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Exploring the Cost-Effectiveness of Energy Efficiency Implementation Measures in the Residential Sector

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Abstract

This research investigates the cost-effectiveness of energy performance measures in French residential buildings. We develop an empirical approach based on a multivariate statistical approach and Cost-Benefit analysis. The strength of this research relies on the designing of a large [cross-sectional](#) database [collected in 2013](#) including rich technical information of about 1,400 dwellings representative of the French residential sector as well as individual recommendations relative to the energy renovations to be implemented, their investment costs, and energy savings potential. We provide valuable information on the cost-effectiveness of energy renovation measures for the entire housing stock. Results show that low-temperature and condensing boilers, as well as floor insulation, are the most cost-effective energy efficiency measures, which could be inconsistent with actual subsidy policies. We demonstrate that the cost-effectiveness of energy renovation measures is widely dependent on dwelling initial characteristics and the value of the inputs used in the economic indicators such as energy-savings amount, energy price, and the discount rate. Moreover, we provide a classification of French dwellings, which may help policymakers, better identify their target. Finally, we show that the renovation of the entire French residential dwelling stock can lead to a great amount of energy–and CO₂–reductions but requires significant financial capacity.

Keywords: Energy Efficiency; Cost-Benefit analysis; Energy demand; Multiple correspondence analysis; Monte Carlo simulation; Energy policy.

1. Introduction

The building sector is one of the largest energy-consuming sectors, accounting for up to 20.1% of the total delivered energy consumed worldwide (International Energy Outlook, 2016). It would contribute up to one-third of global annual greenhouse gas emissions. In the last decade, the International Energy Agency highlighted that building design and the renovation of existing dwellings would have the highest untapped energy savings potential (about 80% of the energy savings potential of energy efficiency in buildings would be untapped). This is particularly true in Western Europe where a great amount of energy savings could be achieved thanks to the renovation of the existing building stock. In 2014 in France, the residential sector accounted for 30% of the final energy consumption; otherwise, 60% of the dwelling stock belonged to an energy class equal or inferior to D (according to Energy Performance Certificates), which corresponded to final energy consumption from 150 to 230 kWh/m²/year (Commissariat Général au Développement Durable, 2015).

For several decades, thermal regulations have been implemented in compliance with the European framework as well as financial incentives to support private investment in order to improve the energy efficiency of new residential and tertiary buildings. Today, with respect to the actual trends, national and international goals regarding energy efficiency and final energy consumption are not at reach. According to a 2019 European Commission report, “if the increasing trend in energy consumption observed since 2014 continues in the coming years, reaching the 2020 target both for primary and final energy consumption could be at risk; therefore, there is a need to further intensify efforts to deliver energy savings in the short term”. In France, despite a large number of energy efficiency measures, the energy-saving targets are still far below the objectives. According to climate-corrected data, CO₂ emissions from residential-tertiary buildings fell by 12% between 1990 and 2014, whereas the target for 2050 is a reduction of at least 75% (Commissariat Général au Développement Durable, 2015).

Over the same period, energy consumption increased by 17% and has only just begun to decline since 2012, whereas the objective is to reduce it by around 50% by 2050 (Plan Bâtiment Durable, 2017).

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. Therefore, estimating the cost-effectiveness of energy efficiency measures for the French residential sector would provide key information to public decision-makers in order to design and promote properly efficient energy retrofit policies.

The present research aims at assessing the cost-effectiveness of energy-efficient solutions for the whole French residential sector by taking into account both the influence of the dwelling stock heterogeneity and the variability of external parameters on the profitability of energy efficiency measures. This study is carried out in 2019. It owes its originality to the creation of an innovative database collected in 2013. The designed database includes rich technical information about 1,400 dwellings representative of the French residential sector as well as individual recommendations relative to the energy retrofits to be implemented, their investment costs, and energy savings potential. The economic analysis of this original database provides turnkey information to policymakers regarding (i) the target of their policies via Multiple Correspondence Analysis in order to identify the least efficient dwelling to renovate in priority; (ii) the cost-effectiveness of energy measures in the French residential sector with a focus on the robustness of the results to several criteria, that is to say considering dwelling heterogeneity and uncertainty of external parameters; and (iii) the amount of energy–and CO₂–savings that could be effectively achieved through the massive implementation of energy efficiency measures as well as the costs that will be incurred by the households.

Results show that low-temperature and condensing boilers, as well as floor insulation, are the most cost-effective energy measures to be implemented in the residential dwelling stock, which could be inconsistent with actual subsidy policies. Moreover, we demonstrate that the cost-effectiveness of renovation solutions is widely dependent on dwelling initial characteristics and the value of the inputs used in the economic indicators. For instance, a small variation in the energy-savings amount, energy price, and discount rate can influence the Net Present Value (NPV) of energy retrofits. Additionally, our classification of the existent building stock yields four distinct clusters, enabling policymakers to better identify their target. The main cluster concerns large individual houses built before any thermic regulation, i.e. before 1970, having a very poor energy efficiency and representing 30% of the current dwelling stock. Finally, we show that the renovation of the entire French residential dwelling stock can lead to a great amount of energy–and CO₂–savings but requires significant financial capacity. Energy policy strategies need to be adapted to foster a high volume of energy retrofits in the residential sector.

This paper is organized as follows. [Section 2](#) provides an overview of energy efficiency policies in France and Europe; [Section 3](#) explores the existing literature about energy renovation solutions by listing the different economic indicators to tackle this issue and discussing the limits of previous studies; [Section 4](#) focuses on the construction of the database and gives some summary statistics; [Section 5](#) introduces the methodology for the Multiple Correspondence and Cost-Benefit Analyses and Monte Carlo simulation as a sensitivity analysis; [Section 6](#) gives the empirical results; [Section 7](#) analyses the potential retrofit of all French dwellings and discusses the resulting implications for public policies; finally, [Section 8](#) concludes.

2. Overview of Energy Efficiency Policies in France and Europe

In France, various incentives and regulatory schemes have been designed to stimulate energy renovation work. The main incentive schemes are the following: (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 in 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 Grenelle Environment Forum, which is a zero-rate loan with no resource conditions to finance a coherent set of energy performance improvement works; 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 a requirement to increase energy efficiency by at least 25%.

On a larger scale, the European Union 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) (European Commission, 2020a). 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 the existing building 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 in the EU countries (European Commission, 2020b). Secondly, the EED, designed in 2012 and revised in 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 the efforts

required to meet the 2020 targets (European Commission, 2020c). Both directives confirm the prominent role of the building sector in achieving the Union'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 1 gives the big picture of the main achievements of efficiency energy programs in the EU.

[Insert Figure 1 here]

Nevertheless, energy efficiency investments in the residential sector seem to lag behind public policy objectives set in several European countries. The issue of understanding why investments in energy efficiency in the building sector remain low, despite the cost-effectiveness and the availability of energy efficiency solutions, has received a 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 paradox (Jaffe and Stavins, 1994; Gerarden et al., 2015; Fowlie et al., 2018). Nevertheless, discussing this topic is beyond the scope of this paper.

3. Literature Review

In the residential sector, in which households are the main actors of the decision-making process regarding the implementation of energy-efficient technologies (see Figure 2 below (Bardhan et al., 2014)), the cost of energy renovation solutions is often quoted as one of the barriers to action at private scale. McCoy and Kotsch (2018) recently demonstrated that, in the UK, energy-saving benefits coming from the implementation of energy efficiency

investments would be lower than expected depending on dwelling and household characteristics, which could question the real profitability of such investments. Further, using experimental and quasi-experimental research design based upon a sample of approximately 30,000 Michigan households that were presumptively eligible for participation in WAP, which is the USA's largest residential energy efficiency program, Fowlie et al. (2018) demonstrated that the aggressive encouragement efforts were disappointing. The results also suggest that the upfront investment costs are about twice the actual energy savings. The model-projected savings are more than three times the actual savings. This calls for further research to explore whether the real-world benefits to investment in energy efficiency deviate so hugely from engineering estimations in other contexts.

[Insert Figure 2 here]

The proposed study relates to three strands of research, at least. The first strand relates to the studies focusing specifically on residential energy consumption. This topic is often studied in parallel with the life cycle theory (Fritzsche, 1981; Lévy et al., 2014). Analyzing the impact of household and housing attributes on residential energy consumption patterns is also at the core of lots of studies (Belaïd, 2016; Belaïd et al., 2019). Alternatively, Bernard et al. (1987) study the energy mix and energy sources in the residential sector. Lastly, the role of habits is studied by Maréchal and Lazaric in 2010. They found that habits have a crucial role in explaining the energy paradox. Interestingly, this study, in particular, is halfway between this strand of research and the next one.

Second, there is another strand of research which is mainly composed of studies outlining the effect of individual preferences for energy-saving behavior and energy-efficient solutions. Via a business model, Kendel and Lazaric (2015) study the potential energy savings through the implementation of smart meters in order to test behavioral change. They 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. Besides, Kendel et al. (2017) provide results showing 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. Additionally, the roles of environmental concern and comfort expectations in the decision to retrofit a dwelling are investigated by Galassi and Madlener (2017). Their findings suggest that thermal comfort preferences are heterogeneous and that air quality is the most important attribute in the decision of retrofitting. Last but not least, a recently published article by Belaïd and Joumni (2020) underlines, in particular, the fluctuations of household energy-saving behavior throughout time.

Finally, there is a growing body of research on the Cost-Benefit Analysis of energy efficiency measures. For a decade, the energy-engineering and economics literature has paid growing attention to Cost-Benefit Analyses of energy retrofit solutions for buildings in order to provide relevant information to decision-makers and propose decision-support tools. These studies cover both the residential and tertiary sectors at different scales of analysis: at the microscale (building or housing scale) and macro-level (*e.g.* national or regional building stock). Based mostly on case studies, the literature review shows that the cost-effectiveness of energy efficiency measures is found to be dependent on several factors such as the characteristics of the building and external parameters that could influence the profitability of the energy measure. Table 1 gathers and details the most recent studies. Most of them are case studies applied to one building (residential or office buildings mostly) using real data. Others consider general methodologies that can be transferred to other renovation projects.

[Insert Table 1 here]

Previous literature demonstrates that the profitability of energy efficiency solutions for buildings seems to be extremely dependent on contextual and economic conditions: cost-effectiveness measures are found to be very sensitive to the variability of economic parameters such as energy price, the discount rate, etc. (Kumbaroğlu and Madlener, 2012; Luddeni et al., 2018; Friedman et al., 2014). Otherwise, initial building conditions and characteristics (initial energy consumption, climate, surface, etc.) are also found to play an important role. For instance, depending on the case study, the cost-effectiveness of some energy measures can vary significantly with buildings characteristics.

