

Impact of public policies on the dynamics of energy retrofit and fuel poverty in mainland France*

Corinne CHATON[†]

October 20, 2023

Abstract

Many public policies encourage households, fiscally or financially, to renovate their homes to improve their energy efficiency. Examples in France include the Zero-Rate Eco-Ready program to finance thermal renovations, the tax credit for energy transition, or the “Living Better” program. Does this aid help to improve the energy efficiency of housing in France? The objective of this study is to present the structure of a new microsimulation model which makes it possible on the one hand to analyze the potential of differentiated public policies on the dynamics of energy renovation of housing and on the other hand to evaluate the impact of these policies on fuel poverty. Thus, from 2013-2017, offering assistance for the energy renovation of housing to the first income quintile alone would have reduced energy poverty very little in 2017. To reduce fuel poverty, it is preferable to target assistance to the first two income quintiles.

Key words: Energy transition, Energy Efficiency, Fuel Poverty.

JEL Codes: I32, Q48

*The author is solely responsible for this work without commitment from the institutions to which she belongs. The author is thankful the support of the French Agency for Ecological Transition (ADEME), HERMES project. The author would like to thank Raphaëlle Villers as well as Gaëtan Chamard-Bois for their participation in the evolution under R of the EPEE microsimulation model towards the EPEEr model. The author would also like to thank Marie-Laure Guillerminet, Alexandre Godzinski and Bruno Quille for their valuable comments and suggestions.

[†]Contact: corinne.chaton@dauphine.psl.eu, Finance for Energy Market Research Centre (FIME), Paris, France.

1 Introduction

It is a fact that living in a “*leaky home*” that is in a very energy-intensive home (i.e., in a home that is in band F or in band G of the French Energy Performance Certificate, EPC)¹, significantly increases basic energy needs because the most energy-intensive homes² consumes up to 10 times more than the most efficient homes³. As a result, households living in poorly insulated housing have a higher probability of being in fuel poverty⁴ than those living in housing with a EPC score of A or B. Thus, as [Best and Sinha \[2021\]](#) note, on the one hand, these households tend to suffer from lower subjective utility because they are more likely to feel unable to achieve healthy temperatures for their dwelling. On the other hand, their energy expenditure must be higher to compensate for insufficient insulation. Consequently, even households with a standard of living above the first three standard of living deciles can, depending on their housing conditions, fall into fuel poverty. This is all the more likely when energy prices are high, as was the case in Europe in 2022. As a result, the energy retrofit of housing appears to be an important lever for lifting certain households out of fuel poverty or preventing others from entering it.

Energy retrofit has a dual environmental and social benefit for public authorities, reducing both energy demand (and therefore the associated CO₂ emissions) and fuel poverty. Without it, it will be impossible to achieve carbon neutrality by 2050. To encourage building energy efficiency retrofits (EERs), the French government has implemented various schemes (the housing energy renovation plan, PREH in 2013; the French law on the energy transition and green growth, TECV law in 2015; the building’s energy renovation plan, REB plan in 2018 and 2021; and national low-carbon strategy, SNBC in 2020). Among these schemes are aids/subsidies that are allocated to households for the energy renovation of their homes. However, what is the impact of such aids/subsidies on EERs and on fuel poverty? The objective of this study is to provide answers to this question.

Thus far, these interventions do not seem to have had the expected effects. It is clear that despite financial aid such as the tax credit for energy transition, Zero-Rate Eco-Ready (Eco-PTZ), the “Better Living” program managed by the French National Housing Agency (Anah⁵) for precarious households, etc. . . and the increase in energy prices, the number of deep energy retrofits undertaken by households does not seem sufficient to achieve some of the objectives set in the various plans/laws launched by the French government to boost the energy renovation of housing. Thus, the objective of renovating all the *leaky homes* in the private residential stock by 2025, enshrined in the TECV law and still relevant, seems compromised, even with the ban on new rental contracts concluded from January 1, 2023, for EPC G-score dwellings⁶. Indeed, [Le Saout et al.](#)

¹For more information, see Annex A.

²A dwelling that is in band G has an energy consumption greater than 450 kWh_{pe}/m²/year.

³The energy consumption of dwellings that are in band A is less than 50 kWh_{pe}/m²/year.

⁴Fuel poverty is defined as follows in French legislation (cf. the July 12, 2010, law, also named Grenelle II): “*a household that has difficulties obtaining the necessary energy to satisfy their basic needs due to the inadequacy of their resources or their living conditions is in fuel poverty under this Act*”.

