity prices under the new method, which would have undoubtedly impacted estimates. Similar to Csereklyei (2020), we adopt a method-adjusted price series, and “report data under the new methodology starting from 2007 and extrapolate the 2007 data reported under the new methodology backward”. Additionally, we deflate national electricity prices using the Household Consumer Price Index (CPI) provided by Eurostat, with 2015 as the base year.

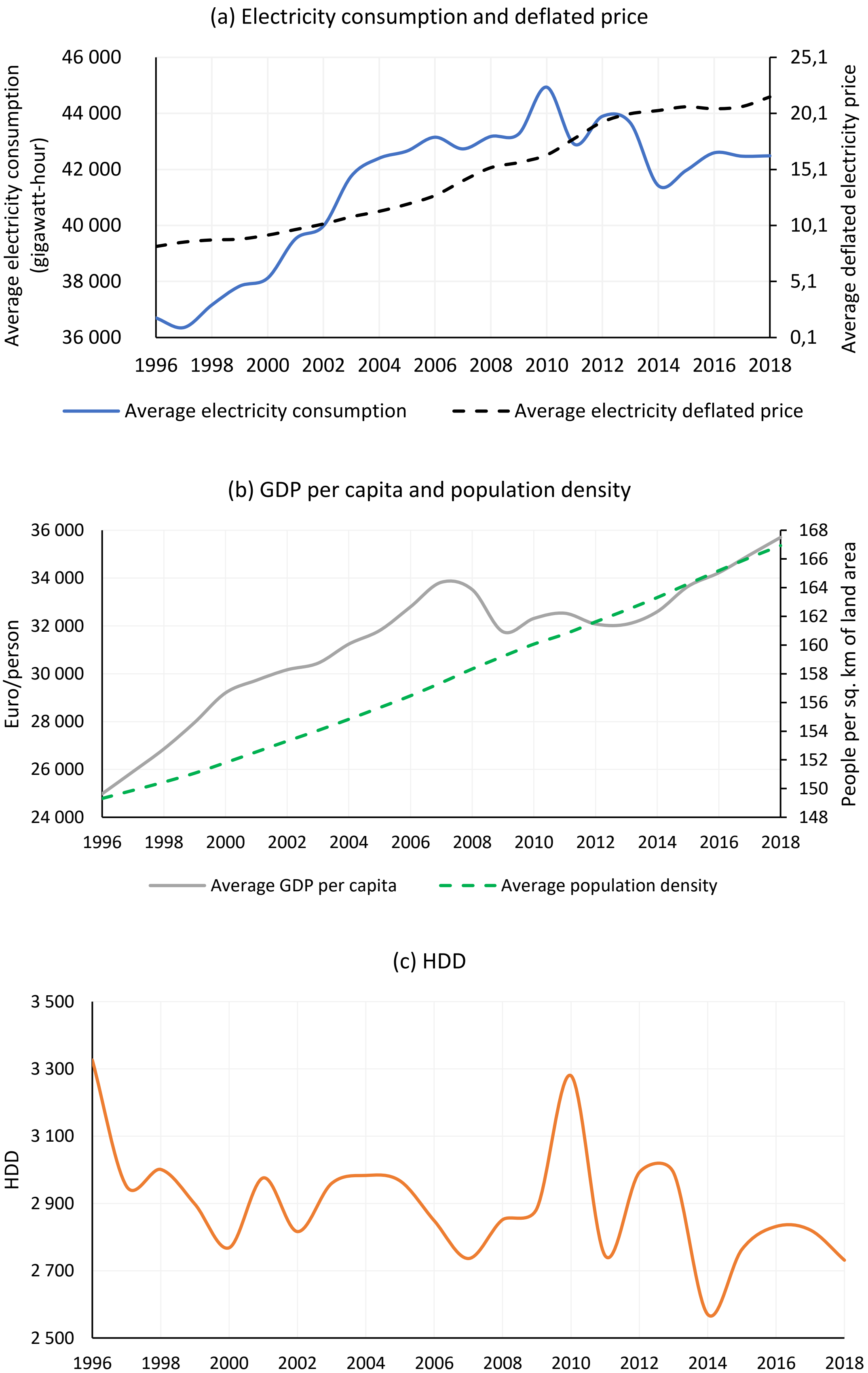
Table 17 provides summary statistics for all input variables utilized in the study, averaged across the 1996-2018 period. Annual summary statistics of the variables and scatter plot matrices of their log-transformations are given in **Appendices C.b** and **C.c**, respectively. Electricity consumption in selected European countries over 1996-2018 ranges from 634 to 166,000 gigawatt-hour, with an average annual consumption of more than 41,000 gigawatt-hour. Moreover, the distributions of electricity consumption and its deflated price averaged across selected countries are shown in **Figure 30(a)**. The European electricity price exhibits an increasing global trend since the mid-1990s, although there is a deceleration in this trend from 2015 onwards. Variations in electricity prices are of first relevance since the rebound effect is actually observable after the response of consumers to a negative change in electricity prices. The distribution of electricity consumption is somewhat fluctuant and experiences many positive and negative shocks during the last decade.

Averaged across selected countries, **Figure 30(b)** shows the distributions of GDP per capita and population density, and **Figure 30(c)** the distribution of HDD. Electricity demand and GDP per capita seem to follow a similar trend over time. Interestingly, they both increase from 1996 until 2007 when they simultaneously experience a drop, undoubtedly due to the beginning of the economic crisis. The population density follows an upward trend. Lastly, the number of days requiring the use of heating energy is captured by the HDD variable. It is included in our model to obtain climate-corrected estimates. **Figure 30(c)** indicates that this variable follows a downward trend over the studied period.

Table 17: Summary statistics

Variables	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
Electricity consumption	41,353.87	45,744.73	634.00	166,129.60
HDD	2,899.69	1,111.42	894.85	6,190.94
GDP per capita	31,319.46	14,591.67	6,780.00	84,420
Population density	158.61	118.27	16.82	511.48
Electricity price	14.490	6.101	1.258	31.807

Figure 30: Time series plot, annual average over the selected countries



5. Empirical strategy

The most common way to measure the direct rebound effect is through the use of elasticities in a demand model for residential electricity consumption (Freire-González, 2010, 2017; Zhang and Peng, 2016; Alvi et al., 2018; Belaïd et al., 2018, 2020a, Han et al., 2019; Yuan et al., 2022). Thus, our model is specified on a standard double-log linear functional form, which is an effective way to obtain robust estimated parameters. Formally, our demand model writes as follows:

$$\ln Elec_{it} = \alpha_{it} + \beta_1 \ln HDD_{it} + \beta_2 \ln GDP_{it} + \beta_3 \ln Popdensity_{it} + \beta_4 \ln Price_{it} + e_{it} \quad (1)$$

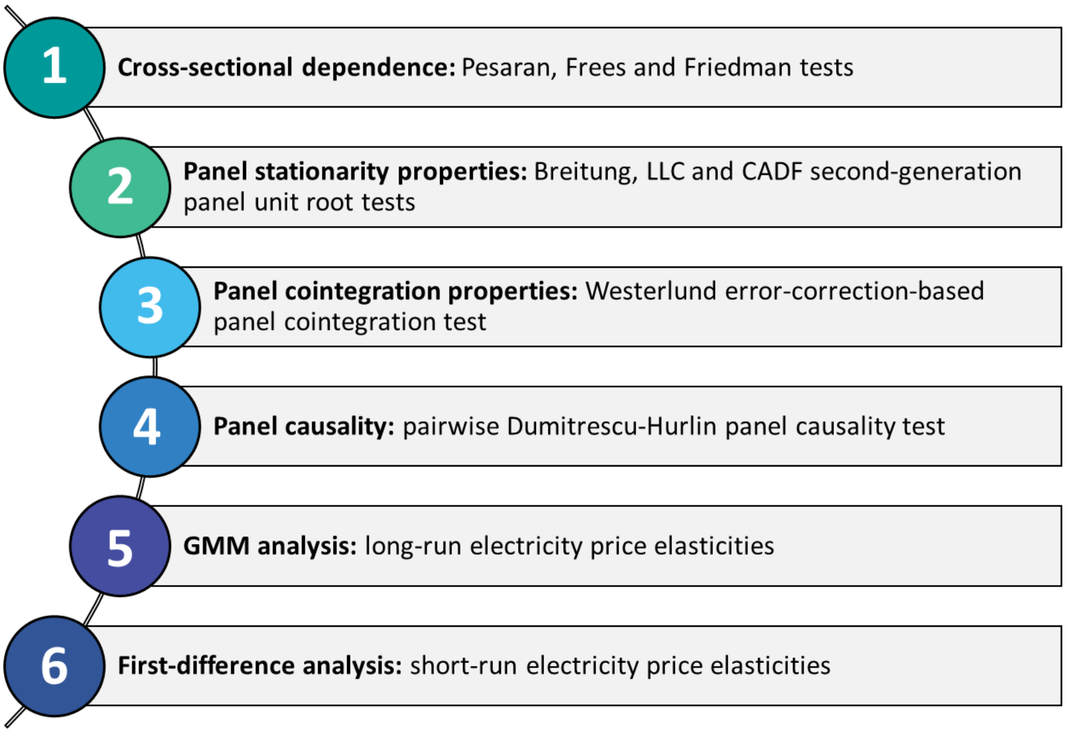
where $Elec$ is the electricity consumption, HDD is Heating Degree Days, GDP is GDP per capita, $Popdensity$ is the population density and $Price$ is the electricity price. e_{it} is the white noise term, assumed to be normally distributed. The subscript $i = 1, \ldots, N$ refers to countries, and $t = 1, \ldots, T$ denotes the year. The coefficients β_1, β_2, β_3 and β_4 are the elasticities of residential electricity consumption with respect to HDD, GDP per capita, population density and electricity price, respectively. By consequence, under this formula, the value of β_4 provides a proxy of the direct rebound effect in residential electricity consumption.