However, the current literature shows several shortcomings. Firstly, the literature often discusses the difficulty to account for other benefits than energy-savings in cost-effectiveness measures. Comfort improvement, an extension of building lifespan, improvement of property value, or rental fees of existing buildings are benefits of energy efficiency renovations widely acknowledged (Liu et al., 2018), but rarely accounted for. For instance, in the residential sector, the rebound effect could reduce the energy-saving potential of up to 60% (Belaïd et al., 2018) but is never included in the Cost-Benefit Analyses (Rakhshan and Friess, 2017). However, this could influence drastically the direct profitability of energy efficiency solutions. Secondly, the literature does not study the impact of dwellings heterogeneity on the profitability of energy measures (Gerarden et al., 2015), which could be a key insight for policymaking. Finally, the influence of the potential uncertainty regarding the inputs of the cost-benefit measure used to assess cost-effectiveness is rarely accounted for.

4. The Database

4.1 Strategy, Objectives, and Construction of the Database

The present research aims at assessing the cost-effectiveness of energy-efficient solutions for the whole French residential sector by considering the influence of the dwelling stock heterogeneity and the variability of economic parameters on the profitability of energy

efficiency measures. The first step is dedicated to building an innovative database gathering precise technical information about dwelling initial real energy consumption, individual energy rate, energy measures recommendations from experts based on an energy audit, real costs, and energy savings potential associated with each energy measure – all for more than 1,400 dwellings of the French residential sector. The second step is to design a typology of all these dwellings in order to better identify their strengths and weaknesses in terms of energy efficiency. Then, thanks to different economic indicators, we calculate (i) the average cost-effectiveness of each energy retrofit measure and provide (ii) a ranking of energy renovation measures, according to their economic interests. We also obtain (iii) the distribution of Net Present Values for the whole residential dwelling stock for each energy retrofit measure. The third step is to assess the robustness of cost-effectiveness indicators through a sensitivity analysis. Finally, in order to provide key elements to policymakers, we estimate (iv) the energy and environmental gains and the costs as a result of the implementation of a global energy renovation strategy.

To conduct the Cost-Benefits Analysis of energy efficiency solutions for the French residential dwelling stock, we need a complete database including both technical information about dwellings of the stock and energy efficiency solutions to be implemented, current energy consumptions, and economic data about energy retrofits and energy costs. As no database includes all this information at once, we aggregate several data sources to design one final consolidated database. Steps to construct the database used in our analysis are summarized in Figure 3 below and described more in detail after.

[Insert Figure 3 here]

Step 1: The Phebus database as a starting sample

Our final database uses the most recent Phebus survey sample from 2013 as initial input. The Phebus survey is punctually conducted by the Department of Observations and

Statistics (SOeS) of the French Ministry of Ecology and Sustainable Development. It is an official detailed cross-sectional survey that gathers approximately 2,000 dwellings representative of French housing units. Phebus gives us access to detailed information about technical characteristics of these dwellings (among them are energy characteristics, [their surface](#), [year of construction](#)), socio-economic information about occupants, final energy consumption in kWh, energy bill, and details concerning energy sources, etc. The Phebus database also provides an Energy Performance Certificate for each dwelling, including an energy label (from A to C, according to the level of energy performance) [and information about the work carried out](#). However, since some of this work is not energy retrofits, the corresponding dwellings are discarded, resulting in a final data set of about 1,400 observations.

Step 2: Extraction of individual energy retrofits recommendations carried out as part of the Phebus survey and matching with the initial sample

For each dwelling from the Phebus database, an energy performance diagnosis was carried out by experts within the framework of the survey. This diagnosis ends with recommendations on the energy retrofits to be carried out in order to achieve significant energy gains. These recommendations, available in the technical files of the Phebus survey are extracted, homogenized, and matched with the dwellings in our initial database. Thus, for each dwelling in the database, we have both information on their actual characteristics and the energy renovation operations recommended by the experts based on an energy audit.

Step 3: Identification and aggregation of data about average costs and energy benefits of energy retrofits from the ANAH database

The Phebus database does not include detailed information about economic data and energy-savings potential associated with the recommended energy retrofit measures. However, this information is necessary for the Cost-Benefit Analysis on the residential stock

scale. To address this issue, we use the information available in the ANAH database provided by the ANAH (Agence Nationale de l'Habitat, [the French National Housing Agency](#)) as part of the “Live Better” program (“Habiter Mieux”). [Including 1,206 dwellings](#), it contains information about: (i) the dwelling and its occupants; (ii) the different energy retrofit solutions and efficient energy equipment: roof insulation, wall insulation, windows replacement, boiler replacement, etc; (iii) the results obtained from these energy efficiency retrofits, expressed in energy savings percentage; and (iv) the cost in euros of energy retrofit solutions. [From the ANAH database, Table 2 displays average investment costs \(euros per square meter\) for each of the energy renovation actions recommended and energy gains obtained by the implementation of each type of work \(expressed as a percentage of the initial energy consumption\). Finally, these costs and energy gains are matched to dwellings from the Phebus dataset according to the recommended energy retrofit solutions.](#)

[Insert Table 2 here]

Step 4: Calculation of individual costs and energy gains retrofit implementation

Based on the average investment costs of each of the energy efficiency solutions highlighted in the ANAH database (see Table 2), individual investment costs can be calculated for each of the dwellings according to the renovation solution recommended by experts as part of the Phebus survey. These individual investment costs depend on the surface area of the dwelling and the energy efficiency solution; thus, they are obtained by multiplying the average cost of investment (euros by square meter) by the surface of the dwelling when it is appropriate.

At the same time, monetarized energy gains are calculated for each dwelling according to the energy efficiency solution implemented. These gains are calculated on the basis of the household's total energy bill and the energy-saving potential of each of the energy efficiency solutions applied (potential estimated on the basis of the ANAH). We simply multiply the

final energy consumption of 2012 by the energy-saving potential and the energy tariff. At the end of this stage, we have a consolidated database of approximately 1,400 observations containing all the information necessary for the economic analysis of the various renovation solutions, in particular (i) the energy and technical characteristics of the dwellings (step 1); (ii) the energy renovation solutions recommended by experts for each of these homes (step 2); and (iii) the costs and energy savings associated with each of these solutions (steps 3 and 4).

Step 5: Conversion of energy gains into environmental gains

In the previous steps, we identified for each dwelling the monetary costs and energy gains resulting from the renovations suggested by the experts. Thus, we further convert energy savings into CO₂ emissions savings in order to assess the environmental impact of energy renovation strategies. According to the type of the main energy source of the dwelling, the carbon content varies; thus, we use several conversion ratios (see Appendix A 1).

Step 6: Conversion of energy gains into monetary gains

As the Cost-Benefit Analysis requires it, energy-saving potential gains must be expressed in euros. Thus, we need to convert the energy savings again but this time into monetary savings. To do so, we multiply the individual energy savings (kWh) (calculated in step 4) by the rate of energy (euros). In the Phebus database, information about the energy contracts subscribed by each household is available but not about the energy rate itself. To obtain an energy rate for each household, we calculate the mean energy rate (euros/kWh) by dividing the total household energy expenditure (expressed in euros) by the final energy consumption (kWh).

After these tedious steps and in addition to points (i), (ii) and (iii) aforementioned, we have for each dwelling (iv) environmental gains (step 5) and (v) monetary gains (step 6) resulting from each recommended energy renovation measure (step 2).

4.2 Overview of French Housing Stock Energy Performance

The latest Enquête Logement (ENL 2013) provided by the INSEE ([French National Institute of Statistics and Economic Studies](#)) indicates that the French dwelling stock is made of nearly 33,5 million dwellings of which 27,8 million are principal residencies. What follows is derived from the Phebus database collected by the SOeS in 2013 from a representative sample of the French dwelling stock. Table 3 displays the French dwelling stock by occupancy status (tenant of public housing, of private housing or owner) and energy class (from A to G).

[Insert Table 3 here]

Regardless of the occupancy status, the top-3 energy classes (A, B, and C) account for 14% of the total French dwelling stock whereas the worst three categories (E, F, and G) represent more than 60% of it. This underlines the relatively poor general state of the French dwelling stock. When comparing tenants between them, we observe that tenants of private housing are always worse off than tenants of public housing. Indeed, with the exception of dwellings of energy class A, less of tenants of private housing live in dwellings of the class B and C and more of them live in dwellings of the worst three energy classes. Additionally, on the right tail of the distribution, *i.e.* for energy-efficient dwellings, owners are better off than tenants, should these latter live in public or private housing. As a matter of fact, dwellings of a good energy class (A, B, and C) are in majority occupied by owners and not tenants. This goes hand in hand with previous research which shows that homeownership is a relevant predictor of energy conservation (Painter, et al., 1983; Black, et al., 1985) as homeowners are more energy conscious (Barr et al., 2005). Table 4 displays the distribution of the French dwelling stock across four construction periods.

[Insert Table 4 here]

The before 1948 construction period: Dwellings built during this period account for 31% of the French dwelling stock in 2013. This period corresponds to the wave of reconstruction

which followed World War II. These dwellings are relatively energy-efficient since they were built according to growing bioclimatic considerations. Note that estimating the class energy of dwellings built during this period was done from the available energy invoices and not from the building thermal simulation.

The 1949-1974 construction period: Dwellings built during this period now account for 30% of the French dwelling stock. Historically, this period corresponds to the Glorious Thirty, characterized by excellent economic growth in France. In this dynamic context, dwellings were built accordingly to the first industrial techniques, and before thermic regulations were even implemented. Consequently, they are categorized as the most energy-intensive ones.

The 1975-1999 construction period: As an answer to the oil shock which put an end to the Glorious Thirty, a first thermic regulation was implemented in France with an objective of a 25%-reduction in the heating consumption of the residential sector, achievable via external wall insulations and better air exchange systems. From 1989 to 1999, two additional thermic regulations were designed to support energy consumption reduction in the residential sector. They tackled the issue of hot water use notably. Consequently, dwellings built during this construction period are less energy-intensive than older ones. All in all, dwellings built during 1975 and 1999 now represent 29% of the French dwelling stock.

The after 2000 construction period: Two new thermic regulations were enacted: RT2000 and RT2005. Both measures go further in the energy consumption reduction in the housing sector and extend this goal to the tertiary sector. Two-thirds of the dwellings built during this construction period are of energy class D or E. However, the number of dwellings of energy class F or G experienced a sharp reduction which is satisfying.

Table 5 gives the main energy sources of French dwellings. The ranking is by far dominated by gas and electricity. As a matter of fact, gas occupies a prominent position as it is used by 38,5% of dwellings. It is followed by electricity which is used in nearly 35% of

dwellings. Fuel reaches the third position: it is used by nearly 16% of dwellings. Wood is the minority as only 6% of dwellings use it.