⁵Anah for Agence nationale pour l’amélioration de l’habitat.

⁶See Decree No. 2021-19 of January 11, 2021, relating to the energy performance criterion in the definition of decent housing in mainland France.

[2022] estimate that on January 1, 2022 (2018), the percentage of *leaky homes* in the stock of principal residences in mainland France is 17% (16.7%). According to these authors, the percentage of these very energy-intensive dwellings varies little with the income of the occupants. Thus, 18% (16%) of households in the first quintile (last quintile) of income live in dwellings with an EPC score of F or G. Energy retrofit does not only concern *leaky homes* but also dwellings with EPC scores C to D. The percentages of these dwellings in the French housing stock are the following: 24% for C scores, 32% for D scores and 22% for E scores [Le Saout et al., 2022]. As a result, it is unlikely that the entire housing stock will be renovated according to “Low Consumption Building” (BBC) standards by 2050, i.e., that the consumption of existing housing will be less than 80 kWh_{pe}/m²/year (which is an objective of the REB plan).

Given the rise in energy prices since 2019 and the state of the French housing stock, it is not surprising that increasing numbers of consumers report restricting the heating of their homes to avoid excessive energy bills. Indeed, according to *the 2022 info-energy barometer* [Le médiateur national de l’énergie, 2022]⁷, 53% of consumers restricted the heating of their homes in 2020. In 2022, this percentage was 69%. By limiting their energy expenditure, these households forgo their thermal comfort and could be qualified as fuel poor households. This relationship between thermal comfort and fuel poverty was highlighted by Healy and Clinch [2002] based on the results of a national household survey in Ireland. *The 2022 info-energy barometer* is also based on the results of a survey. This survey was carried out by the *.becoming* research institute from September 1 to 16, 2022 (for the fourth consecutive year), with a representative sample of 2,006 French households. Of these 2,006 households, 22% suffered from the cold in winter 2020-2021, and 37% (35%) of them declare that the reason is financial (poor insulation). A significant difference can be observed between tenants and owner-occupiers in their dwelling. Indeed, “*Poor insulation is most often cited by tenants (41%)*”. If we consider that consumers who have difficulty paying certain gas and electricity bills are in energy poverty, then the percentage of consumers in energy poverty was 18% in 2020 and 27% in 2022 [Le médiateur national de l’énergie, 2022].

If thermal regulation of residential buildings can reduce fuel poverty by increasing the energy efficiency levels of housing [Matos et al., 2022], can the same be true for investment incentives for energy renovation?

Numerous studies underline that public policies encouraging building EERs do not obtain the expected results. This is partly because there is a significant difference between the levels of investment in energy efficiency that should save consumers money and the investments they actually make. This “efficiency gap” can be explained by many phenomena (e.g., market failures), behaviors (myopia, differences in reference points; see theoretical perspective).⁸ Additionally, as Fowlie et al. [2018] has recently shown, the energy savings measured ex post are much lower than the savings estimated by simulation models. Indeed, the experimental evaluation of a residential energy efficiency program (Weatherization Assistance Program, WAP) that they conduct on a sample of

⁷“Le médiateur national de l’énergie” translated into English as “the National Energy Ombudsman” is an independent public authority whose mission is to offer amicable solutions to disputes with companies in the energy sector and to inform energy consumers of their rights.

⁸See for example Howarth and Sanstad [1995], Allcott and Greenstone [2012], Gillingham and Palmer [2014].

more than 30,000 households, suggests that the initial investment costs (i.e., projected by the model) are approximately 2.5 times the actual savings. The vast majority of these studies are econometric or experimental economics studies. The latest French study that can be cited on the impact of public policies on the rate of energy renovation of housing concerns the increase in the rate of the tax credit (implemented in France on September 1, 2014) on renovation investments by households with modest incomes. [Bouisset et al. \[2023\]](#) show that the increase would have encouraged low-income households to earn more renovation work and to increase the amount invested in renovations, in particular by carrying out several actions, but would not have steered them toward more expensive one-step renovations. Some studies, such as [Borenstein \[2015\]](#), [Xiang et al. \[2018\]](#), [Crampes and Léautier \[2023\]](#), are based on microeconomic analyses of investments in energy savings.