One of the main threats to identification in a demand model is the endogeneity of prices with consumption. This issue, known as reverse causality, can lead bias in parameter estimates. In the field of energy economics, a battery of instruments exists to tackle this point. To name but a few, aggregated prices (Alberini et al., 2011), the prices of similar products like another source of energy (Graf and Wozabal, 2013) or prices in different sectors (Burke and Abayasekara, 2018) are often used as instruments. This article uses the same instrument as Lijesen (2007), Alberini and Filippini (2011) and Csereklyei (2020), namely lagged electricity prices. The validity of this instrument is based on its independence from the error term, and on "its relevance for electricity usage only via the current electricity price" (Csereklyei, 2020).

The empirical estimation of the model proceeds as follows: (i) we investigate the presence of cross-sectional dependence using the Pesaran (2004), Frees (1995) and Friedman (1937) cross-sectional dependence tests; (ii) we carry out second-generation panel unit root tests to determine the stationarity properties of all the variables; (iii) we employ the Westerlund error-correction-based panel cointegration test (Westerlund, 2005) to see whether the variables have a cointegrating relationship; (iv) we test for panel causality to assess the causal link between variables using the Dumitrescu and Hurlin (2012) panel causality test; then we present two distinct models to gauge the direct rebound effect in residential electricity consumption, being (v) a GMM specification for long-run price elasticities; and (vi) a first-difference model for short-run price elasticities. We expect our findings to be in line with the predictions of Miller and Alberini (2016), that is the direct rebound effect is lower in the short-run than in the long-run, as "responses in electricity consumption to changes in prices will be rather slow".

The steps of the model are summarized in **Figure 31** below. The remainder of this section introduces the two selected econometric approaches and provides the application process of diagnostic tests performed prior to the empirical analysis.

Figure 31: Steps of modeling approach
(Source: own elaboration)



5.1 GMM specification for long-run

A dynamic two-step GMM approach is adopted to gauge the long-run rebound effect in residential electricity consumption in selected European countries. Thus, Model (1) is estimated using GMM where the electricity price is instrumentalized by its first lagged value. In the presence of heteroskedasticity[5], the estimator derived from a regular OLS regression using instrumental variable is no longer efficient. The efficient estimator in this case is the GMM estimator (Stock and Watson, 2015). This estimator is also known for its large sample properties. In this paper, as we are dealing with a moderate T and N panel (23 and 17 respectively), the GMM estimator is very consistent and asymptotically normal. In addition, the advantage of this technique lies in its ability to allow for more flexible identification: requiring minimal assumptions about the data generating process, GMM estimates can be obtained by any set of moments from the data, as long as the number of parameters to estimate is greater than or

[5] Breusch-Pagan (1979) heteroskedasticity tests for cross-sectional regressions of Model (1) for all years from 1996 to 2018 do not show enough evidence to reject the null hypothesis of constant variance of errors ($p > 0.1$). However, the null hypothesis is rejected when the entire dataset is considered as one and only one cross-section ($p < 0.01$).

equal to the number of moments from the data (Hansen, 1982). In our case, from the Sargan-Hansen overidentifying restriction test (Sargan, 1958; Hansen, 1982), Model (1) where the electricity price is instrumentalized by its first lagged value is exactly identified. The GMM regression is estimated with robust standard errors.

However, dynamic panel approaches may suffer from dynamic panel biases, particularly in short panels, *i.e.*, for small T (Baltagi, 2005). The time period covered in this empirical study being large enough ($T = 23$), these biases is not a serious threat. Besides, the GMM estimator actually treats these dynamic panel biases, but presents another drawback, namely its susceptibility to problems with weak instruments. Fortunately enough, lagged electricity prices used to instrumentalize electricity prices to solve reverse causality issues pass the Stock and Yogo (2005) weak instrument test.

5.2 First-difference estimates for short-run

A first-difference approach is used to estimate the short-run rebound effect of residential electricity consumption in selected European countries over the period 1996-2018. Then, Model (2), being the first-difference of Model (1), writes as follows:

$$\Delta\ln Elec_{it} = \delta_{it} + \gamma_1 \Delta\ln HDD_{it} + \gamma_2 \Delta\ln GDP_{it} + \gamma_3 \Delta\ln Popdensity_{it} + \gamma_4 \Delta\ln Price_{it} + \varepsilon_{it} \qquad (2)$$

where Δ is the first-difference operator, so that $\Delta \ln X_t = \ln X_t - \ln X_{t-1}$, and γ_4 acts as an estimator of the short-run rebound effect.

In order to tackle the endogeneity of prices in this demand model, the first-difference of electricity prices is instrumentalized by its first lag. Although the response to price changes can be slow, a disadvantage of this method, the instrument passes the Stock and Yogo (2005) weak instrument test.

Using first-difference methods can make variables stationary (see Section 5.3 for a discussion of the stationarity properties of variables). Additionally, "it allows us to estimate the regression in annual growth rates, measuring the year-to-year response electricity consumption to changes in price" (Csereklyei, 2020). Serial autocorrelation tests (Wooldridge, 2002) suggest the rejection of the null hypothesis of no first order serial correlation in the idiosyncratic errors. This model is estimated with robust standard errors. Lastly, Model (2) is exactly identified, based on the Sargan-Hansen overidentifying restriction test (Sargan, 1958; Hansen, 1982).

5.3 Diagnostic tests

Before starting our analysis, the correlation among the units (here countries), the stationary properties of variables, and the eventual cointegration and causal relationships between them must be investigated. First, the issue of cross-sectional dependence among countries is tackled. Theoreticians argue that cross-correlation of errors could come from omitted common effects, spatial effects, or the presence of unobserved components that finally become part of the error term (Robertson and Symons, 2000; Pesaran, 2004; Baltagi, 2005). Besides, Phillips and Sul (2003) and Sarafidis and Wansbeek

(2012) add that ignoring cross-sectional dependence of errors in panel models may affect the first-order properties (unbiasedness and consistency) of panel estimators, lead to correlation in the residuals, and then cause incorrect statistical inference. Therefore, we employ several cross-sectional dependencies tests, including the Pesaran (2004), Frees (1995) and Friedman (1937) tests. Results are given in **Table 18**. The null hypothesis of cross-sectional independence is statistically rejected by all the tests at the 1% significance level, *i.e.*, there is cross-sectional dependence in all series, concluding that a shock occurring in one of the selected countries can affect another country.

Second, unit root tests are performed to assess the series stationarity. Two generations of tests can be identified. The first generation of panel unit root tests, mostly developed in the seminal work of Maddala and Wu (1999), Hadri (2000), Choi (2001) and Im et al. (2003), relies on the cross-sectional independence hypothesis. The second generation of panel unit root tests relaxes this hypothesis and allows cross-sectional dependence, making the tests robust to it (Moon and Perron, 2004; Pesaran, 2007). Consequently, to tackle the presence of cross-sectional dependence that was previously brought to light, we run second-generation unit root tests, including Breitung (2000; Breitung and Das, 2005), Levin-Lin-Chu (2002) and Pesaran Cross-sectional Augmented Dickey Fuller (Pesaran, 2007) tests. Their null hypothesis is that all series contain a unit root. As illustrated in **Table 19**, all variables included in the model follow an I(0) or I(1) process, *i.e.*, they are all stationary at their levels or first-differences.

Third, given that each variable presents a unit root, the existence of long-run relationship across regressors must be studied, by testing for the presence of cointegration. To do so, the Westerlund error-correction-based panel cointegration test (Westerlund, 2005) is carried out. This test derives a variance ratio test statistic for the null hypothesis of no cointegration by investigating the stationarity of the error term in Model (1). The alternative hypothesis is that the series in all the panels are cointegrated. Rejecting the null hypothesis implies that the error term is stationary, meaning that the dependent variable and the regressors are cointegrated. The main advantage of the Westerlund error-correction-based panel cointegration test, using a variance ratio test statistic, is that it does not require modeling or accommoding for the heteroskedasticity and serial correlation properties of the data (Westerlund, 2005). As in our framework, the p-value associated to this test is zero, the null hypothesis of no cointegration among our regressors is rejected in favor of the alternative hypothesis. Therefore, we conclude that long-run cointegration clearly emerges.

Finally, we employ pairwise Dumitrescu-Hurlin panel causality tests (2012) to assess the presence of panel causality across the sample. This set of tests prevails over the traditional Granger causality test (Granger, 1969) in its ability to consider two dimensions of heterogeneity: the heterogeneity of the regression model used to test the Granger causality and the heterogeneity of the causal relationship. **Table 20** presents the results of the Dumitrescu-Hurlin causality tests, showing bi-directional causal flows between electricity consumption and GDP per capita, electricity consumption and population density, and electricity consumption and electricity price. Electricity consumption also causes HDD while the opposite does not hold. HDD seem causal to electricity price and GDP per capita, while electricity price only causes GDP per capita. Finally, the population density is caused by and causes all other variables. A graphical summary of these results is provided in **Figure 32**.