[Insert Table 5 here]

5. Methodology

First, this section develops the methodology for the Multiple Correspondence Analysis which seeks to classify the French dwelling stock, as it is crucial to better understand and characterize it before analyzing the cost-efficiency of energy efficiency solutions. Second, it introduces the methodology for the Cost-Benefit Analysis which seeks to identify the most efficient measures. [Finally, it motivates and explains the performed sensitivity analysis.](#)

5.1 Multivariate Statistical Approach

The analysis of the housing stock profiles is mainly used to have a picture of the French dwelling energy performance. Further, it helps to identify housing segments that are more in need of renovation. Initially, a Multiple Correspondence Analysis is carried out. Afterward, housing stock profiles are defined using the Ascending Hierarchical Classification.

The Multiple Correspondence Analysis is intimately linked to the Principal Component Analysis. The first one is a technique valid for nominal categorical data whereas the latter is valid for quantitative variables. The objectives of the Multiple Correspondence Analysis, and then by extension of the Principal Component Analysis, are several: (i) analyzing similarities between individuals, when variables have categories in common *e.g.*; (ii) synthesizing variables in a limited number of variables which are then called factors; and (iii) analyzing links and relationships between the different categories nominal variables can take (Benzécri, 1973).

Via Ascending Hierarchical Classification, we gather individuals, here dwellings, by computing pairwise distances between them. Thus, the closest dwellings are grouped in

classes that are themselves merged if they are close. The linkage criterion used is Ward's criterion which consists of grouping classes together until doing so brings too much inertia loss. This method results in a dendrogram which, in the end, represents a class hierarchy (Ward, 1963).

Below is the list of input variables for the Ascending Hierarchical Classification. Note that our goal is twofold here: we want to assess the relationships (i) between the energy efficiency of the French dwelling stock and the energy efficiency solutions that could be implemented on this stock, and (ii) between the potential energy gain of these solutions and their cost. As explained in [section 4.2](#), this information is provided for (i) by Phebus and (ii) by ANAH. Therefore, input variables must be common to both databases. They are given in Table 6 below, as well as their frequencies.

[Insert Table 6 here]

5.2 Cost-Benefit Analysis

The objectives of the Cost-Benefit Analysis are several: (i) sorting energy efficiency measures accordingly to their cost-effectiveness by taking into account dwelling heterogeneity;(ii) studying the robustness of the results with regard to the variability of external parameters (discount rate, energy price) but also of individual costs and gains; and (iii) assessing global cost and energy/environmental gains of retrofitting the French residential dwelling stock.

To study the relative cost-effectiveness of energy efficiency measures, we estimate all costs and benefits during a predetermined cycle project. To do so, we use three indicators: the Net Present Value, the Internal Profitability Rate, and the Rate of Return.

The Net Present Value (NPV) is the difference between the present value of cash inflows (the benefits) and the present value of cash outflow (the costs) over a period of time (here, the lifetime of the energy solution). This indicator includes the sum of yearly cash flows

evaluated in current money, which is accounted for by the use of a discount rate. On the one hand, a positive NPV indicates that the project benefits will exceed the project costs; on the other hand, a negative NPV indicates a net loss. An investment with a higher NPV is more profitable than an investment with a lower NPV. It is calculated as follows:

$$NPV(\tau) = -I_0 + \sum_{i=1}^{\tau} \left(\frac{CF, i}{(1 + d)^i} \right)$$

with τ the calculation period, I_0 the investment cost of the energy efficiency measure considered, CF, i the net cash flows of year i (it corresponds here to the energy-saving benefits for the year i expressed in euros), and d the discount rate.

The Internal Profitability Rate (IPR) equalizes the benefits to the costs of an investment. It corresponds to the profitability rate such as the NPV is equal to 0; thus, it measures the attractiveness of a project. If the IPR is superior to the discount rate, the project is profitable. It writes such that:

$$0 = -I_0 + \sum_{i=1}^{\tau} \left(\frac{CF, i}{(1 + IPR)^i} \right)$$

The Payback Period (PP) is one of the simplest investment appraisal techniques (Liu et al., 2018). This indicator evaluates how quickly the cost of an energy efficiency investment is recovered. It does not allow us to measure the profitability of the project and does not consider the time value of money. The lower it is, the better it is from a private perspective. Contrasting both NPV and PP is a good way to compare different projects based on the criterion of cost-effectiveness. To calculate the Payback Period indicator, simply divide the initial renovation cost by the annual energy gain as follows:

$$PP = \frac{\text{Initial investment}}{\text{Annual energy gain}}$$

In the Cost-Benefit Analysis, energy savings are considered as regular, and constant cash flows over time. Costs and gains used in the Cost-Benefits Analysis are calculated by averaging the individual costs and gains over the households to who it was recommended to implement the energy efficiency measure considered (see section 4.1 for more information about the calculation of these variables).

5.3 Sensitivity Analysis: Monte Carlo Simulation

We perform a sensitivity analysis to test the robustness of our results with respect to a variation of several external parameters that could affect the final investment profitability such as the discount rate and the lifespan of the energy retrofit measures. We believe that energy retrofit measures costs could vary according to local conditions of the energy retrofits market and that benefits could vary if there is a rebound effect or if the climate is more or less favorable for instance. Previous research already confirms our first belief. Indeed, on one hand, Stocker et al. (2015) show that energy prices, changes in the proportion of window areas, changes in the interest rate, price variation, and changes in the initial costs, most influence the cost of the renovation project. On the other hand, Ortiz et al. (2016) find that the variation of the energy price, the measure cost, and the interest rate have the greatest impact on the global cost of energy retrofit solutions (see Table 1).

Therefore, to investigate the sensitivity of our results, we perform a stochastic evaluation for each renovation solution using the Monte Carlo simulation. This approach allows us to describe the risk and uncertainty of variables that influence the profitability of the renovation measure, based on the profitability distribution. By doing so, we seek to determine the distribution of the NPV from the variables that affect project performance, resulting in a so-called expected NPV in what follows. In fact, at the beginning of the investment, we

ignore the exact value of input parameters. Nevertheless, by describing the interval and the possible values of each random variable, we can use simulation to generate the distribution of the resultant NPV of each renovation solution (Belaïd, 2011). The Monte Carlo simulation we conduct consists of a 3-step procedure:

- **Step 1:** we determine the distributions of each input parameter by (i) identifying the main risk factors, which happen to be here energy price, discount rate, and energy gain; and (ii) describing their distributions using the historical values.
- **Step 2:** we estimate the distribution of the output parameter, which is the NPV in our case, based on Monte Carlo simulation with 10,000 trials.
- **Step 3:** we record the results of the simulation, that is to say, derive the distribution of the expected NPV, and the variance for the profitability of each solution.

6. Results and discussion

6.1 Multiple Correspondence Analysis Results

Since we do not know a priori the number of clusters to be retained from the sample, we used hierarchical clustering methods to identify possible clustering solutions based on the Ward method, which minimizes variance within clusters. The main axes of the Multiple Correspondence Analysis retained for classification explain about 57% of the total variance. Besides, based on the “Elbow” method, the Ascending Hierarchical Classification algorithm of the Multiple Correspondence Analysis suggests keeping four dwelling classes, as the optimal number of clusters. As mentioned in section 5.1, this number is obtained applying Ward’s criterion, which consists of grouping classes together until it results in too great a loss of inertia. One of the results is the dendrogram which shows the progressive grouping of the data. This helps to gain an idea of a suitable number of classes. Our findings show the optimal number of clusters is four. Thus, it is not necessary to have a fifth class that brings little

additional inertia. The corresponding dendrogram is given in Appendix B. The four classes are characterized as follows (see Table 7 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 which indicates 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 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). Built considering all the existing thermic regulation, 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.

[Insert Table 7 here]

The Phebus database provides us with data on dwelling characteristics, energy performance as well as retrofit recommendations established by energy experts. For each dwelling, various recommendations are possible. Table 8 displays (i) in columns, the four most recommended solutions by class expressed in percentage of dwellings advised; and (ii) in lines, the share of dwellings to which energy efficiency solutions were recommended by energy efficiency solution. Percentages below each class category are a reminder of the share each class represents in the total French dwelling stock.

[Insert Table 8 here]

The condensing boiler is the most recommended energy efficiency solution across the total French dwelling stock: it is recommended to 35% of dwellings. In Class 2, nearly one dwelling out of two is advised to adopt this solution. Being suggested to 31% of dwellings in total, solar domestic hot water comes after and is by far recommended to dwellings of Class 3. Windows replacement and external wall insulation follow and are equally recommended. However, the latter is only recommended for Classes 1 and 2. Indeed, Class 3 dwellings are of intermediate energy efficiency. By consequence, recommendations are focused on dwellings suffering from poor and very poor energy efficiency, *i.e.* Classes 1 and 2 dwellings.

The last line of Table 8 also indicates that Class 2 accounts for 37% of recommendations alone which is undoubtedly linked with the definition of Class 2 itself: it gathers the least energy-efficient dwellings. Therefore, this class 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.

6.2 Cost-Benefit Analysis Results

In this section, we report the main results of the Cost-Benefit Analysis for all energy efficiency measures. In compliance with the European Commission recommendations¹, we assume that the discount rate is equal to 4% and the lifespan of energy efficiency solutions is of 30 years (European Commission, 2014).

We compute the average NPV (respectively the IPR) and the individual NPV distribution (respectively IPR distribution) for each solution.

[Insert Table 9 here]

[Insert Figure 4 here]

Table 9 and Figure 4 show that average NPVs range from -5 202€ to 8 790€. Since a higher and positive NPV indicates a more profitable energy renovation solution, we can affirm that the most profitable solutions are the condensing boiler, low-temperature boiler, and floor insulation. Moreover, windows replacement, wood equipment, internal wall, and roof insulation, hot and solar hot water are also profitable as they have a positive NPV. However, studying the NPV highlights the non-profitability of two energy efficiency retrofits: external wall insulation and heat pump system. The negative sign of the NPV associated with these two retrofit solutions comes from the fact that their IPR is less than the discount rate, equal to 4%. External wall insulation is also found to be non-attractive by Friedman et al. (2014) in Israel.

Figure 5 illustrates the position of energy efficiency solutions according to their average NPV on the x-axis and PP on the y-axis for a 4% discount rate and a 30-year lifespan. There is a tradeoff between these two indicators. Indeed, a high NPV is the sign of high profitability and a low PP indicates that cost will be recovered by benefits quickly. Therefore,

¹ According to Article 19 (Discounting of cash flows) of Commission Delegated Regulation (EU) No 480/2014, “the European Commission recommends that a 4 % discount rate in real terms is considered as the reference parameter for the real opportunity cost of capital in the long term” (European Commission, 2014).

the best solutions in terms of profitability are those positioned in the South-East dial of the graph.