This study contributes to the literature on the impact of public policies encouraging energy renovations on the energy renovation decision and on fuel poverty through the development in R of a microsimulation model (see Section 2). The use of a microsimulation model makes it possible, among other things, to overcome the lack of relevant current and past data on housing and its occupants in France. This lack was confirmed by the Cour des comptes⁹, which carried out a “survey relating to the production and use of data useful for housing policy since 2017”. This investigation resulted in referral no. S2022-0931, of May 12, 2022, signed by Pierre Moscovici, President of the Cour des comptes, and addressed to Ms. Pompili, Minister of the Ecological Transition and to Mr. Le Maire, Minister of the Economy, Finance and Recovery. It yielded the following quote: *“In terms of housing policy, this requirement¹⁰ imposes a reasonable knowledge of the stock of social and private housing in order to establish, according to territorial realities, the expression of the needs of the applicants and of the human and social characteristics of the latter, the most suitable strategies in terms of the supply of new housing, the fight against insalubrity, energy renovation, etc. They must allow the monitoring of the beneficiaries of these policies to verify their However, the State’s capacity seems insufficient with regard to the stated ambitions. In general, the databases that can be used are difficult to access and not very interoperable.”*

The model developed in this study is an adaptation of that of [Chaton and Gouraud \[2020\]¹¹](#), which initially used data from the 2006 “Enquête Nationale Logements” (ENL, [the French Housing Survey](#)). Subsequently called EPEEr, it is now based on the penultimate ENL conducted between 2012 and 2014 (ENL2013). It is the most recent and comprehensive source of information available at the time of writing this study on household domestic energy consumption. By way of comparison, the Phébus¹² survey, produced in 2012 and used, among others, by [Giraudet et al. \[2020\]](#), to configure the French housing stock to quantify the medium- and long-term impact of energy renovation policies, has fewer than 6,000 households questioned against more than 26,000 for the ENL2013. With a larger sample size, the estimator is more precise (lower variance). The explanatory power of a model tends to increase with sample size. Finally, another

⁹The Cour des comptes is the supreme body for auditing the use of public funds in France.

¹⁰To have reliable, exhaustive, recent and accessible data.

¹¹Model named EPEE for Estimation de la Précarité Énergétique via l’Econométrie (Estimation of Fuel Poverty Via Econometrics).

¹²Enquête Performance de l’Habitat, Équipements, Besoins et Usages de l’énergie (Phébus).

significant advantage of using the ENL and not the Phébus survey is that the latest housing survey (ENL) was carried out between October 2019 and April 2021¹³, while there is no information on a future Phébus survey apart from the fact that “*it could be renewed in the future*”. The Phébus survey makes it possible to calculate the normative energy expenditure linked to housing and therefore does not account for, or does so very little (via elasticities), the behavior of households. The ENL, on the other hand, reflects this behavior and the heterogeneity of households. Thus, the technical-economic model Res-IRF (used by [Giraudet et al. \[2020\]](#)) and the microsimulation model of [Chaton and Gouraud \[2020\]](#) are complementary. There is another tool comparable to that developed by Chaton and Gouraud (i.e., simulating fuel poverty in mainland France via ENL data), which is used by the Observatoire national de la précarité énergétique, ONPE¹⁴ (see [Devalière et al. \[2018\]](#)). This tool is based on Prometheus, developed by the General Commission for Sustainable Development but for which, unfortunately, there is little information on its structure.

To assess the impact of public policies supporting the energy renovation of French housing,

1. two databases, namely the ENL2013 and the ADEME¹⁵ EPC database were matched;
2. the thermal renovation block of the EPEE model (in which, among other things, the probability of renovating a home is determined via a logit) has been modified.

Thus, for owners occupying their homes, the decision to invest in a high-performance renovation (i.e., allowing a jump in the EPC band) is now based on an analysis of the life cycle cost of the investment. For renting households, the renovation decision depends mainly on the owner. However, from information on the energy performance of French housing in 2017 given by [Merly-Alpa et al. \[2020\]](#),¹⁶ it is possible to determine the probability that rental housing will be renovated. This probability obviously depends on the EPC score of the accommodation.

After presenting the methodology in Section 2, calibration and simulations are carried out in Section 3. While the investment cost matrix of switching from one EPC band to another is input data, the effects of the renovation (invoice savings due to the EPC improvement and rebound effects) are estimated and intangible costs¹⁷ are determined by calibration. According to the simulations, better information on aid for energy renovation of homes and the targeting of this aid on the first income quintiles contribute to reducing fuel poverty. A policy targeting lower living standard deciles should have a greater effect on reducing fuel poverty. The calculated effect is nevertheless moderate: -0.93% at the end of 2017 if only the households likely to be helped (from 2013 to 2017)

¹³Survey data were not available at the time of writing this study. They were made available in June 2023. Furthermore, the objective of this study being to study the impact of energy efficiency policies on the renovation dynamic and on fuel poverty (apart from the health crisis), it seems more appropriate to use ENL2013.