All in all, the performed diagnostic tests jointly confirm the suitability of our panel data to answer our research question.

Table 18: Pesaran (2004), Frees (1995) and Friedman (1937) cross-sectional dependence tests

Test	Pesaran	Frees	Friedman
Fixed effects model	7.683***	3.620***	65.588***
	(0.000)	(0.000)	(0.000)
Random effects model	7.337***	3.803***	63.880***
	(0.000)	(0.000)	(0.000)

Note: p-values in parenthesis; *** $p < 1\%$

Table 19: Panel unit root tests

Variables	Level			First-difference		
	Breitung	LLC	CADF	Breitung	LLC	CADF
Log of electricity	1.195	-6.133***	-1.747	-8.021***	-9.646***	-2.900***
consumption	(0.884)	(0.000)	(0.504)	(0.000)	(0.000)	(0.000)
Log of HDD	-1.361*	-12.932***	-3.159***	-2.654***	-13.267***	-3.734***
	(0.086)	(0.000)	(0.000)	(0.004)	(0.000)	(0.000)
Log of GDP per capita	2.241	-6.314***	-1.881	-2.723***	-7.553***	-2.326***
	(0.988)	(0.000)	(0.289)	(0.003)	(0.000)	(0.007)
Log of population	7.989	-1.391*	-2.982***	-3.212***	-3.478***	-2.141**
density	(1.000)	(0.082)	(0.000)	(0.001)	(0.000)	(0.048)
Log of electricity price	2.981	-2.022**	-2.268**	-2.247**	-8.601***	-2.765***
	(0.999)	(0.022)	(0.014)	(0.012)	(0.000)	(0.000)

Note: LLC stands for Levin-Lin-Chu; CADF stands for Cross-sectional Augmented Dickey Fuller;
p-values in parenthesis; *** $p < 1\%$; ** $p < 5\%$; * $p < 10\%$

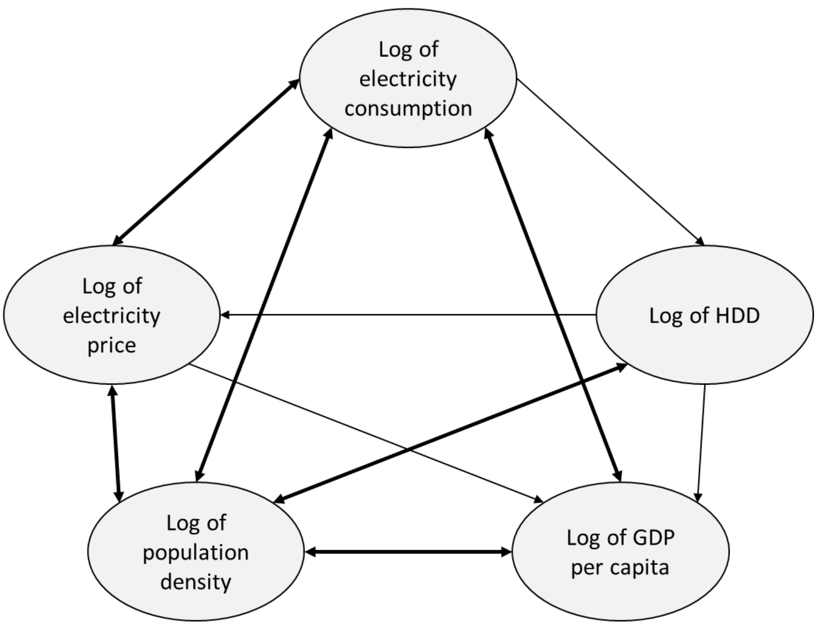
Table 20: Pairwise Dumitrescu-Hurlin panel causality tests

Null hypothesis		**W statistics**	**Z-bar statistics**	**p-value**
Log of electricity consumption	Log of HDD	4.843	11.203	0.000***
Log of HDD	Log of electricity consumption	1.219	0.640	0.523
Log of electricity consumption	Log of GDP per capita	4.734	10.888	0.000***
Log of GDP per capita	Log of electricity consumption	1.994	2.897	0.004***
Log of electricity consumption	Log of population density	3.080	6.065	0.000***
Log of population density	Log of electricity consumption	12.147	32.498	0.000***
Log of electricity consumption	Log of electricity price	1.775	2.259	0.024**
Log of electricity price	Log of electricity consumption	8.417	21.625	0.000***
Log of HDD	Log of GDP per capita	1.770	2.245	0.025**
Log of GDP per capita	Log of HDD	0.616	-1.120	0.262
Log of HDD	Log of population density	2.104	3.219	0.001***
Log of population density	Log of HDD	1.869	2.534	0.011**
Log of HDD	Log of electricity price	2.097	3.198	0.001***
Log of electricity price	Log of HDD	0.659	-0.994	0.320
Log of GDP per capita	Log of population density	2.808	5.272	0.000***
Log of population density	Log of GDP per capita	13.881	37.555	0.000***
Log of GDP per capita	Log of electricity price	1.320	0.933	0.351
Log of electricity price	Log of GDP per capita	5.234	12.344	0.000***
Log of population density	Log of electricity price	18.890	52.158	0.000***
Log of electricity price	Log of population density	6.105	14.885	0.000***

Note: *** $p < 1\%$; ** $p < 5\%$

Figure 32: Summary of panel causality results

(Source: own elaboration)



6. Results

Having confirmed the existence of long-run cointegration and causal relationships between the variables used in our model, this section presents empirical results derived from the GMM and the first-difference estimators, for the long- and short-run rebound effect, respectively.

6.1 Long-run estimates of the rebound effect

We investigate the magnitude of the rebound effect in the long-run using a two-step GMM specification, the results of which are presented in **Table 21** (second step only). Most of the control factors are statistically significant at the 5% level at least. Results confirm the existence of a negative and statistically significant relationship between electricity price, instrumented by its lagged value, and electricity consumption, meaning that the demand for residential electricity increases as the electricity price falls. More precisely, a 1% decrease in the electricity price will cause a 0.425% increase in electricity demand, everything else being equal. This is suggestive of a direct rebound effect of residential electricity consumption of approximately 42.5% in the long-run. In other words, when electricity efficiency improves, 42.5% of the expected electricity savings are offset by the extra electricity consumption resulting from the efficiency improvement and the lower electricity price, and 57.5% of the expected electricity savings are attained.

Accordingly, our findings reject the hypothesis of a backfire effect in residential electricity demand in selected European countries, a situation in which an energy efficiency improvement could not reduce electricity intensity. This is then a satisfactory result as it suggests that energy consumption reductions are achievable after an energy efficiency improvement.

Compared to other research, we find that our rebound effect estimates in the long-run are very close to those of Freire-González (2010), who finds a long-run direct rebound effect of 49% in electricity consumption in Catalan municipalities between 1991 and 2002. Our results are also in the same range as those of Han et al. (2019), who estimate a 37% direct rebound effect in Chinese provinces. Finally, our findings are in the low average of the range of the rebound effect suggested by Belaïd et al. (2020a), developing a quantile panel model on French data.

Results of the GMM estimation of Model (1) also show that HDD, population density and the GDP per capita have positive effects on residential electricity demand, implying that an increase in the number of days requiring the use of heating, in population density, or in GDP per capita leads to increased residential electricity demand. Interestingly, the coefficient of GDP per capita suggests that a 1% increase in this factor leads to an increase in residential electricity use by 0.307%. Although this result is not statistically significant, the sign of this effect agrees with the literature on the rebound effect and energy demand models, which often control for the GDP per capita or household income. Indeed, a 1% increase in GDP per capita is found to yield: (i) a 0.47% increase in residential electricity use in Pakistan (Alvi et al., 2018); (ii) a 0.71% increase in electricity consumption of urban residents in China (Han et al., 2019); and (iii) a 0.61% increase in residential electricity consumption in the EU (Csereklyei, 2020). Note that the magnitude of the effect estimated in this paper is in the lower range of results.

Table 21: GMM estimation results of Model (1) with instrumental variables method

Dependent variable: Log of electricity consumption	
Variables	**Model (1)**
Log of HDD	0.527**
	(0.208)
Log of GDP per capita	0.307
	(0.210)
Log of population density	0.341***
	(0.054)
Log of electricity price	-0.425**
	(0.191)
Constant	5.16***
	(0.725)
Observations	374
Sargan-Hansen overidentifying restriction test: p-value	0.000
Wald test of overall significance: p-value	0.000

Notes: instrumented variable: Log of electricity price; instrument: lagged Log of electricity; robust standard errors in parenthesis; *** $p < 1\%$; ** $p < 5\%$

6.2 Short-run estimates of the rebound effect

In order to study the existence of a rebound effect in residential electricity use in selected European countries in the short-run, a first-difference regression is estimated. The empirical results, where the electricity price is instrumented by its lagged value, are presented in **Table 22**. The signs of parameter estimates agree across the GMM model and the first-difference specification, *i.e.*, across long- and short-run. First-difference results are suggestive of a rebound effect in residential electricity use of 17.8% in the short-run, which is obviously less than estimates obtained in the long-run, as expected by Miller and Alberini (2016). This difference in the magnitude of the effect indicates that the residential electricity use in selected European countries is more price inelastic in the short-run than in the long-run. The reported estimates for the direct rebound effect are very close to the meta-analysis performed by Labandeira et al. (2017). Indeed, the price elasticity of electricity demand is -0.13, which would be equivalent to a 13% rebound effect. Once again, a backfire effect, a special case with greater energy consumption than before the price reduction, is refuted.