[Insert Figure 5 here]

A glance at Figure 5 indicates that lots of energy efficiency solutions are packed together in the South-East dial. However, some stand out. If we consider solutions aiming at improving the insulation of the dwelling envelope, floor insulation and internal wall insulation are the most profitable solutions. Windows replacement also appears to be economically attractive which goes against Rakhshan and Friess (2017) since they find that windows replacement “are not financially viable” in Dubai. When it comes to the heating system, condensing and low-temperature boilers are recommended. Installing a solar hot water system is also economically relevant. Furthermore, roof insulation does have a positive NPV but the payback period of this project is 12.5 years, making it unattractive to most households. It is consistent with Friedman et al. (2014) in Israel and Rakhshan and Friess (2017) in Dubai. Finally, external wall insulation and the installation of a heat pump are the least profitable solutions as they display a negative average NPV and a relatively high payback period (26 and 23 years respectively).

So far, we focused on average NPV but the granularity of our data allows us to study the profitability of energy efficiency measures at the dwelling scale as well. Thus, Figure 6 gives the distribution of individual NPV for each energy efficiency retrofits with a discount rate of 4% and a lifespan of retrofits of 30 years. Analyzing these plots enables us to better assess the large disparity in the distribution of NPVs.

[Insert Figure 6 here]

What these plots suggest is that even if, on average, some energy efficiency measures are associated with a strictly positive average NPV, there are cases for which these solutions are not profitable. For instance, remember from Table 9 that windows replacement and internal wall insulation solutions have a positive NPV. However, looking at the corresponding plots in Figure 6 tells us that these two solutions are not profitable for some dwellings since the individual NPV might lie in a strictly negative interval. The opposite occurs as well: Table 9 indicates that external wall insulation solution has a negative average NPV whereas Figure 6 shows that it can be profitable for some dwellings since the distribution of individual NPVs is spread beyond 0. Finally, we notice that individual NPV remains quite scattered across the negatives and the positives. This is indeed the case for solutions such as low-temperature boiler, heat pump, and wall insulation. All in all, the variability in the distribution of individual NPVs for all solutions underlines the influence of changes in dwelling characteristics, costs, and other technical specificities. Rakhshan and Friess (2017) separate Dubai-based modern villas from traditional villas (the criterion is the year of construction) and find different results for each type of dwelling.

6.3 Monte Carlo Simulation Results

In this section, we present the main results of the Monte Carlo simulation analysis performed to examine the variability of the profitability of energy efficiency solutions. More precisely, this approach allows the integration of the investment risk by assessing the sensitivity of the economic output, *i.e.* the NPV, to the main economic inputs, including energy prices, discount rate, and energy gain. [We performed our cost-benefit analysis with a discount rate of 4% based on the recommendations of the European Commission.](#) However, [the sensitivity analysis performed using the Monte Carlo simulation allows us to test the sensitivity of the NPV and the risk associated with this assumption.](#)

We provide tornado charts to visually illustrate the sensitivity of our results. Tornado charts are a standard analysis tool allowing the investigation of the sensitivity of the results to a change in selected input factors. They display the effect of varying each input parameter at a time on the output, keeping all the other input factors constant (at their initial value). We also plot the distribution of the expected individual NPV. Figure 7 sums up the results for five energy efficiency solutions: low-temperature boiler, external and internal wall insulation, floor, and roof insulation.

[Insert Figure 7 here]

The existing literature indicates that the profitability of energy efficiency solutions for buildings is extremely dependent on contextual and economic conditions such as energy price, discount rate, etc., and to building and climate initial conditions. Here, tornado charts highlight that energy gain (in blue) is the largest driver of uncertainty about the mean of the output, namely the NPV of the implemented renovation solutions. This holds for four solutions out of five, the exception being internal wall insulation. Results also indicate that the discount rate (in green) and energy price (in yellow) have an impact on the NPV uncertainty but lower. Luddeni et al. (2018) support our claim on the discount rate. However, unlike in the present study, previous research shows that energy price, also referred to as energy cost, has a great impact on the profitability of energy retrofits. Indeed, (i) Kumbaroğlu and Madlener (2012) find that energy price changes “significantly affect the profitability of retrofit investments”; (ii) Guardigli et al. (2018) point out that the expected increase of energy price in the next future is one of the most important factors to determine the profitability of energy-efficiency retrofits; (iii) Liu et al. (2018) also find that energy price is the most sensitive factor; and (iv) Friedman et al. (2014) state that “a sustained increase in the cost of electricity (*i.e.* energy) of only 1% or 2% per year greatly improves the return on the investment”.

7. Energy Renovation of the Total French Dwelling Stock and Implication for the Policy-Making Process

In this section, we estimate the total cost of renovating the entire French housing stock as well as the resulting energy and environmental gains. Such estimation is relevant because energy renovation on a country-scale may confer benefits from three different perspectives. Firstly, the most obvious potential benefits of energy efficiency investments are environmental benefits. Having more energy-efficient buildings would drive down fossil fuel usage, leading to less greenhouse gas emissions (Patiño-Cambeiro et al., 2019), which is key to achieve the EU target of a decarbonized building stock by 2050. Lowering greenhouse gas 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 in France and imply a good potential for job creation. This could be especially beneficial considering high unemployment rates in the country (Saheb et al., 2018; Staniaszek et al., 2013). On a more macro-level, greater energy efficiency in European buildings could mean less energy dependence on other countries, which applies to the French case. Benefits would heavily outweigh the renovation costs (Patiño-Cambeiro et al., 2019). Finally, from a societal point of view, energy efficiency investment has 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 at the same time. On the other hand, energy efficiency investment fosters healthier environments since energy-efficient homes tend to be warmer and less moldy than energy inefficient homes and also have better air quality. With less sickening

environments, well-being will increase while encouraging economic growth (Grey et al., 2017).

Table 10 displays the results of this estimation displayed by class previously determined by the Ascending Hierarchical Classification. See Appendix A2 for formulas.

[Insert Table 10 here]

According to our hypothesis, results indicate that retrofitting the entire French dwelling stock would cost around 32 billion euros and allow energy gains of nearly 4.8 Mtoe. The government would also reduce CO₂ emissions by 31%; 15.3 Mton precisely. We saw in section 6.1 that Class 2 is the class grouping the least efficient dwellings, making them the main target of energy efficiency policies. Our estimates show that retrofitting all dwellings of Class 2 would cost 13.6 billion euros to households. Besides, this is for dwellings of Class 2 that retrofitting is the most beneficial in terms of environmental gain. Indeed, by doing so, the government would reduce CO₂ emissions by 7.74 Mton, which represents half of CO₂ emissions reduction that are attainable by retrofitting the total French dwelling stock.

We previously saw that the renovation of the entire French residential dwelling stock could lead to a great amount of energy- and CO₂- savings. Households would bear the costs of this renovation. In order to financially support households, the French government designed several measures. The first one is the Tax credit for energy transition (“Crédit d’impôts pour la transition énergétique”). Implemented in 2017, this tax credit depends on the income level of households and can be granted for energy retrofits. It is being progressively replaced by a new energy transition premium “MaPrimeRenov”. This grant is allowed by the ANAH to the lowest income households. Households can also benefit from very financially interesting loans. In France, a zero-rate eco-loan exists and is only granted if it is used to finance energy

retrofits. Thanks to the loan, households no longer have to pay the money in advance nor pay any interest. The loan amount can vary from 7,000 to 30,000 euros per household and depends on the size and the level of the renovation, *i.e.* deeper and larger is the renovation, higher is the loan (ADEME, 2020; Service Public, 2020).

For all policies aiming at fostering energy retrofits, works must be done by companies selected by the government. No specific energy efficiency measure is favored: all measures are equally suggested by the government. The only message the government suggests is that “it is usually more efficient to start isolating and ventilating your dwelling and then after to install efficient heating and hot water systems”. Our Cost-Benefit analysis indicates that low-temperature and condensing boilers, as well as floor insulation, are the most profitable energy efficiency solutions. Therefore, from a policy perspective, we reckon that policies should recommend these solutions first but more explicitly.

8. Conclusions and Policy Implications

This paper aims at providing a typology of the French dwelling stock via Multiple Correspondence Analysis. It also aims at assessing the cost-effectiveness of energy-efficient solutions for the whole French residential sector by considering both the influence of the dwelling stock heterogeneity and the variability of external parameters on the profitability of energy efficiency measures. Finally, it seeks to analyze these results in light of existing energy efficiency policies.

After identifying four dwelling classes among the French dwelling stock, we characterize the least energy-efficient dwellings: large individual houses built before 1948 having a high real energy consumption, resulting from their size and poor energy-efficiency. From the Cost-Benefit Analysis performed on the Phebus and ANAH databases, we can assert that most of the renovation operations are economically viable. More precisely, we find that

low-temperature and condensing boilers, as well as floor insulation, are the most cost-effective energy measures. Implementing these energy efficiency measures at a country scale may ensure a great potential in terms of energy-saving and environmental quality improvement. Besides, the Monte Carlo simulation highlights the importance of considering the variability of input factors in assessing the cost-effectiveness of the energy renovation solutions. Our results confirm that energy gain is the largest driver of the uncertainty of NPVs. The discount rate and energy prices also have a significant impact. From a policy perspective, the findings of this study and the proposed economic assessment approach have several potential policy implications that encourage the acceleration of existing building renovation process in France and beyond. These findings could contribute to estimating the total costs of energy renovation and the financing (public and private) needed to stimulate the energy renovation market in France. Results will also be helpful to understand the barriers to the large-scale implementation of energy renovation, and in the benchmark of the existing renovation business models.

The analysis undertaken does not aim to be exhaustive in policy implications terms, but rather to provide some information on the cost-effectiveness of energy renovation solutions implemented, bearing in mind that other factors may play important role in accelerating the renovation of the existing building stock (*e.g.*, behavioral, situational and contextual factors). Knowing that we also find that a small variation in the energy-savings amount, energy price, and discount rate can influence the profitability of energy retrofits, is uncertainty about cost-effectiveness a barrier to action? Indeed, Qiu et al. (2014) find that “policymakers [...] should consider the source of risk and take actions to mitigate the risk burdened by households”. Therefore, to foster energy renovation, further work will have to focus on behavioral and contextual issues. There should be a policy shift away from technically oriented efficiency programs towards a mixture of renovation and behavioral

change. In order to achieve high levels of energy savings, the government should design policies that support the improvement of the energy efficiency of existing dwellings and promote better flexibility within existing regulatory frameworks. Specifically, the role of individual environmental concern should be taken seriously and accounted for in the policy-making process. The recent development of “green nudges” makes them a promising tool to encourage households to adopt a more environment-friendly behavior, notably through the energy-efficient renovation of their homes. Environmental awareness must be taught, educated and goals must be set by assigning reduction targets to increase extrinsic motivation. Households must be financially supported by fiscal incentives and monetary rewards for those on the lowest incomes. Finally, all this must be made possible by increasing means and attenuating barriers in order to decrease uncertainty and increase opportunities for households in the fuel poverty trap.