¹⁴ONPE is a think tank in charge of studies linked to fuel poverty.

¹⁵The French Agency for the Environment and Energy Management.

¹⁶The target year for calibration is the end of 2017.

¹⁷These costs include, among other things, the inconvenience linked to renovation work, time spent searching for craftsmen, etc.

belong to the first quintile.¹⁸ If the objective is to reduce fuel poverty, according to the simulations, it is preferable to target aid to the first two income quintiles

2 Methodology

The objective of this study is to analyze the impact of aid/subsidies for housing EERs on fuel poverty in mainland France. It is therefore necessary to rely on a model that accounts for the three predominant factors in the concept of fuel poverty, namely household resources, energy prices and quality of housing. This is the case of the microsimulation model developed by [Chaton and Gouraud \[2020\]](#) (model named EPEE). This model is based on the following three main blocks: income, energy prices and thermal renovations (see [Figure 1](#)). However, the thermal renovations block is based on a logit regression to assess the probability that a household will or will not conduct an energy renovation of their dwelling. It therefore does not make it possible to answer the question, what is the impact of these aids/subsidies on investment in energy renovation and on fuel poverty? It is therefore necessary to modify/refine this block relating to the thermal renovations of the dwelling.

EPEE is a two-period model. The initial period corresponds to the ENL data collection period (from March 2005 to December 2006 for ENL2013 and from June 2013 to June 2014 for ENL2013) and the final period, which is the target year. The new energy renovation block is annual. Therefore, the number of periods considered for this block depends on the target year.¹⁹

Subsequently, interest only relates to so-called high-performance renovations, defined as follows.

Definition 2.1. *A renovation is considered efficient when it allows at least one EPC band jump (a positive jump of course).*

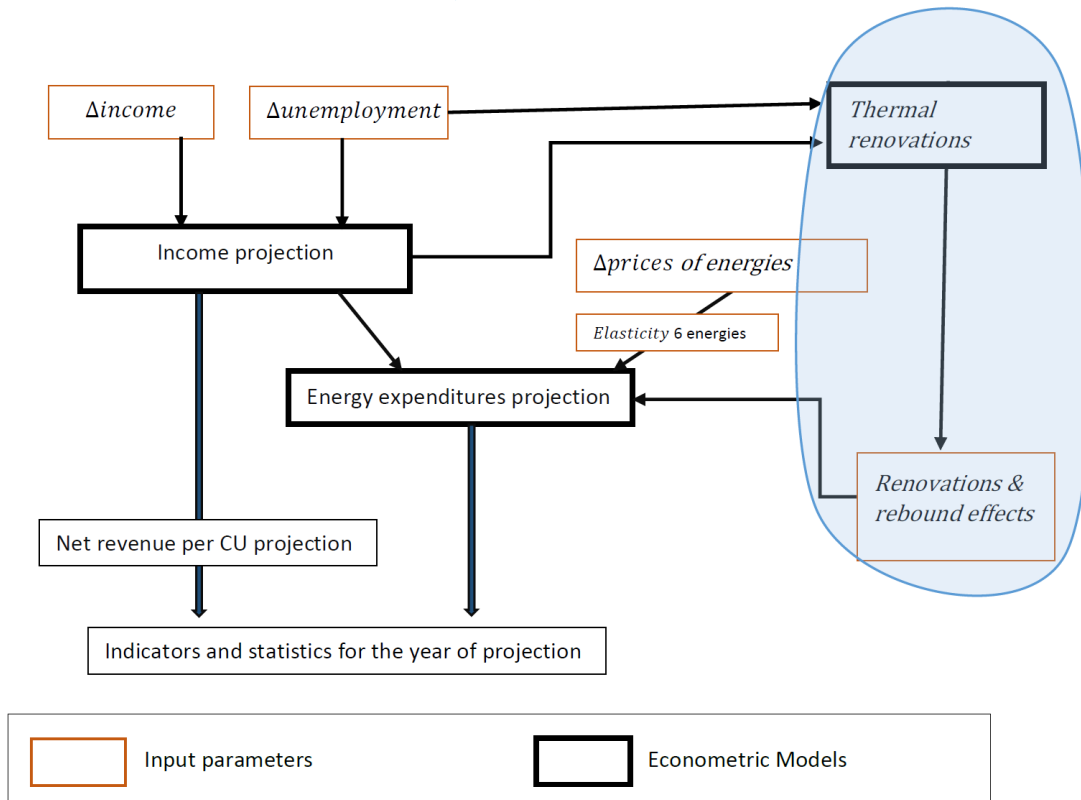
However, in the ENL2013, the survey on which the microsimulation model is now based²⁰, no EPC score is associated with housing. Thus, initially, an EPC score is assigned to each ENL2013 dwelling ([Subsection 2.1](#)).