Table 22: First-difference estimation results of Model (2) with instrumental variables method

Dependent variable: ΔLog of electricity consumption	
Variables	**Model (2)**
ΔLog of HDD	0.134***
	(0.025)
ΔLog of GDP per capita	0.152
	(0.099)
ΔLog of population density	0.857**
	(0.439)
ΔLog of electricity price	-0.178**
	(0.089)
Constant	0.005**
	(0.002)
Observations	374
Sargan-Hansen overidentifying restriction test: p-value	0.000
Wald test of overall significance: p-value	0.000

Notes: instrumented variable: ΔLog of electricity price; instrument: lagged ΔLog of electricity; robust standard errors in parenthesis; *** $p < 1\%$; ** $p < 5\%$

7. Discussions and policy implications

This section aims at providing an in-depth discussion on the policy implications of our empirical findings for Europe. In an international energy consumption reduction context, Sorrell (2010) suggests three rebound mitigation strategies that can be classified according to their goal: (i) "consuming more efficiently" by increasing energy and environmental efficiency across sectors; (ii) "consuming differently" by favoring a shift to greener consumption patterns; and (iii) "consuming less" by downsizing consumption.

First, the strategy "consuming more efficiently" seeks to improve energy efficiency in all sectors, *i.e.*, in residential and tertiary buildings, to reduce the magnitude of the rebound effect. Energy efficiency has already showed itself to be useful in meeting the EU's GHG emissions reduction target (Belaïd et al., 2021a). Therefore, fostering innovative and performant energy efficiency solutions appears crucial and of primary importance to develop the use of cleaner technologies among households. However, as shown in this article, further energy efficiency improvement may create additional rebound effects through additional demand, which would offset energy reductions and have an ultimate opposite effect. These new improvement actions should therefore be paired with other environmental and industrial measures to ensure positive overall effects. The development and promotion of massive renovation programs should also be supported. Specifically, in June 2021, the European Council of the EU emphasized "the need to at least double energy-related renovation rates by 2030 and to promote deep energy renovations". Generalizing the application of emission reduction and energy conservation technologies could even enhance welfare by providing more energy services to consumers and producers, in addition to improving living conditions and making homes healthier.

Second, the strategy "consuming differently" intends to shift from polluting to clean energy sources, such as renewables energies (wind, solar) or nuclear. Decarbonization policies for energy production and consumption should then be encouraged. On this matter, Sterner and Coria (2003) suggest environmental taxation policies which, when applied appropriately, are "a successful way to push consumers' and businesses' behavior towards more sustainable practices". Energy and carbon taxes are in fact the most popular political tool and can be of two types: either a product- or sector-specific tax, to mitigate the direct effect from specific products or sectors, or a transversal tax across economic sectors, to control and reduce both direct and indirect effects by improving the general environmental intensity of the entire economy (Saunders, 2011; Font Vivanco et al., 2016). As a matter of fact, at the European scale, all member states of the EU are part of the EU Emissions Trading System (EU ETS), a market created in 2005 to trade a capped number of GHG emission allowances. This program has already proven its effectiveness in delivering cost-efficient emissions reductions: emissions from installations covered by the EU ETS experienced a 35% reduction between 2005 and 2019 (European Commission, 2020b).

Third, the strategy "consuming less" places household behavior at the center of energy consumption patterns. Indeed, based on our empirical results suggesting the existence of considerable rebound effects both in the short- and long-run, only relying on energy efficiency improvement cannot realize the expected energy saving targets. Accordingly, Aydin et al. (2017) find evidence of a significant potential for energy savings in the residential sector but write that "the behavioral response of households offsets part of the projected energy savings". Therefore, it is necessary to continue the work already begun to raise awareness among households to reduce their energy consumption.

All in all, deepening the understanding of the mechanisms of the rebound effect would allow a better assessment of the impact of public policies aiming at controlling, or even reducing, the energy consumption and the GHG emissions in the residential sector. The rebound effect should be considered when designing energy efficient improvement policies, in order to make them more effective.

8. Conclusions

The rebound effect issue has been at the core of recent academic debate, and many authors suggest policy instruments, such as pricing mechanisms, to mitigate its magnitude. As things stand, there exist diverse methodological approaches, and the results of the estimates remain sparse and dependent on data. Quasi-experimental approaches remain rare due to measurement difficulties, while econometric approaches are subject to biases, both related to the approach and the quality of the data.

This work is unique in its ability to offer estimates of the rebound effect in residential electricity use for 17 European countries over more than two decades, distinguishing between the short- and long-run. Based on a Eurostat and World Bank annual panel data covering the period 1996-2018, we develop a two-sided econometric approach using (i) dynamic GMM techniques to estimate the long-run rebound effect in residential electricity use; and (ii) a first-difference model to estimate the short-run rebound effect. We also use instrumental variable techniques to tackle the reverse causality of electricity price in an energy demand model. The most important contribution of this article is that it confirms the existence of a direct rebound effect for residential electricity consumption in Europe. More precisely, results indicate that this direct rebound effect is approximately 18% in the short-run and approximately 43% in the long-run. A summarized version of the results is presented in **Figure 33**. The residential electricity use in selected European countries is therefore more price inelastic in the short-run than in the long-run. Our results highlight the importance of the rebound effect and the price sensitivity of households in explaining variations in electricity consumption in the European residential sector, all in the context of the EU achieving its 2030 climate and energy efficiency goals.

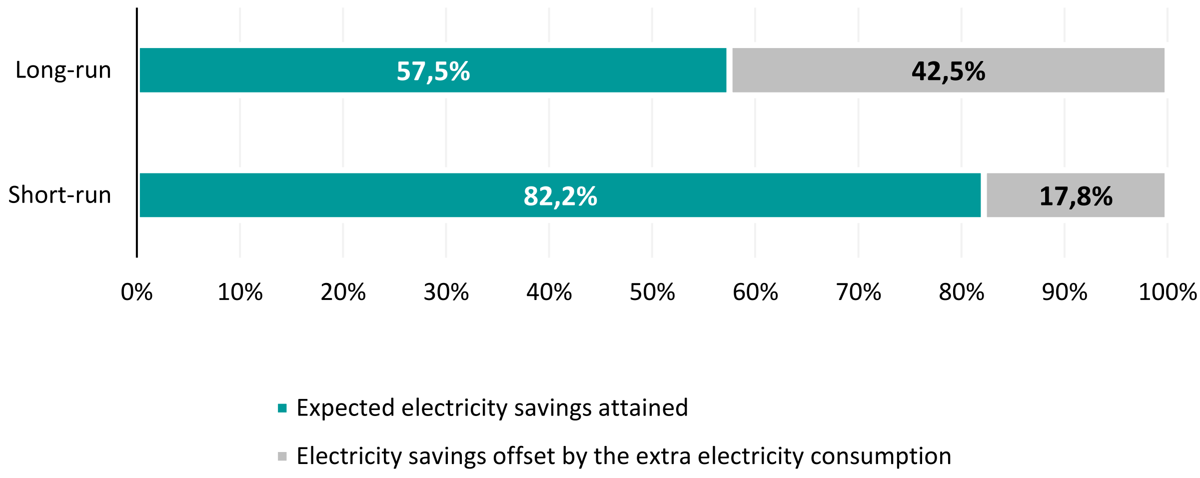
One limitation of this study is that it does not account for dwelling characteristics, such as size, type, or geographic area, which can greatly influence measures of energy efficiency, and therefore an assessment of the rebound affect. Including more sociodemographic features about household occupants may also be important when considering households' heterogeneity. For instance, investigating the effect of family composition or age of household members could provide more insight into the understanding of the rebound effect and its drivers. Unfortunately, such data at the European level are extremely rare.

This paper and its techniques could also be extended to other energy sources. As demonstrated here, there exists a rich literature on the rebound effect in the electricity consumption. However, the subject is little debated with regard to renewable energies for instance. Besides, studying the rebound effect and its magnitude in a specific energy consumption, but by usage (*e.g.*, space heating, cooking, water heating, lighting) could also be extremely beneficial to policy makers.

Finally, even though our empirical model distinguishes between short- and long-run estimates, the relationships between the selected variables in our model remain linear. Thus, estimating the nature of these relationships at different levels of energy consumption, *i.e.*, according to the distribution of the dependent variable, using a quantile regression much like Belaïd et al. (2020a), would be a valuable and appropriate extension of this study. A second extension to tackle the nonlinearity of the statistical relationships between variables would be to develop a panel threshold model, as used in Zhang and Peng (2016). By testing whether or not the model has threshold effects, this specification can examine the nonlinear relationship between residential electricity consumption and influencing factors, for instance GDP per capita or household income, and provide an estimate of the rebound effect for low- and high-income households. Policy makers may also take an interest in such studies.

Figure 33: Summary of the results

(Source: own elaboration)



General conclusion

In this thesis, we propose analyzing the diffusion of energy-efficient technologies in the French housing sector, whose current underinvestment ultimately fuels the energy efficiency paradox. Facing the urgent necessity to curb energy demand and its associated CO2 emissions massively, we also studied the rebound effect, influenced by behavioral aspects, which endangers these objectives. This General conclusion will synthesize the results of the three chapters of this thesis, and present some energy policy recommendations derived from the discovered outcomes. Then, it will identify the challenges and limits of this thesis. Finally, it will offer directions for future research, focusing on how to change household behaviors, as they are at the heart of the energy transition and energy demand fluctuations.