Although the procedures used provide consistent results, for the most part, interpretations of the results ought to be treated with caution. Results and conclusions indeed depend on the dataset quality and the representativeness of renovation solutions implemented. Also, emphasizing the most economically promising energy renovation investment is not straightforward. Without a doubt, apart from cost-effectiveness computations, various real-world barriers have to be addressed to accelerate energy efficiency implementation across EU countries. Nevertheless, ignoring occupant heterogeneity, behavior, lifestyle, local market conditions may lead to the so-called “energy efficiency gap”, in which theoretically expected/optimal energy efficiency policies are more costly or less efficient when implemented.

Finally, the present study reaches its limits in that the Phebus dataset is a punctual survey. Indeed, the use of micro-level data provides us with richer information about household behavior and energy consumption, which is priceless. In the same vein and the

context of growing environmental concerns, it would be interesting to perform this study on more recent data and then to compare their evolution. We, therefore, recommend that the Phebus survey be conducted on a regular basis.

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Appendix

[Insert Appendix A1 here]

[Insert Appendix A2 here]

[Insert Appendix B here]

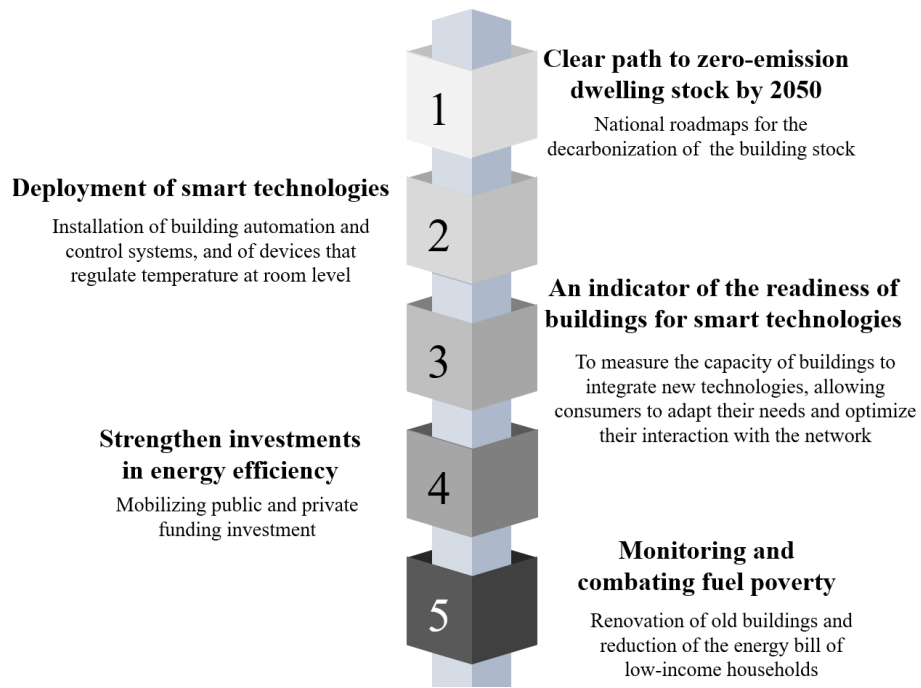


Figure 1: Main achievements of European Union energy efficiency programs

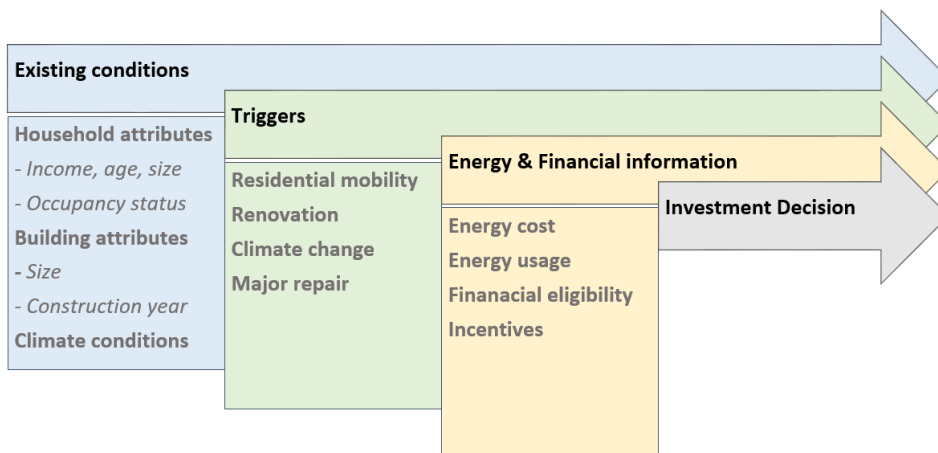


Figure 2: Residential energy efficiency investment decision process

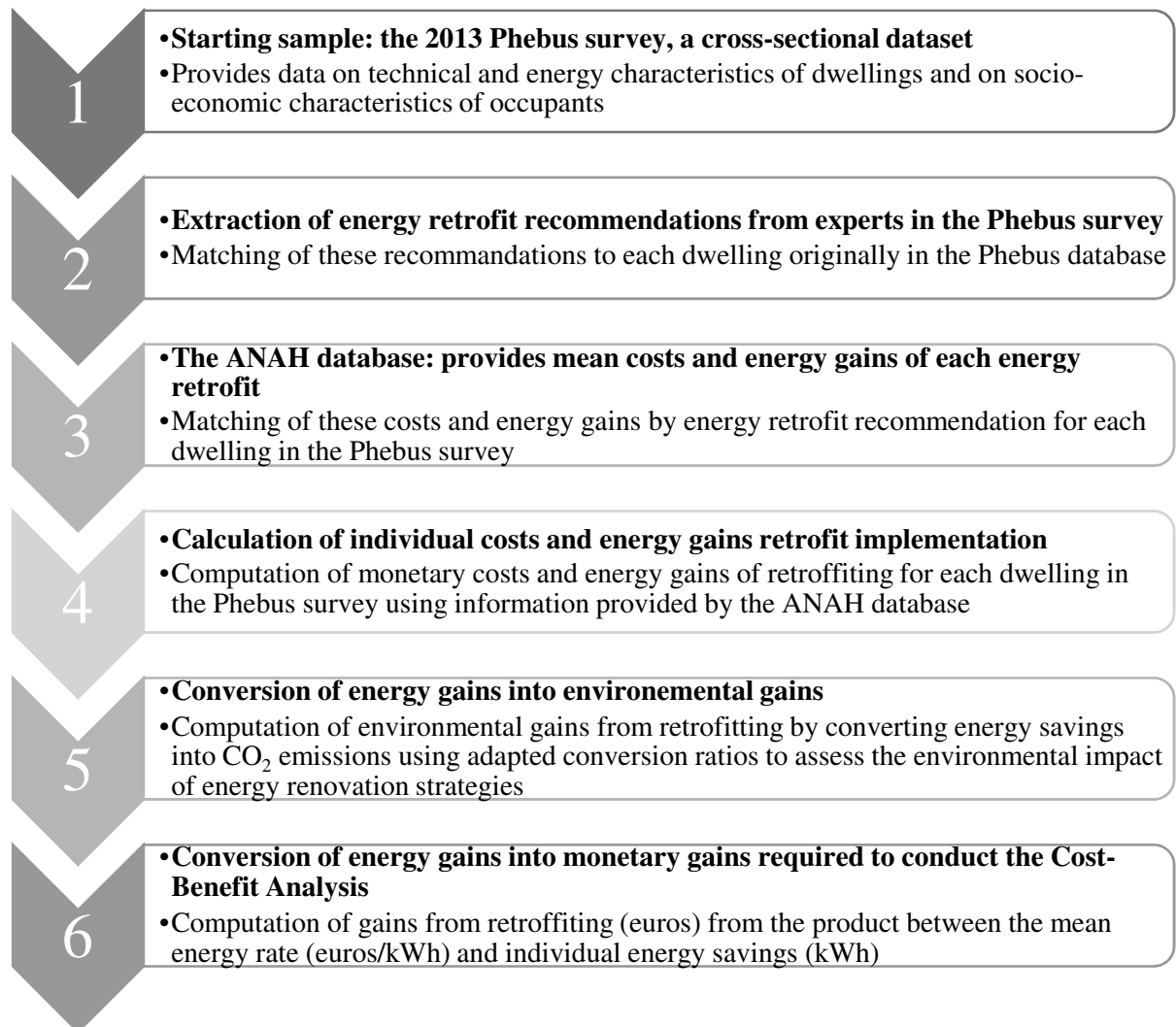


Figure 3: Main steps of the construction of the database

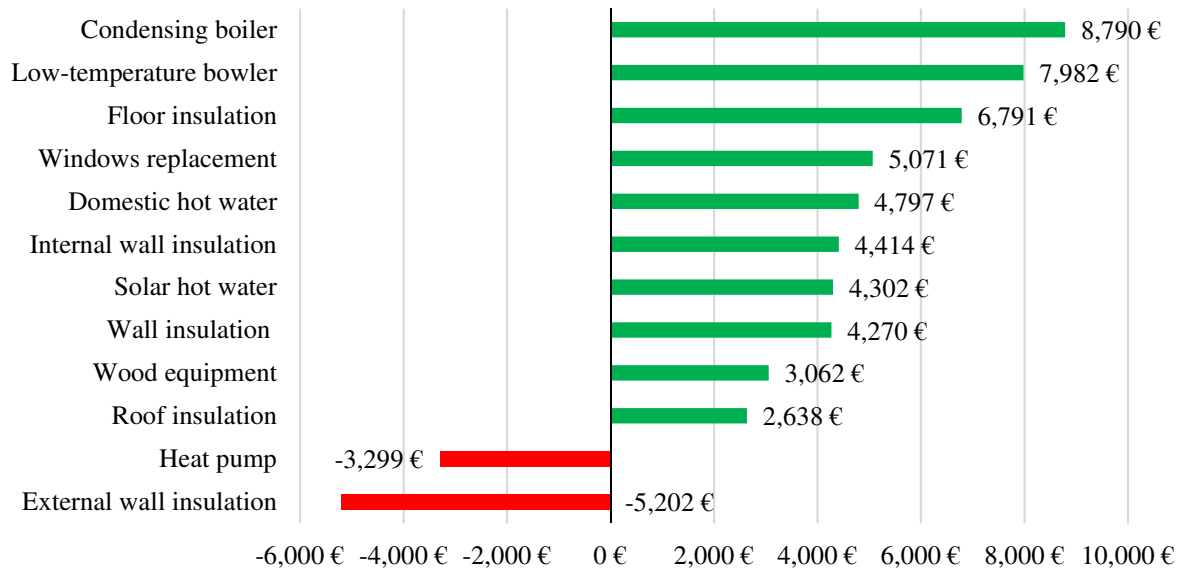


Figure 4: Ranking of the energy efficiency measures according to their NPV (4%-discount rate and 30-year lifespan)