Starting from the observation that it is substantially more difficult for tenants than for owners to have their accommodation renovated (because it largely depends on the decision of their landlord), tenants and owner-occupiers are treated differently. Specifically, the renovation block is modified to integrate an economic model for the renovation decision of owner-occupiers, a decision that depends on aid/subsidies for renovation ([Subsection 2.2](#)). For tenants, renovation is addressed in a very simple way. On the basis of an annual rental housing renovation target by score (the value of the targets is taken from [Merly-Alpa et al. \[2020\]](#), a working document of the General Commission for Sustainable Development), a draw is made for tenants benefiting from the renovation ([Subsection 2.3](#)).

¹⁸If the EPC score transition cost matrix considered is that defined by [Giraudet et al. \[2020\]](#).

¹⁹Thus, if for example, the initial year is 2013 and if the target year is 2018, this block will include 5 periods.

²⁰In [Chaton and Gouraud \(2020\)](#), the microsimulation model is based on ENL2006.



Interpretation: The program is based on three econometrics models providing an estimation of household gross income with a multilinear model; an estimation of probability of renovation with a Logit model and an estimation of energy expenditures with another multilinear model. Using these econometric models and input data it is possible to make projections on income; on the probability of carrying out a thermal renovation as well as on energy expenditure. From these projections it is possible to calculate indicators of fuel poverty

Figure 2. The main stages of the simulation process

Note: Source [Chaton and Gouraud \[2020\]](#). The circled and bluish part is modified. Indeed, the initial econometric model concerning the thermal renovation of housing is partly replaced by a decision-making model of housing energy efficiency retrofits for homeowning households.

Figure 1: Structure of the EPEE microsimulation model

2.1 An EPC score for ENL2013 housing

An EPC score is assigned to each dwelling in the ENL2013 database. Although the ENL2013 provides information on energy expenditure (declared expenditure and not on energy consumption), it provides no information on the contract between the household and the energy supplier, and thus, it is difficult to calculate an EPC for each accommodation in the ENL2013 base. Consequently, the method used consists of matching the ENL2013²¹ and the ADEME²² databases. A potential difficulty in matching stems from the fact that the ADEME EPC data are raw and include selection bias. Indeed, only the housing scores of people who requested a score are represented. As shown in Figure 2 (left figure), the dwellings represented in the ADEME EPC database are of better

²¹With a total of 26,264 respondents, the database is representative of the housing stock in mainland France. Table 18 provides some statistics for this database.

²²In 2020, there were 280,000 selected respondents. The database is not representative of the housing stock in mainland France.

quality (i.e., with better scores) than the mainland French housing stock (the INSEE Phébus survey is representative of the mainland French housing stock in 2013)²³.

The filtered EPC database. Before July 1, 2021, the determination of an EPC score for a French dwelling was based on two methods: the conventional consumption calculation method (known as 3CL and used in the Phébus survey) and the so-called “on invoice” method.²⁴ To carry out the matching, only the dwellings whose EPC has been defined by the invoice method or by the 3CL method are taken into account. Dwellings whose EPC was determined by a combination of the two methods or poorly defined are not retained. Other filters have been applied. Thus, in the ADEME EPC database, only dwellings (i.e., residential EPCs) are considered for which the date of award of the EPC is between 2012 and 2014 (the period of the ENL2013 survey). Observations whose energy consumption does not fall within the theoretical consumption bounds, according to the EPC score (see Annex A for the definition of the bounds), are deleted. Regarding the year of construction of the dwelling, the following changes have been made. Negative values have been replaced by their opposite (-1930 = before 1930). Dates from 19,000 to 20,200 were divided by 10. Only observations with a housing construction date between 1400 and 2014 were retained. Observations in which the surface of the dwelling, the energy bill (in euros and in euros per m²) are outside the ENL limits by type of dwelling (house, apartment) are not considered. The last filter concerns the average price of energy for households/dwellings (in KWh_{pe}/m²). Specifically, the average prices (defined by the invoice/consumption ratio) not belonging to the interval [3, 50] are deleted. The same is true for observations whose price/price ratio estimated by regression is outside the interval [0.8, 1.2]. Table 1 reports the average primary energy consumption per m² according to the EPC score and the EPC allocation method (on invoice or 3CL) taken from the filtered ADEME EPC database. Consumption on invoice is on average slightly lower than “theoretical” consumption, with the exception of dwellings classified in band A of the EPC. The ADEME database on EPCs after the various treatments/filters contains 1,168,741 observations.