1. Main results of the thesis

To wrap up the main empirical results of all the three chapters together:

- **Chapters 1** and **2** confirm what the empirical literature has largely demonstrated, that is the role of individual and dwelling heterogeneity in the energy renovation decision-making process. More precisely:
    - Household heterogeneity significantly affects the decision to retrofit: getting older, having a high income, and having children are incentive factors.
    - Dwelling heterogeneity also affects the decision to retrofit but to an even greater extent: a greater likelihood of renovating is associated with home ownership and older housing. The influence of the dwelling surface is strong, but mixed, just as the literature on the subject had previously indicated.
- **Chapter 1** reveals the importance of behavioral barriers to the acceptability of energy-efficient technologies among French households:
    - Perceiving energy renovation as a risky investment (in terms of financial profitability or operational costs related to the implementation of the work) is a non-negligible obstacle to the adoption of energy efficiency measures. This aligns with the portfolio and prospect theories.
    - Households behave consistently in terms of pro-environmental habits. If renovating a dwelling is considered a pro-environmental action, then the probability of households to renovate their dwelling increases with the fact that they are already behaving pro-environmentally in terms of urban mobility, waste sorting and consumption habits.
- **Chapter 2** highlights structural barriers to energy efficiency. A case study focusing on the effect of financial aid aimed at boosting the renovation of the French dwelling stock reveals a threshold effect in their final effectiveness. Estimated around 3,000 euros, this cutoff level suggests the

importance of the financial capacity of households to afford such a major investment, who are, in the end, in desperate need for financial help from the State.

- **Chapter 3** shows the existence of a direct rebound effect occurring after an energy efficiency improvement, proxied by an electricity price fall. The granularity of the employed time series data and the selected estimation allow us to distinguish the rebound effect between the short and long run: it is of 18% in the short-run and 43% in the long-run. It means that, when electricity efficiency improves in the short run (in the long run, respectively), 18% (43%, respectively) of the expected electricity savings are offset by the extra electricity consumption resulting from the efficiency improvement and the lower electricity price, and 82% (57%, respectively) of the expected electricity savings are attained.

As a main result, this predominantly empirical thesis shows that the diffusion of energy-efficient technologies in the French housing sector is slowed down by structural barriers, such as limited financial capacity and liquidity constraints, and behavioral barriers, including individual preferences such as attitudes toward energy efficiency and risk, and energy context perception. The rebound effect also limits the expected energy demand and CO2 emissions reductions. Households' energy renovation decisions are then strongly linked to individual preferences as well as to their sociodemographic characteristics and dwelling' conditions.

However, these obstacles are not insurmountable. Energy efficiency requires consumers to change their behavior regarding both energy use and technology investment. By proposing innovative tools, accompanying households or targeting public policies to reduce energy consumption and promote energy-saving behaviors, it seems possible to lift some of the significant barriers to energy efficiency.

2. Energy policy recommendations and key levers for climate change mitigation

As part of the EU's roadmap for transitioning to a competitive low-carbon economy, cutting domestic carbon emissions by at least 80% by 2050, when compared to 1990, and managing residential energy consumption have become a priority for many European governments. From many different perspectives, this thesis' findings can act as a valuable resource for energy policymakers to achieve these stated objectives.

First, energy policies should strongly stimulate the consumption of decarbonized energies in existing buildings, as they are already widely used in new constructions, in compliance with the recent environmental regulation, RE2020 (Régulation Environnementale). The recent COVID-19 pandemic economic ravages and the ongoing energy tensions in Europe generated a significant energy supply crunch, spreading over various energy sources and leading to unprecedented energy price surges. In the economic context of a global supply shock, already impacting various facets of our lives by generating energy shortages and outstanding inflation rates all across Europe, the price of energy, and especially of electricity, must be stabilized. Rising prices imminently impact consumers' energy bills and potential power outages (Belaïd, 2021; Mestneer and Belaïd, 2022). Local governments must improve and ensure the affordability of modern energy, including electricity and low-carbon energy sources, at the household level. The tariff shield currently in place in France since September 2021, seeking to support citizens' purchasing power, has indeed allowed limiting the increase in electricity prices to 4% in 2022. Without this protective measure, the households' energy bills would have increased by 40%, according to the French government. The INSEE also highlighted the positive impact of this shield: without it, inflation between the second quarters of 2021 and 2022 would have been 3.1 percentage points higher (INSEE, 2022b). We can only recommend maintaining this tariff shield. Initially scheduled to expire at the end of 2022, the promise to renew it in 2023 seems to be coming true.

Second, long-term renovation strategies should encourage the renovation of the housing stock, since better-insulated buildings, using innovative and more efficient energy-saving technologies, can significantly reduce residential energy demand and its associated CO2 emissions. The same policies can apply to the tertiary and industrial sectors, which, together, also contribute to increases in national final energy consumption. In particular, **Chapter 2** has shown the role of financial aid schemes for energy renovation in households' decision-making process, in addition to financial resources. An efficient regulatory legal framework should be included in energy policies, setting sectorial targets since not all sectors have the same energy demand and CO2 emissions reduction potentials. More flexible, generous, and easily accessible financial programs are a potent lever for energy renovation at a national scale, although by now, financial incentives for non-residential buildings and private companies remain scarce and limited in France. This effort must be made in order to comply with the European Council of the EU and the HCC's desires to accelerate, even double, the renovation rate in Europe by 2030. By lowering the upfront cost of renovation work, financial schemes can allow investors, *i.e.*, retrofitters, to diversify their portfolios in order to reduce the non-profitability risk involved in such a big investment.

Third, aligning with our former point, **Chapter 1** confirmed previous findings about the role of uncertainty and risk preferences in energy retrofit decisions. Mitigating risk aversion's dissuasive effect is crucial to make energy renovation economically attractive to reluctant households. Developing national labels recognizing and acknowledging the quality of craftsmen can help rehabilitate their image with retrofitters. To limit attrition, *i.e.*, households initially interested in renovation but who become discouraged, better psychological support and more professional management of renovation projects are desirable. Energy experts coming before, during and after renovation work can also help reduce risks of defects and non-profitability, along with ensuring their seriousness and quality. Therefore, strengthening France's legal and political framework for energy renovation is essential.

Fourth, actions on the demand side should also become an essential objective. Accordingly, facing a tense situation in terms of nuclear production, the French electricity transmission system operator, RTE, asked French households to moderate their energy consumption on April 4, 2022. The low availability of the nuclear park mainly caused this tension in the electrical system. By addressing consumers directly, RTE hoped to reach the very heart of its practices. However, this communication action did not produce enduring effects due to the incompressibility of energy consumption of French households affected by energy poverty. Therefore, securing reliable and equal access to energy services is vital before long-term plans raise awareness among households of the need to reduce their environmental footprint by adopting more rational and responsible energy consumption habits.

Fifth, a new set of practices have recently emerged, called energy sobriety or energy sufficiency, and aims to consciously reduce energy consumption by taking up technologies, such as low-energy lighting, smart meters, or electric cars. In addition to energy efficiency, which consists of using innovative technologies with better efficiency and fewer energy losses (in production or consumption), energy sufficiency implies deliberately changing energy consumption habits. This concept has never been more topical at a time of international tensions over energy production and consumption in Europe. By cutting energy waste, European countries plan to reduce their gas consumption by 15% until March 2023, adopting measures going from national awareness-raising campaigns about energy management to more drastic measures, such as heating and air-cooling temperature limitations in public places. **Table 23** summarizes the recent sobriety commitments of some European countries, which have been widely acclaimed in the media. In an area where the explanatory and predictive power of individual behavior becomes more and more potent, future energy policies must combine the concepts of energy efficiency and energy sufficiency to pave the way toward a decarbonized and sustainable economy.

Table 23: Energy sufficiency measures in selected European countries
(Source: own elaboration based on multiple press articles and TV spots)

Measure / Country	**Benelux**	**France**	**Germany**	**Greece**	**Ireland**	**Italy**	**Spain**	**Sweden**	**UK**
Awareness-raising campaigns (reduce time spent in the shower, limit heating temperature, use a bicycle, defrost the freezer, buy energy-efficient products, *etc*.)	X	X	X	X	X	X	X	X	X
Compulsory door closing automatic mechanism in heated and air-conditioned public places		X	X				X		
Energy audit for too energy-intensive companies and/or subsidies to upgrade lighting and heating equipment		X	X	X					
Limitation of heating temperature in public buildings and private companies to 19°C (sometimes 18°C or 20°C)		X	X		X	X	X		
Limitation of air-cooling to 27°C (sometimes 26°C)		X	X	X		X	X		
Lowering of the speed limit in order to save petrol use	X	X			X			X	X
Stop of illuminated advertising and store windows from 10pm		X	X			X	X		

Note: Benelux includes Belgium, the Netherlands, and Luxembourg

Sixth, as documented in **Chapter 1**, households behave consistently in terms of pro-environmental behaviors. If energy renovation is deemed to be a pro-environmental behavior, promoting green behaviors can positively influence the likelihood of households renovating their dwelling. With non-contagion among behaviors, the only worthy environmental and energy policy strategy would be to act on each behavior and promote it one by one, which does not seem efficient, and could be somewhat difficult for targeted households and expensive for policymakers. However, in the presence of spillover effects among pro-environmental behaviors, targeting one behavior is the same as targeting them all. Energy-saving political strategies should then directly strengthen these broad worldviews, and simply wait for the beneficial spillover effects.