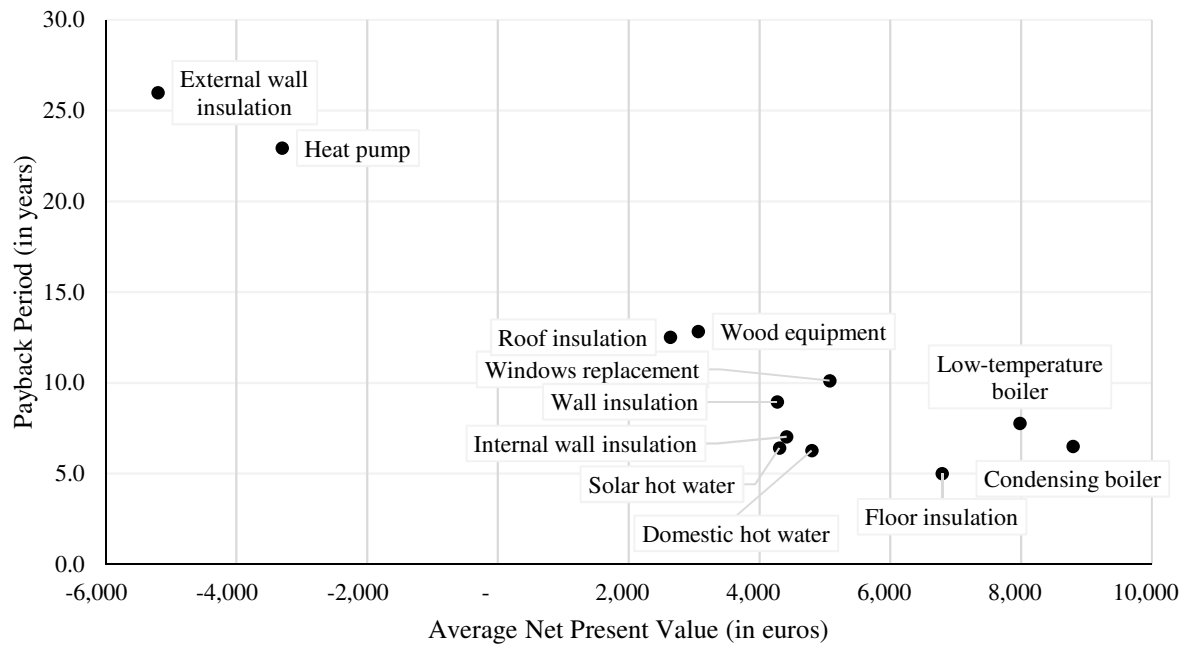
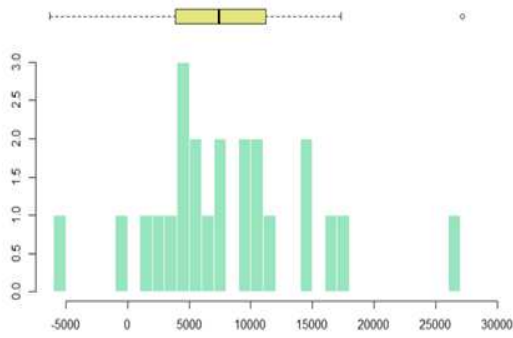
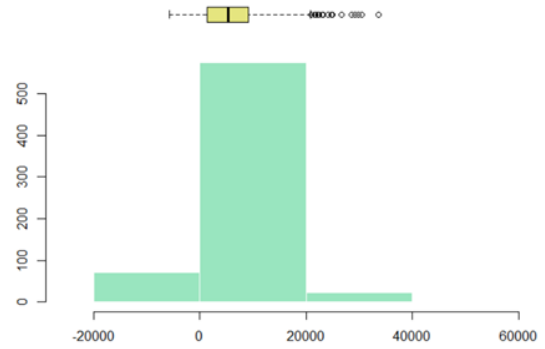


Figure 5: Distribution of solutions according to their average NPV and Payback Period (4%-discount rate and 30-year lifespan)