EPC Scores	A	B	C	D	E	F	G
On invoice	40.53	66.41	123.54	187.85	269.17	373.77	491.73
3CL	39.56	67.70	124.82	192.74	276.87	380.55	500.18

Table 1: Average consumption (filtered database of ADEME EPCs - in KWh_{pe}/m²/year)

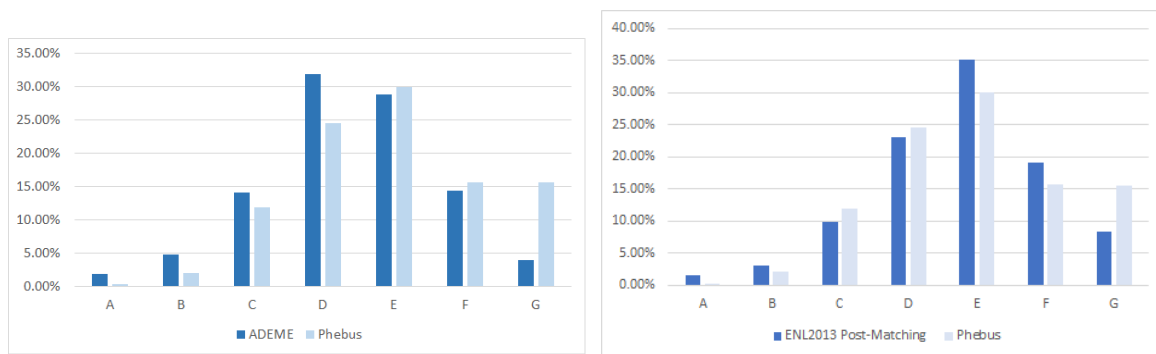
The matching variables used are as follows: the type of dwelling (detached house or other), its construction period (before 1974; between 1975 and 1989 and after 1990); its living area (less than 25 m²; 25 to 40 m², 40 to 70 m², 70 to 100 m², 100 to 150 m², or more than 150 m²); the annual energy bill (total and per m²); and the region

²³Note that data collection for the Phébus survey was carried out from April to October 2013.

²⁴Since July 1, 2021, only the 3CL method has been used. This method is based on theoretical consumption calculated from the technical characteristics of the dwellings and assumptions on fixed dwellings. The on-invoice method is based on the actual consumption of a household.

and the year of response to the EPC questionnaire²⁵. The database resulting from this pairing is named ENL2013EPC.

The accuracy of the matching of data from ENL2013 and ADEME’s EPC cannot be verified directly. It is however possible to compare the distribution of the scores obtained post-matching with that of the Phébus survey data (see Figure 2 (right figure)). The differences observed are probably due to the calculation methods used for the EPC (only 3CL for the Phébus survey and 3CL and “on invoices” for the EPC post-matching of the ENL2013) and to the periods that are not the same. The collection of the Phébus survey was carried out from April to October 2013, while the energy expenditure declared in the ENL relates to the period from June 2012 to June 2014. Moreover, according to Merly-Alpa et al. [2020], the Phébus survey overestimates *leaky home*.



Note: The figure on the left (the right) compares the distribution of dwellings according to the EPC scores obtained via the filtered ADEME EPC database (post-matching, i.e. obtained by matching data from the ENL and ADEME EPC) and those of the Phébus survey.

Figure 2: Distribution of dwellings according to their EPC score (2012-2014)

Some statistics about the ENL2013EPC database can be found in appendix B.1.

2.2 A renovation model for homeowners living in their home

The logit model that constitutes the renovation block in Chaton and Gouraud’s microsimulation model is partly replaced by a renovation model for homeowners households (i.e., 57.4% of French households in 2013). In this model, three key moments are considered: decision-making (to renovate or not), the quality of the renovation (choice of the type of work, quality of the work carried out), and the behavior of the household after the renovation (the rebound effect or the Jevons Paradox²⁶).