Seventh and last, the rebound effect, studied in **Chapter 3** and occurring after the adoption of energy-efficient technologies, or after an energy retrofit, may jeopardize the theoretically expected energy reductions. This effect is not necessarily a "bad" effect *per se*, but rather a legitimate behavior from households eager to catch up on some comfort. Yet, in order to moderate this compensatory phenomenon, energy retrofit policies must be paired with behavioral tools. The better knowledge of energy retrofit behavior, brought to light by this thesis, can help policymakers to design effective two-sided policies.

To conclude, household behaviors are the cornerstone of the current energy and environmental transition. Energy policies must take them into account to ensure the sustainability of their effects over time. It is, therefore, crucial to consider and sometimes change household behaviors. Therefore, this thesis opens the way to a new strand of literature on the tools and practices for shifting behaviors.

3. Challenges and limits of the thesis

This thesis has highlighted the existence of a significant need for empirical research to contribute to the empirical validation of the energy efficiency gap theory. As this theory relies on behavioral aspects, it is essential to precisely and robustly observe individual behaviors, in terms of energy savings, investments, preferences, in order to incorporate them into the estimation process. Data at the micro level, as used in **Chapters 1** and **2**, are scarce and it is becoming increasingly difficult to access large surveys, allowing for quality statistical inference.

If this thesis has proposed some solutions to narrow the energy efficiency gap and accelerate investments in energy efficiency, such as reducing the financial risk of default, accompanying households financially and psychologically, or taking advantage of spillover effects by promoting environmentally-friendly behaviors, there remains a non-negligible obstacle: the rebound effect. Difficult to gauge, as evidenced by the plurality of estimation methods, it may call into question the results of this thesis. In fact, the adoption of energy-efficient technologies, through housing renovation notably, will not convey all of its results if the rebound effect persists within individual practices. The complexity of the energy consumption process itself, which involves many factors, including the energy price, households preferences, *e.g.*, for comfort, and dwelling technical attributes, makes it tricky to analyze. It seems hardly attainable to perfectly observe all the parameters playing a role in the residential energy consumption process in order to predict it with certainty. In other words, there will always be omitted variable bias in econometric models.

In this regard, the availability of the data may curtail empirical research on the subject. Nevertheless, on the bright side, it also becomes a stimulating challenge. Collecting and storing data in a reliable way, and making it public, or at least more easily accessible and less opaque, will considerably improve the quality of future studies, which will ultimately feed the economic and political debate and constitute a solid knowledge base for energy policymakers.

4. Future research perspectives

The overall results of this doctoral research call for different avenues for future research. Indeed, behavioral tools, including nudges and boosts, have been identified as promising in terms of energy consumption reduction and the promotion of green behaviors. On the one hand, a nudge is “any aspect of the choice architecture that alters people's behavior in a predictable way without forbidding any options or significantly changing their economic incentives” (Thaler and Sustein, 2008). It is a simple and low-cost measure developed to encourage the decision-maker to act in the desired direction and to gradually correct habits. This soft influencing technique is an alternative to more restrictive and less effective measures. Contrary to economic incentives, which use financial motivation to restrict or encourage certain behavior, nudges influence individuals’ behavior by indicating the right way to act in a given context, without removing any of the choices available to them, nor affecting their economic incentives. Together, these individual changes can have a positive impact on a large scale. On the other hand, a boost is a behavioral tool as well, but differs from a nudge in that it not only pushes the individual toward the right behavior but also shows the tools and actions to implement to solve the concerned issue. The academic literature has recently proved the effectiveness of “green” nudges (Charlier et al., 2020; Buckley and Llerena, 2021; Ruokamo et al., 2022) and boosts (Lazaric and Toumi, 2022) in an energy conservation framework. Although the ethics and sometimes non-lasting effects of behavioral interventions have been discussed (Allcott and Rogers, 2014; Schubert, 2017), these practices should not be neglected and could be complementary to the massive promotion of energy efficiency measures already being done by energy policymakers in France and abroad.

If such actions on energy consumers' habits are possible and foreseen by behavioral economics, it remains necessary to act on the deep structure of our societies and cities. Facing the growing phenomenon of urbanization of the population (in its 2019 report, the UN reported global population projections of 9.8 billion by 2050, with more than two-thirds of the world population living in urban areas), cities are particularly well-positioned to play a leading role in tackling climate change and fostering the transition to a more sustainable world. This intensive urbanization already presents serious challenges, including environmental quality degradation, increasing socioeconomic inequalities, energy insecurity, intensive energy use, and natural and human-made disasters fueling climate change. Thus, smart cities promise to address these challenges and make cities more sustainable, resilient, eco-friendly, and livable. Often based on the production and consumption of renewable and low-carbon energies, smart cities also integrate nudges into their internal functioning, making the building user an actor in the energy transition more globally. Overall, this thesis’ results suggest the need to design mixed international effective energy policies: taking the full advantage of behavioral interventions, such as nudges and boosts, will not be possible without the environment of energy consumers, *i.e.*, the cities and the place where they live, being designed smartly and sustainably.

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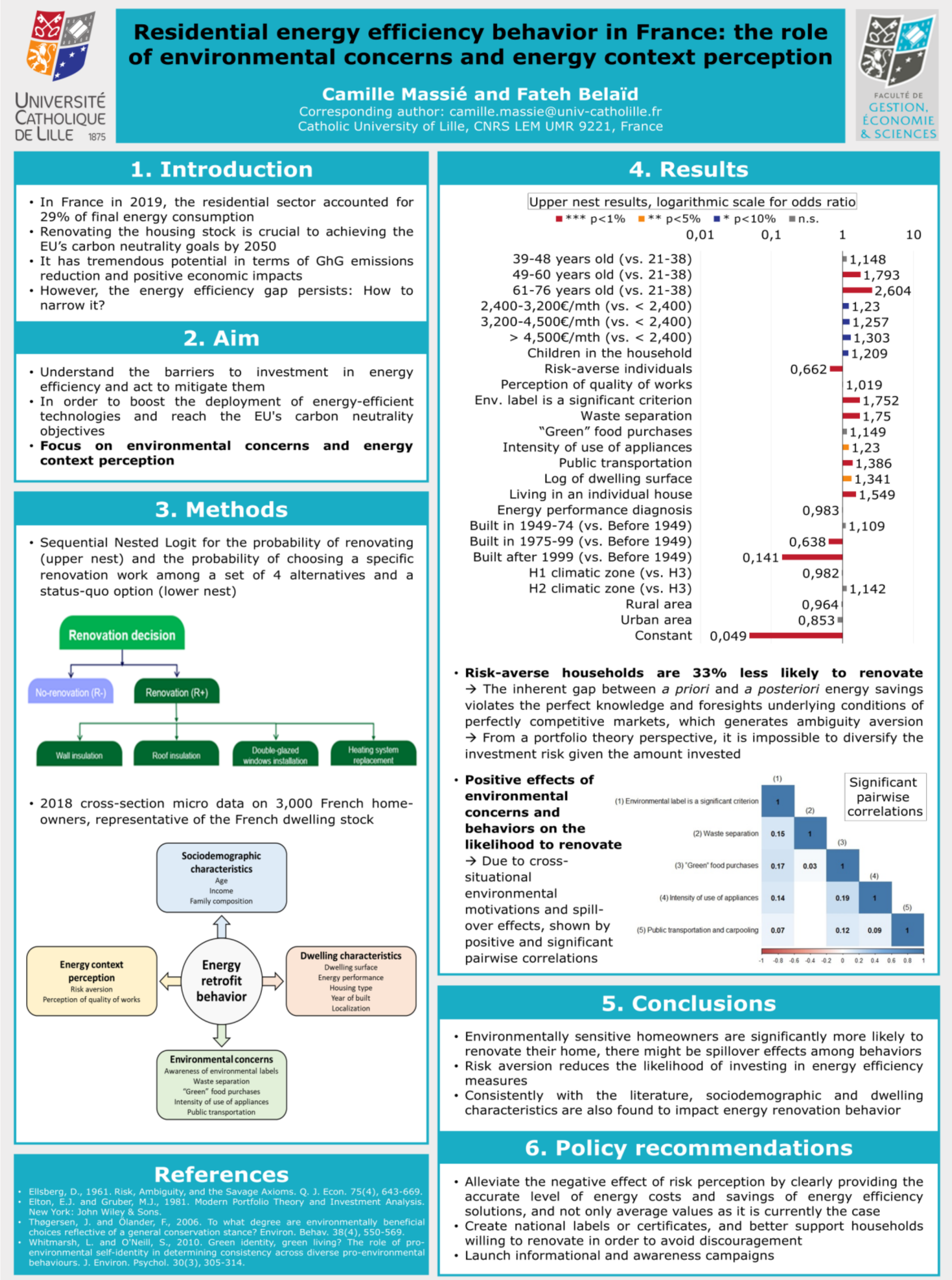
Appendices

A. Appendices to Chapter 1

a. My poster for the 3rd International Conference on ERSS



B. Appendices to Chapters 1 and 2

a. Energy renovation questionnaire, Questionnaire de rénovation énergétique

Source: adapted from Bakaloglou and Belaïd (2022)

Echantillon et consignes pour le déroulement de l'enquête en ligne : 3000 individus de plus de 18 ans représentatifs des propriétaires français (critères de représentativité : date de construction du logement et localisation aire urbaine). Des commentaires sur le déroulement de l'enquête sont inscrits *en italique* dans le questionnaire.