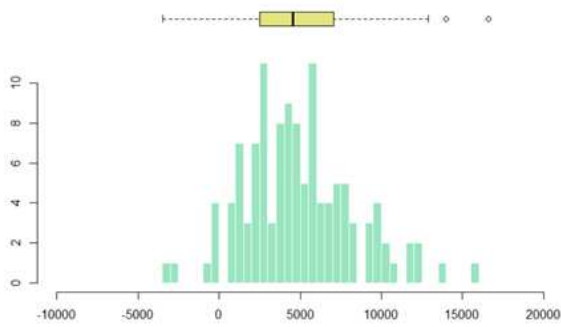
Low-temperature boiler



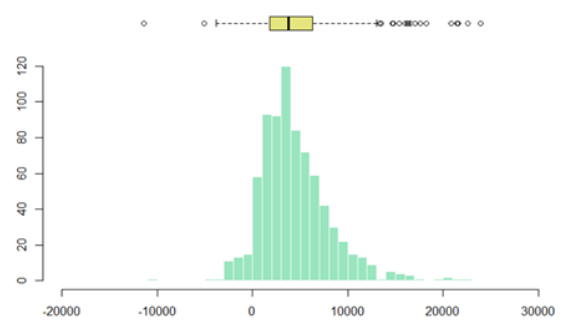
Condensing boiler



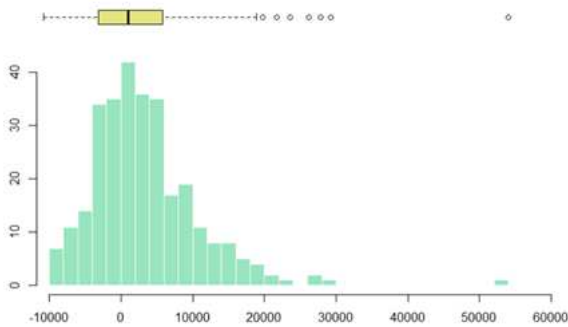
Domestic hot water



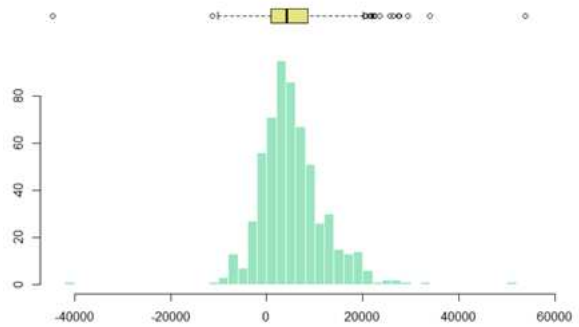
Solar hot water



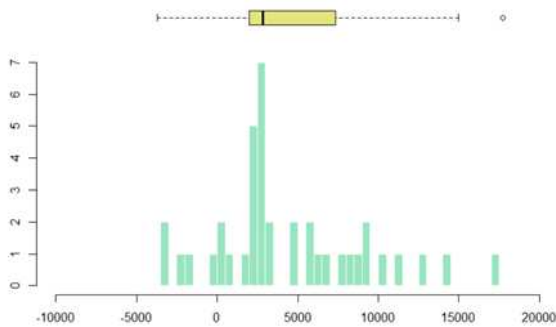
Wood equipment



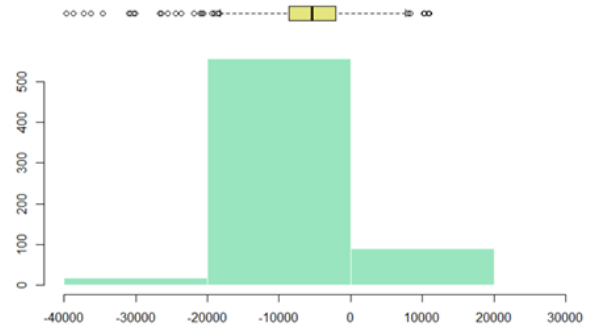
Windows replacement



Wall insulation



External wall insulation



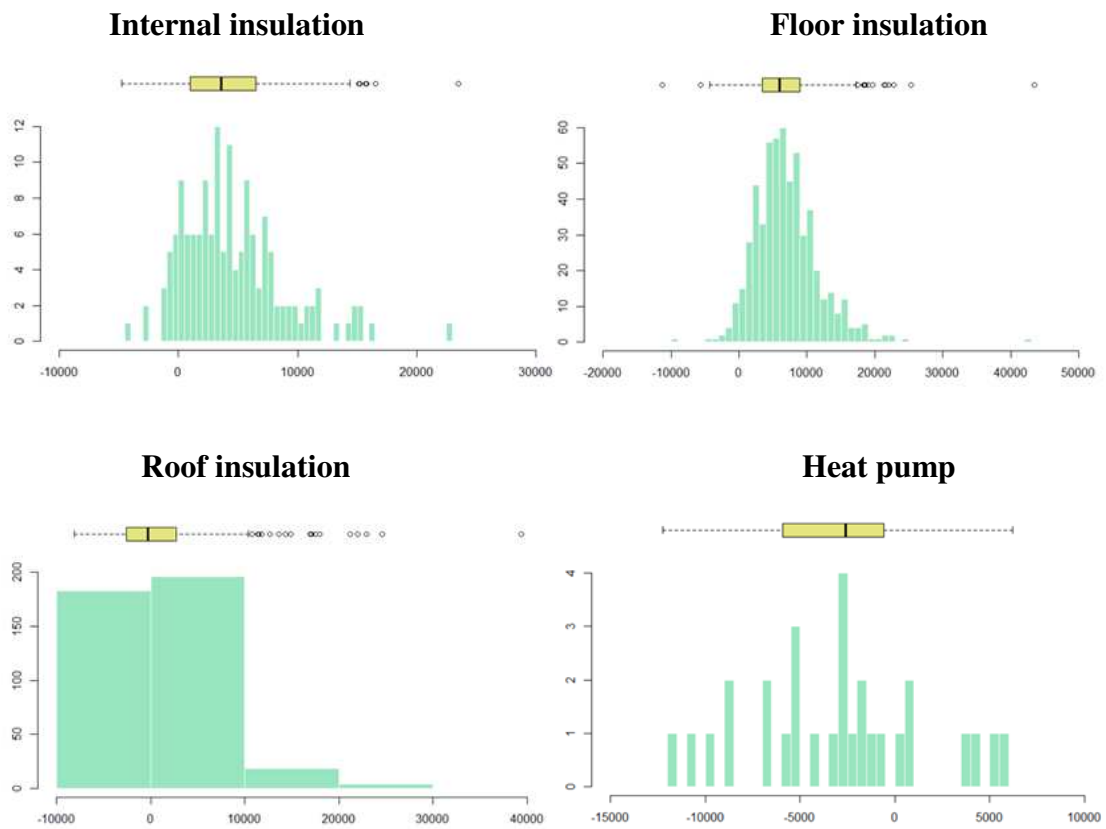
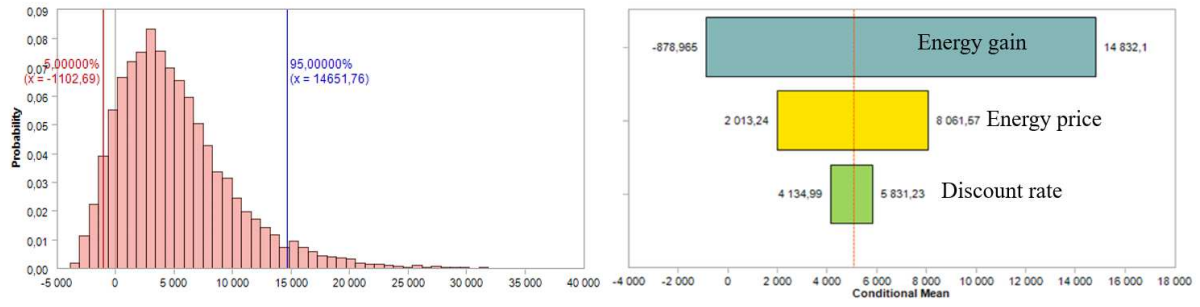
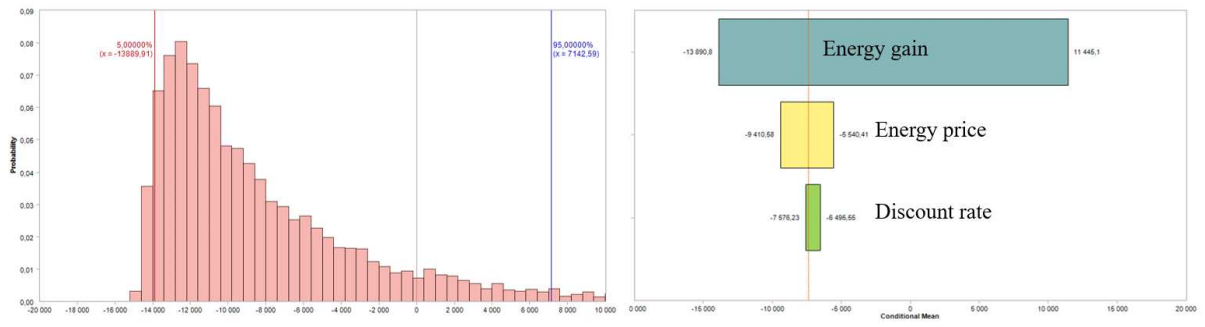


Figure 6: Distribution of individual NPV for all energy efficiency retrofits (4%-discount rate and 30-year lifespan)

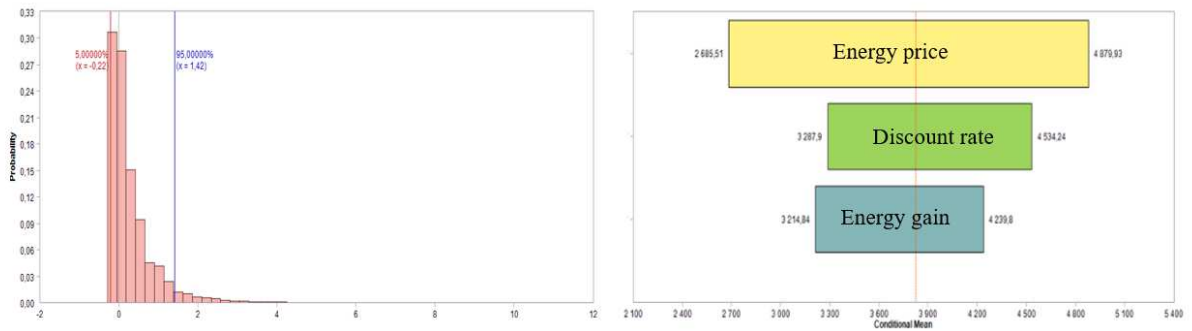
Low-temperature boiler



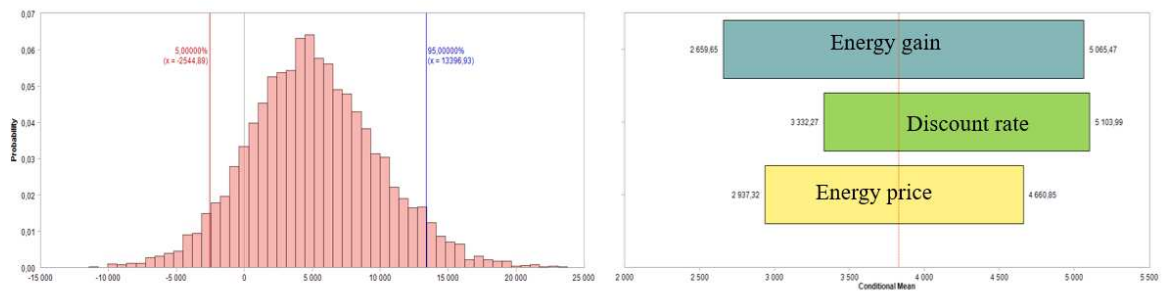
External wall insulation



Internal wall insulation



Floor insulation



Roof insulation

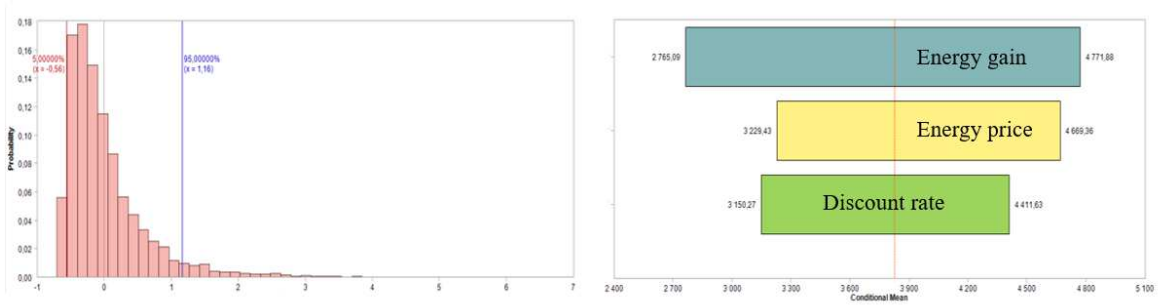


Figure 7: Distribution of expected individual NPV and tornado charts for five energy efficiency solutions
*Note: Left plot: distribution of the expected individual NPV. X-axis: NPV, Y-axis: probability.
Right plot: tornado charts. X-axis: conditional mean, Y-axis: variable*

Appendix B. Class Dendrogram resulting from the Ascending Hierarchical Classification

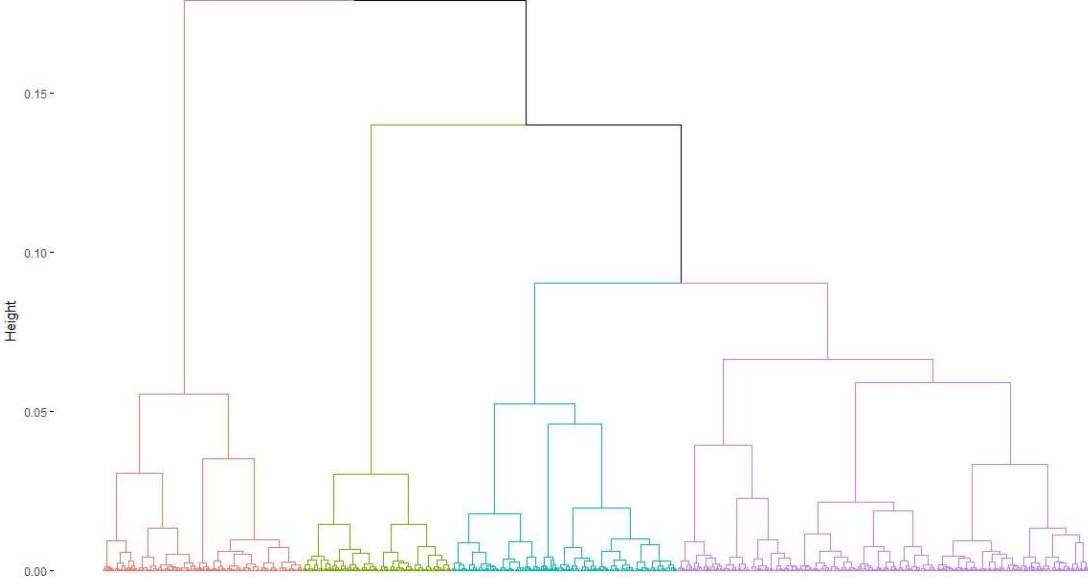


Table 1

Literature review about Cost-Benefit Analysis of energy retrofit solutions in the building sector

Reference	Country	Scale of analysis	Financial indicator	Additional information about the data, methodology, and results
Kumbaroğlu and Madlener, 2012	Germany	General method with a case study for an office building	Net Present Value	The method includes four modules: (i) an energy management system data compilation module; (ii) a tool to evaluate building energy performance based on technical and environmental conditions; (iii) a matrix of retrofit measures, potential energy and CO ₂ savings, investment and operating cost estimates; and (iv) an economic module. Authors find that energy price influences significantly the NPV (tackled by Monte Carlo simulation).
Friedman et al., 2014	Israel	Case study on two prototypes	Payback period Net present Value	The study uses a thermal simulation software that includes climate characteristics. The analysis is conducted from both private and social perspectives. A sensitivity analysis is performed to assess the effect of potential changes in electricity tariffs, <i>i.e.</i> energy price.
Becchio et al., 2015	Italy	Ex-industrial building	Global cost	This paper investigates a simulation with an energy model. Data relating to costs come from market analyses. 24 retrofit schemes are analyzed and compared in terms of economics and efficiency. The running costs cause the greatest degree of variation among global costs.
Stocker et al., 2015	Austria	Renovation of eight school buildings in the Alps	Global cost	The theoretical model is based on several scenarios to find the optimum between energy retrofit schemes. The sensitivity analysis shows that energy prices, changes in the proportion of window areas, changes in the interest rate,

				price variation and changes in the initial costs influence the most the cost of the renovation project.
Ortiz et al., 2016	Spain	Multi-family building	Global cost	The paper uses a building simulation and realizes a sensitivity analysis to assess the impact of some parameters on the global cost. Authors find that the variation on the energy price, the measure cost and the interest rate have the greatest impact.
Zhou et al., 2016	China	Case study of an office building retrofit	Payback period	The study considers the retrofit of the envelope and heating/cooling system of an office building based on before/after energy retrofit data. Authors find that the retrofitting of the heating, ventilation and air conditioning system and the improvement of the building insulation yield less energy consumption and satisfaction of the building occupants.
Rakhshan and Friess, 2017	United Arab Emirates	Villas	Payback period	This paper uses a computational energy simulation using a matrix of retrofit measures. The model is calibrated with metered energy use. Costs data come from the NREL database (US data) to assess the viability of the retrofits measures. Authors find that replacing windows offers lower financial viability.
Guardigli et al., 2018	Italy	Global methodology and case study on a housing stock	Payback period Global cost	The decision support system links energy viability and energy performance for several energy measures to provide the most efficient design alternatives for each building typology. The sensitivity analysis shows that an increase in the energy rate from 3,3 to 4,3% could reduce the payback period by 10–25% for some technologies.