One of the difficulties encountered when developing a decision model for renovating one’s home comes from the fact that the choice to renovate or not involves a large number of factors that are not financial. Thus, for example, Ebrahimigharehbaghi et al. [2019] show that the main drivers for Dutch homeowners’ decision for energy

²⁵The year of response to the questionnaire makes it possible to correct for global climatic variations and variations in energy prices.

²⁶Improved productive or energy efficiency can actually lead to greater use of the product and its associated energy: “It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.” [Jevons, 1866].

efficient renovations (EERs) is the desire to improve the quality of their life, rather than the financial benefits and “*the main barriers are the costs of EERs, complexities in the process, information barriers, and finding reliable experts and information*”. In France, according to the 2017 and 2020 TREMI surveys²⁷, improving comfort²⁸ is the primary motivation for households renovate their house (see [Energies Demain et al. \[2018\]](#) and [Caumont et al. \[2022\]](#)). Despite this observation and the importance of nonfinancial/economic variables in consumers’ decisions regarding investment in energy efficiency²⁹, in what follows, the likelihood that a homeowners household will renovate their home is based on an originally “financial” criterion, namely the cost of the life cycle of the investment³⁰. However, in this cost, there are intangible costs that include, among others, negative costs reflecting the improvement in comfort, political voluntarism, etc.

2.2.1 The life cycle cost of an investment, LCC

This cost, which is used to define the probability of renovation of a homeowners household, is the sum of the following elements:

1. The investment cost (zero if there is no renovation);
2. Assuming that the household borrows the amount necessary to carry out the work, and that it pays for the work before receiving public assistance, the investment cost breaks down into the present value of the loan (nominal plus interest), plus intangible costs (positive: inconvenience related to renovation work, time spent looking for craftsmen, etc., negative: improvement in aesthetics, comfort, political voluntarism, etc.) minus grants awarded;
3. To these investment costs is added the discounted amount of the energy bills (initial bill if there is no renovation, minus the theoretical effect in the opposite case).

Thus LCC is defined as

$$LCC_{i,j,q,S,B^Y} = (\alpha_i - g_{q,i})I_{i,j,s} + \sum_{t=1}^T \frac{(1 + (T - t + 1)r)I_{i,j,s}}{T(1 + \beta)^t} + \sum_{t=1}^L \frac{(1 + \Delta_{i,j})B^Y}{(1 + r)^t}, \quad (1)$$

where

- i the initial EPC score,
- j the final EPC score,
- q the household income quintile,
- s the living area,

²⁷The TREMI 2017 survey (TREMI 2020 survey) concerns the works carried out between 2014 and 2016 (2017 and 2019) in the individual French houses (private and public park).

²⁸Being warmer at home (thermal comfort) / Beautifying the home / Improving air quality / Soundproofing the home.

²⁹For [Stern \[1986\]](#) psychological considerations (e.g., commitment and motivation) play a key role in these decisions.

³⁰See [Woodward \[1997\]](#).

- B^Y the estimated bill on January 1 of year Y ,
- α_i , the intangible costs, depends on the initial EPC score,
- $g_{q,i}$ the subsidy rate, can be set based on the initial EPC score and household income quintile,
- $I_{i,j,s}$ the estimated cost of renovation, which depends on the initial EPC score, the final EPC score and the living area,
- T the duration of the loan (10 years by default),
- r the interest rate of the loan (4% by default),
- β the household discount rate (10% by default),
- L the lifetime of an investment (30 years by default) and
- $\Delta_{i,j}$ the expected reduction in the bill by a jump from EPC score i to j .

The first element of the right-hand side of (1) i.e. $(\alpha_i - g_{q,i})I_{i,j,s}$ corresponds to the correction made by the intangible costs and the subsidy rate, expressed as a percentage of the amount of the initial investment. The second element, i.e. $\sum_{t=1}^T \frac{(1+(T-t+1)r)I_{i,j,s}}{T(1+\beta)^t}$, is the present value of the loan made at the time of the investment. The last element, i.e. $\sum_{t=1}^L \frac{(1+\Delta_{i,j})B^Y}{(1+r)^t}$, corresponds to the sum of discounted invoices over the life of the investment. These invoices, which depend on the initial year, are corrected for the theoretical renovation effect. In other words, when deciding on the energy renovation of the home, the household is myopic with regard to its future behavior (it does not take into account rebound effects) and it is myopic with regard to energy prices (it considers constant prices from the time of observation).

2.2.2 Probability that a homeownership household renovates its dwelling

The lower the lifetime cost of an investment, the more profitable that investment is for the household. The household will therefore compare all its options (from “do nothing” to “renovate to reach the A score of the EPC”).