Ce questionnaire s'inscrit dans le cadre d'un travail de recherche sur les décisions de rénovation énergétique par les ménages français. Les réponses ne seront exploitées qu'à des fins de recherche et traitées de façon anonyme. Merci de votre participation !
Ce questionnaire est composé de deux sections : la première comporte des questions usuelles sur vous et votre logement ; la deuxième s'intéresse à vos actions de rénovation énergétique.

Section 1 : Caractéristiques du ménage et du logement

1. Ménage

1) Quelle est votre année de naissance ?

XXXX numérique

2) Quelle est votre situation ? (plusieurs réponses possibles)

Célibataire sans enfants

Célibataire avec un ou des enfants d'âge inférieur à 25 ans présents dans le logement

Couple seul

Couple avec un ou des enfants d'âge inférieur à 25 ans présents dans le logement

Couple accueillant une/d'autre(s) personne(s) de la famille

3) Quel est le code postal de votre lieu de résidence principale ?

XXXXX numérique

4) Quelle est le type de la zone géographique dans laquelle votre logement se situe ?

Paris intra-muros

En centre-ville d'une ville ayant plus de 100 000 habitants

En centre-ville d'une ville ayant entre 10 000 et 100 000 habitants
En centre-ville d'une ville ayant entre 2 000 et 10 000 habitants
En centre-ville d'une ville ayant moins de 2 000 habitants
Dans le péri-urbain/banlieue d'une ville ayant plus de 100 000 habitants
Dans le péri-urbain/banlieue d'une ville ayant entre 10 000 et 100 000 habitants
Dans le péri-urbain/banlieue d'une ville de moins de 10 000 habitants
En zone rurale

2. Logement et performance énergétique

5) Quelle est la surface habitable de votre logement (en mètres carrés) ?
XXX numérique

6) Votre logement principal est il… ?
Une maison
Un appartement
Autre

7) Quelle est l'année de construction de votre logement ? (arrondir à la décennie si difficultés)
XXXX numérique

8) Votre logement a-t-il été l'objet d'un diagnostic par experts (audit énergétique, DPE, label, *etc.*) ?
Oui, c'est un logement très performant d'un point de vue énergétique (étiquette A ou B si DPE ou équivalent)
Oui, c'est un logement performant d'un point de vue énergétique (étiquette C si DPE ou équivalent)
Oui, la performance énergétique du logement est moyenne (étiquette D si DPE ou équivalent)
Oui, la performance énergétique du logement est faible (étiquettes énergétiques E, F ou équivalent)
Oui, la performance énergétique du logement est très faible (étiquette énergétique G ou équivalent)
Non, le logement n'a pas fait l'objet d'un diagnostic énergétique

3. Comportement et préférences individuelles

9) Dans la vie de tous les jours, votre sensibilité environnementale a-t-elle un impact sur vos comportements pour les postes suivants ? (plusieurs réponses possibles)
Tri des déchets

Achats alimentaires
Transport
Participation active au sein d'une association environnementale
Profession

10) Etes-vous attentifs à l'étiquette énergétique de vos équipements domestiques lors de leurs achats ?

Oui, critère majeur de choix
Oui, critère mineur de choix
Non

Section 2 : Travaux énergétiques

11) Pensez-vous que les malfaçons sont des problèmes courants lors de la réalisation de travaux par des entreprises du bâtiment ?

Note de 0 à 10 ; 0 : ce n'est jamais un problème ; 10 : les malfaçons sont systématiques

12) Estimez-vous que les travaux de rénovation énergétique constituent un investissement « risqué » ? C'est-à-dire, considérez-vous qu'il existe un risque de perdre de l'argent ou de ne pas rentabiliser votre projet quand vous investissez en rénovation énergétique ? (plusieurs choix possibles)

Aucun risque
Risque/incertitude sur la rentabilité du projet, il est difficile de se projeter dans l'environnement économique présent et futur
Risque sur la qualité finale des travaux par rapport à ce qui est annoncé
Risques opérationnels, on ne connait pas de façon certaine les coûts réels de ces travaux car possibilité d'imprévus (faillite de l'entreprise, coûts additionnels, *etc.*)
A la vente du bien, les travaux énergétiques réalisés peuvent ne pas être valorisés à leur juste prix dans son prix de vente, ainsi mon investissement peut ne pas être rentable
Autre

13) Avez-vous réalisé des travaux de rénovation énergétique sur votre logement d'habitation depuis emménagement (isolation thermique mur, sols, combles, fenêtres, changement du système de chauffage) ?

Oui
Non

Si « Oui » → question suivante ; si « Non » → question 22

Si réalisation de travaux de rénovation énergétique

14) Avez-vous réalisé une isolation thermique des murs ?

Oui, isolation thermique par l'intérieur

Oui, isolation thermique par l'extérieur

Non

15) Avez-vous réalisé une isolation des combles/toiture ?

Oui

Non

16) Avez-vous réalisé une isolation thermique des sols ?

Oui

Non

17) Avez-vous réalisé une pose de double/triple vitrage sur certaines de vos fenêtres/baies ?

Oui, pour 100% des fenêtres/baies

Oui, pour plus de 50% des fenêtres/baies

Oui, pour quelques fenêtres/baies

Non

18) Avez-vous réalisé un remplacement du système de chauffage ?

Non

Oui, chaudière à condensation

Oui, chaudière hybride

Oui, pompe à chaleur

Oui, micro-cogénération gaz

Oui, énergie hydraulique

Oui, énergie éolienne

Oui, énergie solaire

Oui, autre dont système de chauffage « classique »

19) Avez-vous bénéficié d'aides publiques pour votre rénovation énergétique ? (plusieurs réponses possibles)

Aide de l'Anah

Crédit d'impôt pour la transition énergétique (CITE)

Déduction fiscale

Autre

Non

20) De quel montant total avez-vous bénéficié pour les aides à la rénovation énergétique (réduction d'impôt comprise) ? (en euros)

XXXXX numérique

21) Auriez-vous réalisé ces travaux sans aide ?

Oui

Non

Suite question 26 pour ceux qui ont fait de la rénovation énergétique

Si pas de travaux de rénovation énergétique

22) Prévoyez-vous de faire des travaux de rénovation énergétique dans les deux prochaines années ?

Oui, changement de système de chauffage

Oui, isolation thermique des murs

Oui, isolation thermique des combles/toit

Oui, isolation du sol

Oui, isolation des fenêtres

Oui, énergie renouvelable

Oui, autre

Je ne sais pas

Non

Si « Non » → questions suivantes 23, 24, 25 ; Si autre que « Non » → question 26

23) Si non, pourquoi n'avez-vous pas réalisé de travaux de rénovation énergétique ? Raison principale (un choix possible)

Je suis satisfait de mon état actuel

Le logement est neuf

Ce type d'investissement n'est pas dans mes priorités et préférences

Sujet techniquement trop complexe

Cela m'intéresse mais l'investissement nécessaire est trop élevé

Cela m'intéresse mais c'est impossible compte tenu du contexte légal (copropriété, code urbanistique, *etc.*)
Cela m'intéresse mais je ne suis pas certain que les gains financiers suivent
Cela m'intéresse mais je n'ai pas confiance en la qualité des travaux réalisés
Cela m'intéresse mais le dérangement occasionné est trop important
Déménagement prochain
Je ne suis pas sûr que la rénovation énergétique de mon logement soit valorisée dans le cas d'une vente
Autre

24) Freins secondaires (plusieurs choix possibles)

Je suis satisfait de mon état actuel
Le logement est neuf
Ce type d'investissement n'est pas dans mes priorités et préférences
Sujet techniquement trop complexe
Cela m'intéresse mais l'investissement nécessaire est trop élevé
Cela m'intéresse mais c'est impossible compte tenu du contexte légal (copropriété, code urbanistique, *etc.*)
Cela m'intéresse mais je ne suis pas certain que les gains financiers suivent
Cela m'intéresse mais je n'ai pas confiance en la qualité des travaux réalisés
Cela m'intéresse mais le dérangement occasionné est trop important
Déménagement prochain
Je ne suis pas sûr que la rénovation énergétique de mon logement soit valorisée dans le cas d'une vente
Autre

25) Quels sont les éléments principaux qui pourraient vous faire changer d'avis ? (plusieurs choix possibles)

A l'occasion de la réalisation d'autres types de travaux, je pourrais envisager les travaux de rénovation énergétique (mutualisation des coûts et gêne)
La meilleure reconnaissance de la valeur patrimoniale de la performance énergétique du logement
De l'information personnalisée : par exemple, les conseils d'un expert objectif pour la réalisation de mes travaux
La garantie de la réalisation des gains économiques prévus au moment de la décision de rénovation énergétique
Des aides publiques plus facilement accessibles
L'augmentation importante prévue du prix de l'énergie dans les futures années

Un système de financement des travaux plus souple. Par exemple : emprunt et tiers financeur qui se rembourse sur les économies d'énergie réalisées

Aucune de ces raisons

Rien

A tous

Section 1 bis : Situation financière

Les informations financières demandées ne seront utilisées qu'à des fins de recherche dans le cadre d'une étude sur la réalisation de travaux de rénovation énergétique et seront traitées de façon complètement anonyme ; elles permettront de reconstituer une information sur le portfolio type du ménage occupant, merci de contribuer à notre travail !