Liu et al., 2018	China	Case study of a retrofit project	Payback period Internal Rate of Return	Using real data of costs and benefits (before/after retrofit data), authors find that (i) retrofitting heat sources and outdoor heating pipe networks are cost-effective and that (ii) renovation of building envelopes is ineffective in terms of Discounted Payback Period.
Luddeni et al., 2018	Italy	Global methodology and a case study on the Italian office building stock	Global cost	This article develops a simulation-based approach with optimization analysis to choose the optimal set of energy efficiency measures (genetic algorithm). The optimal set of measures depends strongly on building typology and climate. Roof insulation and boiler retrofit seem to be the least effective in reducing building primary energy consumption, but their implementation cost is relatively low. Windows retrofit has a moderate potential in reducing energy use but the highest implementation cost.

Retrofit solutions	Cost in euros/m²	Energy gains in %
Low-temperature boiler	6,744	38%
Condensing boiler	5,456	38%
Domestic hot water	2,812	27%
Solar domestic hot water	2,611	27%
Wood equipment	9,475	38%
Windows replacement	7,480	41%
Wall insulation	4,768	29%
External wall insulation	15,020	30%
Internal wall insulation	3,119	28%
Floor insulation	2,829	29%
Roof insulation	7,378	28%
Heat pump	12,720	38%

Table 2

Costs and energy efficiency gains for energy efficiency retrofit solutions ([ANAH database](#))

Occupancy status	Energy Class							
	A	B	C	D	E	F	G	Total
Tenant of public housing	0	93,357	636,605	1,352,881	1,422,544	383,080	523,033	4,411,500
	0%	0.35%	2.39%	5.07%*	5.33%	1.44%	1.96%	17%
Tenant of private housing	18,833	63,311	424,500	999,869	1,940,349	1,318,701	1,804,239	6,569,803
	0.07%	0.24%	1.59%	3.75%	7.27%	4.94%	6.76%	25%
Owner-occupant	66,136	391,426	2,102,593	4,190,407	4,640,401	2,485,302	1,823,852	15,700,117
	0.25%	1.47%	7.88%	15.71%	17.39%	9.31%	6.84%	59%
Total	84,969	548,094	3,163,699	6,543,156	8,003,294	4,187,083	4,151,124	26,681,419
	0.32%	2.05%	11.86%	24.52%	30%	15.69%	15.56%	100%

Table 3

Distribution of the French dwelling stock by occupancy status and energy class (total dwelling stock)

* Reading key: 5.1% of the dwelling stock is made of public housing occupied by tenants ranked in the D energy class.

Occupancy Status	Before 1948	From 1949 to 1974	From 1975 to 1999	After 2000	Total
Tenant of public housing	2.3%	7.5%	5.3%	1.4%	16.6%
Tenant of private housing	9.9%	6.3%	5.2%	2.8%	24.2%
Owner-occupant	18.5%	16.0%	18.4%	6.3%	59.2%
Total	30.7%	29.9%	28.9%	10.5%	100%

Table 4

Distribution of the French dwelling stock by year of construction and status occupancy

Energy source	Share
Gas	38.5%
Electricity	34.6%
Fuel	15.7%
Wood	5.9%
Other	5.2%

Table 5
Main energy sources in the French dwelling stock

Variable	Definition	Frequency
Dwelling type	Collective dwelling	27%
	Individual dwelling	72%
Year of construction	Before 1948	26%
	1948-1974	28%
	1975-1989	22%
	After 1989	24%
Dwelling size	Less than 75m ²	24%
	75-100m ²	29%
	100-130m ²	23%
	More than 130m ²	24%
Occupancy status	Tenant	24%
	Owner	76%
Energy class	A-B-C	16%
	D	27%
	E	30%
	F-G	27%
Surface coefficient of heat exchange (it represents the dwelling insulation quality; the lower the coefficient, the better the insulation of the envelope)	Low (0.18-0.90)	25%
	Middle (0.91-1.28)	25%
	High (1.29-1.82)	25%
	Very high (more than 1.83)	25%
Real energy consumption, expressed in kilowatt hours on year 2012	1,000-8,500	25%
	8,500-15,000	25%
	15,000-25,000	25%
	25,000-65,000	25%
Systematic energy source	Electricity	3%
	Fuel	35%
	LPG	16%
	Wood	2%
	Gas	6%
	Urban heating	37%
	Other	1%
Heating system type	Collective	10%
	Individual	77%
	Mixed	13%
Region	The 13 French regions	
Climatic zone	H1	59%
	H2	30%
	H3	11%
Urban size	Rural commune	22%
	2,000-20,000 habitants	18%
	20,000-200,000 habitants	17%
	More than 200,000 habitants	25%
	Paris region	18%
Renovation changes	Yes	46%
	No	54%

Table 6

Input variables for the Ascending Hierarchical Classification and their frequencies

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.

Table 7
Summary description of the classes identified

Retrofit solutions	Class 1 (25%)	Class 2 (30%)	Class 3 (30%)	Class 4 (15%)	Total
Low-temperature boiler	-	-	-	-	-
Condensing boiler	37%	48%*	22%	34%	35%**
Domestic hot water	-	-	-	-	-
Solar domestic hot water	42%	-	53%	33%	31%
Wood equipment	-	-	-	16%	2%
Windows replacement	38%	44%	22%	-	29%
Wall insulation	-	-	-	-	-
External wall insulation	61%	46%	-	-	29%
Internal wall insulation	-	-	-	-	-
Floor insulation	-	49%	20%	-	21%
Roof insulation	-	-	-	19%	3%
Heat pump	-	-	-	-	-
Total	45%	56%	35%	15%	151%
Total (on 100%)	29%***	37%	23%	10%	100%

Table 8

The four most recommended energy efficiency retrofits, by class and total

* Reading key: condensing boiler is recommended as an energy efficiency retrofit to 48% of dwellings in Class 2, knowing that this class represents 30% of the total French dwelling stock.

** Reading key: regardless of classes, condensing boilers are recommended to 35% of dwellings.

*** Reading key: 29% of recommendations are directed to dwellings of class 1, regardless of what was recommended.

Note: the sum of the Total column and line is not 100% because one dwelling can receive several recommendations.

Retrofit solutions	Average NPV 4%, 30 years	IPR 30 years
Low-temperature boiler	7,982 €	12%
Condensing boiler	8,790 €	15%
Domestic hot water	4,797 €	16%
Solar hot water	4,302 €	15%
Wood equipment	3,062 €	7%
Windows replacement	5,071 €	9%
Wall insulation	4,270 €	11%
External wall insulation	-5,202 €	1%
Internal wall insulation	4,414 €	14%
Floor insulation	6,791 €	20%
Roof insulation	2,638 €	7%
Heat pump	-3,299 €	2%

Table 9
Cost-Benefit Analysis results

	Class 1	Class 2	Class 3	Class 4	Total
Initial real energy consumption (before retrofitting) (in Mtoe)	4.30	13.50	6.02	3.23	27.05
Emissions by class (in Mton of CO₂)	7.14	23.60	11.70	5.80	48.24
Total cost of retrofitting all dwellings in a class (in billion euros)	10.20	13.60	6.00	2.30	32.10
Energy gains resulting from retrofitting all dwellings in a class (in Mtoe)	1.36	0.45	1.90	1.07	4.78
Environmental gains resulting from retrofitting all dwellings in a class (in Mton of CO₂)	2.20	7.74	3.48	1.85	15.27

Table 10

Environmental and economic impacts of retrofitting the entire French dwelling stock

Appendix

Appendix A 1

Conversion ratios by energy source (ADEME, 2020 (b))

Note: NCL stands for Net Calorific Value, also referred to as Lower Calorific Value. It is the amount of heat released during the combustion of a specified amount of a substance.

Energy source	Conversion ratio
Gas	0.187 kgCO ₂ /kWh NCL
Electricity	0.178 kgCO ₂ /kWh
Butane	0.23 kgCO ₂ /kWh NCL
Wood	0.0188 kgCO ₂ /kWh NCL
Coal	0.345 kgCO ₂ /kWh NCL

Appendix A2

Formulas for the simulation of the entire French dwelling stock retrofit

Emissions by class expressed in Mton of CO₂
<p>CO₂ emissions by class = weighted sum of individual CO₂ emissions by class where individual CO₂ emissions $= 0.6 \times (\text{initial energy consumption}) \times (\text{conversion rate g/kWh})$ where 0.6 is the share of heating in final consumption; the initial energy consumption is given in kWh and the conversion ratio in g/kWh depends on the main energy sources (see Appendix 1).</p>
Environmental gains resulting from retrofitting all dwellings in a class in Mton of CO₂
<p>total CO₂ gains = weighted sum of individual CO₂ gains × 10⁹ where individual CO₂ gains $= 0.6 \times (\text{average potential economic gain of retrofit})$ $\times (\text{initial energy consumption}) \times (\text{conversion ratio g/kWh})$ where 0.6 is the share of heating in final consumption; the initial energy consumption is given in kWh and the conversion ratio in g/kWh depends on the main energy sources (see Appendix 1).</p>
Energy gains resulting from retrofitting all dwellings in a class in Mtoe
<p>energy gains in a class = weighted sum of individual average energy gains by class</p>

where $1\text{kWh} = 0.086 \times 10^9 \text{ Mtep}$

Total cost of retrofitting all dwellings in a class in billion euros

total cost of retrofitting in a class
= weighted sum of the individual average cost of energy retrofit