26) Quel est le revenu mensuel net de votre ménage ? (y compris les salaires nets, allocations familiales, pensions et autres revenus, en euros)

XXXXX numérique

Fin pour tous

C. Appendices to Chapter 3

a. Data definitions and sources

Variable	Definition	Source and file name	Link
Electricity consumption	Final residential electricity consumption, measured in gigawatt-hour	Eurostat nrg_cb_e	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_cb_e&lang=en
Heating Degree Days	Weather-based technical index designed to describe the need for the heating energy requirements of buildings, presented as Celsius temperature sums	Eurostat nrg_chdd_a	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_chdd_a&lang=en
GDP per capita	Measured in constant 2015 euro	Eurostat nama_10_pc	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_pc&lang=en
Population density	People per sq. km of land area	World Bank	https://data.worldbank.org/indicator/EN.POP.DNST
Electricity price	Bi-annual electricity prices for domestic consumers, averaged by year, expressed in euro per kilowatt-hour	Eurostat nrg_pc_204 nrg_pc_204_h	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204&lang=en https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204_h&lang=en
Household Consumer Price Index	Measures the change over time of the prices of consumer goods and services acquired by households, 2015 as the base year	Eurostat prc_hicp_aind	http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=prc_hicp_aind&lang=en

b. Summary statistics by year for the retained sample (391 observations)

Year	Variable	Mean	Standard deviation	Minimum	Maximum
1996	Electricity consumption	36,698.88	43,065.81	661.00	134,151.00
	Heating Degree Days	3,326.35	1,243.57	1,239.35	5,902.72
	GDP per capita	2,4981.76	11,124.25	6,780.00	56,440.00
	Population density	149.31	114.86	16.82	460.03
	Electricity price	8.23	3.21	1.26	14.21
1997	Electricity consumption	36,357.06	42,138.37	634.00	130,812.00
	Heating Degree Days	2,951.02	1,205.34	894.85	5,760.89
	GDP per capita	25,909.41	11,543.87	7,010.00	58,890.00
	Population density	149.88	115.39	16.87	462.40
	Electricity price	8.61	3.11	2.12	15.49
1998	Electricity consumption	37,161.53	4,3055.38	659.00	130,476.00
	Heating Degree Days	3,001.07	1234.70	1,137.47	6,007.49
	GDP per capita	26,855.29	12,031.53	7,300.00	61,670.00
	Population density	150.45	116.00	16.92	465.26
	Electricity price	8.81	3.12	2.52	15.90
1999	Electricity consumption	37,834.41	43,697.78	659.00	131,281.00
	Heating Degree Days	2,898.03	1,136.24	1,272.09	5,640.79
	GDP per capita	27,967.06	12,840.20	7,540.00	65,950.00
	Population density	151.07	116.66	16.96	468.37
	Electricity price	8.88	3.08	3.071	15.19
2000	Electricity consumption	38,118.31	43,912.64	792.33	130,500.00
	Heating Degree Days	2,768.04	1,034.34	1,258.81	5,228.63
	GDP per capita	29,200.59	13,717.52	7,900.00	70,460.00
	Population density	151.81	117.34	16.99	471.73
	Electricity price	9.24	3.10	3.51	15.19
2001	Electricity consumption	39,521.07	45,324.78	801.25	134,000.00
	Heating Degree Days	2,975.93	1,184.54	1,247.77	5,761.11
	GDP per capita	29,726.47	13,823.48	8,240.00	71,440.00
	Population density	152.56	118.03	17.03	475.30
	Electricity price	9.74	3.20	4.06	16.25
2002	Electricity consumption	39,980.38	45,353.18	808.46	136,500.00
	Heating Degree Days	2,816.28	1,168.30	1,152.61	5,738.01
	GDP per capita	30,167.06	14,122.46	8,660.00	73,380.00
	Population density	153.31	118.65	17.07	478.35
	Electricity price	10.23	3.20	4.69	17.43

2003	Electricity consumption	41,760.96	47,649.61	822.38	141,554.00
	Heating Degree Days	2,959.49	1,130.97	1,240.37	5,671.74
	GDP per capita	30,442.94	14,094.06	9,040.00	73,650.00
	Population density	154.05	119.14	17.11	480.61
	Electricity price	10.87	3.31	5.00	18.29
2004	Electricity consumption	42,400.22	48,238.96	838.77	143,380.00
	Heating Degree Days	2,983.20	1,107.41	1,348.00	5,558.62
	GDP per capita	31,242.35	14,402.75	9,490.00	75,270.00
	Population density	154.83	119.55	17.16	482.28
	Electricity price	11.36	3.22	6.66	18.50
2005	Electricity consumption	42,657.73	47,973.30	845.09	141,300.00
	Heating Degree Days	2,967.12	1,045.76	1,342.27	5,309.79
	GDP per capita	31,809.41	14,656.26	9,910.00	76,460.00
	Population density	155.64	119.89	17.22	483.41
	Electricity price	11.99	3.44	7.46	19.17
2006	Electricity consumption	43,149.02	48,657.42	830.99	143,327.00
	Heating Degree Days	2,848.80	1,083.19	1,185.33	5,459.06
	GDP per capita	32,800.00	15,172.37	10,330.00	79,190.00
	Population density	156.47	120.20	17.32	484.19
	Electricity price	12.77	3.71	7.18	20.44
2007	Electricity consumption	42,732.79	48,100.13	843.57	141,589.00
	Heating Degree Days	2,736.21	1,075.36	1,241.43	5,334.62
	GDP per capita	33,826.47	16,147.66	10,370.00	84,420.00
	Population density	157.38	120.58	17.39	485.24
	Electricity price	14.09	3.78	8.83	21.13
2008	Electricity consumption	43,176.29	49,285.64	776.43	152,652.00
	Heating Degree Days	2,851.54	1,070.38	1,273.66	5,350.86
	GDP per capita	33,520.59	15,543.21	10,500.00	81,880.00
	Population density	158.34	121.19	17.48	487.13
	Electricity price	15.26	3.99	10.04	24.72
2009	Electricity consumption	43,266.58	48,644.70	904.45	149,032.00
	Heating Degree Days	2,884.11	1,158.98	1,151.28	5,619.86
	GDP per capita	31,755.88	14,601.03	9,810.00	76,900.00
	Population density	159.22	122.04	17.57	490.08
	Electricity price	15.71	3.74	10.36	24.20
2010	Electricity consumption	44,936.33	50,789.47	815.16	161,520.00
	Heating Degree Days	3,279.93	1,323.73	1,293.97	6,190.94
	GDP per capita	32,312.94	15,164.32	9,900.00	79,160.00
	Population density	160.07	122.91	17.65	492.60
	Electricity price	16.39	3.62	11.87	25.30

2011	Electricity consumption	42,894.42	47,566.86	851.62	146,269.60
	Heating Degree Days	2,744.52	1,062.61	1,092.56	5,233.56
	GDP per capita	32,531.76	15,367.82	10,110.00	79,310.00
	Population density	160.77	123.82	17.73	495.05
	Electricity price	17.87	4.09	12.73	28.42
2012	Electricity consumption	43,895.67	49,460.22	916.49	158,184.20
	Heating Degree Days	2,992.14	1,181.75	1,347.63	5,855.40
	GDP per capita	32,080.59	15,136.01	1,0010.00	77,240.00
	Population density	161.62	124.56	17.82	496.89
	Electricity price	19.33	4.25	14.22	29.52
2013	Electricity consumption	43,660.11	50,275.33	979.40	166,129.60
	Heating Degree Days	2,991.89	1,073.01	1,339.36	5,274.05
	GDP per capita	32,070.00	15,339.40	10,230.00	78,030.00
	Population density	162.44	125.34	17.90	498.80
	Electricity price	20.07	4.51	13.60	29.50
2014	Electricity consumption	41,422.69	46,555.78	1,011.25	149,021.30
	Heating Degree Days	2,570.16	1,082.18	1,146.46	5,244.71
	GDP per capita	32,595.88	15,628.28	10,690.00	79,490.00
	Population density	163.31	126.11	17.97	500.59
	Electricity price	20.35	4.84	11.73	30.32
2015	Electricity consumption	41,964.94	47,357.81	989.69	155,430.90
	Heating Degree Days	2,763.05	1,032.65	1,075.56	5,032.28
	GDP per capita	33,653.53	16,361.78	11,130.00	81,300.00
	Population density	164.26	126.99	18.03	502.82
	Electricity price	20.69	4.96	11.36	30.55
2016	Electricity consumption	42,591.61	47,937.98	976.49	161,164.30
	Heating Degree Days	2,831.53	1,092.00	1,237.10	5,337.55
	GDP per capita	34,225.29	16,680.57	11,410.00	82,880.00
	Population density	165.19	127.87	18.08	505.50
	Electricity price	20.51	5.29	11.25	30.86
2017	Electricity consumption	42,472.60	47,545.38	970.46	159,206.60
	Heating Degree Days	2,821.11	1,142.81	1,054.56	5,524.31
	GDP per capita	34,970.59	16,727.79	11,930.00	82,550.00
	Population density	166.09	128.77	18.12	508.50
	Electricity price	20.71	5.59	11.62	31.12
2018	Electricity consumption	42,485.33	47,575.33	930.64	158,330.10
	Heating Degree Days	2,731.28	1,100.12	1,304.61	5,363.53
	GDP per capita	35,701.76	17,066.61	12,560.00	83,470.00
	Population density	166.93	129.63	18.15	511.48
	Electricity price	14.49	6.10	1.26	31.81

c. Scatter plot matrices for log-transformations of variables