The heterogeneous behavior of owner households for the energy renovation of their homes. The existence of this heterogeneity is found and demonstrated in several articles. Thus, for example, [Frondele and Vance \[2013\]](#) show that the effect of home energy audits on the likelihood of renovation is ambiguous. Indeed, their results suggest that these effects vary considerably from one household to another, and that it does not necessarily increase the probability of investments in residential energy efficiency. [Aydin et al. \[2017\]](#) studies the rebound effect of residential heating in the Netherlands (using a sample of 563,000 households). This measured effect is 26.7% among owners and 41.3% among tenants. They also highlight significant heterogeneity in the rebound effect, determined among other things by household wealth and income. This heterogeneity in the behavior of owner households means that households with identical characteristics do not necessarily make the same energy renovation choices for their housing. Otherwise, owner households would all choose the most profitable option

for them. Thus, if the benefits of improved thermal comfort are not included in the *LLC* or if they are very low (which is very likely), the option chosen by households will often be to do nothing. However, there are renovations, which do not correspond to the highest *LLC*. To have a greater probability on the option with the lowest *LLC*, the parameter $\nu > 0$ (with the minus sign in front of ν) is then used in the definition of the probability that an owner household renovates its dwelling so that its EPC score varies from i to j , i.e.,

$$P^Y(i \rightarrow j|q, i, s, B^Y) = \frac{(LCC_{i,j,q,s,B^Y})^{-\nu}}{\sum_{k=i}^A (LCC_{i,k,q,s,B^Y})^{-\nu}}. \quad (2)$$

This parameter ν is used to modulate heterogeneity³¹. The lower ν is, the more random the behavior of households.

2.3 Renovation of rental housing

The renovation of rental housing is considered in a very simple way. It is based on an annual renovation objective for these dwellings by EPC score (the value of the objectives is taken from Merly-Alpa et al. [2020] and is given in the Table 2) and is done by drawing many tenants who benefit from a change in the EPC score.

Year	A	B	C	D	E	F	G
2012-2014	1.3%	3.9%	12.1%	25.0%	33.6%	15.7%	8.6%
2018	1.7%	4.1%	17.5%	34.1%	25.8%	11.1%	5.7%

Note: The percentage of rented dwellings in each EPC band is given in this table. For the period 2012-2014, they correspond to those of rental housing in the ENL2013EPC database, i.e., after matching (see Subsection 2.1), and for the year 2018 to those calculated by Merly-Alpa et al. [2020].

Table 2: Housing rented by energy performance band

2.4 Simulation of public policies (aids/subsidies for housing EERs)

Five housing renovation aid/subsidies are taken into account.

Zero-Rate Eco-Ready (Eco-PTZ). Created in 2009 following the Grenelle de l’environnement, its objective is to encourage the energy renovation of old dwellings to improve their energy performance and therefore to reduce the energy bill of owner-occupiers and to reduce emissions of French greenhouse gases. The maximum amount of the eco-PTZ was €30,000 until the end of 2021. Since 2022, it has been €50,000 if the owner carries out a range of works “making it possible to achieve a minimum overall energy performance” (decree of 05/02/2022). It can be requested without income condition for projects over €5000. It is simulated as an interest repayment a loan contracted for a maximum amount of €30,000. The reimbursement rate is 4% (consumer

³¹The minus sign increases the probability of the option with the weakest *LLC*.

loan) repayable over 10 years. It is expressed as a percentage of the initial investment amount, I_0 , as a subsidy rate calculated as follows:

$$\frac{1}{I_0} \sum_{j=1}^{10} \frac{0.04 \times (10 - j + 1) \times \iota}{(1 + \beta)^j}, \quad (3)$$

where β is the household discount rate and $\iota = \min(I_0, 30000) \mathbb{1}_{I_0 > 5000}$.

Energy Transition Tax Credit (CITE). Since January 1, 2021, it has been replaced by “MaPrimeRénov” energy transition premium. This tax credit was available, subject to means testing, for certain energy improvement works. It concerns dwellings occupied as a principal residence. It is simulated as a 17% subsidy received the year following the work.

Reduced VAT rate for renovation of a dwelling. Renovation works are subject to a reduced VAT of 5.5%, instead of the normal rate of 10% that applies in the building sector.

Energy saving certificates, CEE. These certificates were introduced in France by the POPE law of July 13, 2005, to promote the reduction of energy consumption in certain sectors (such as the building sector) [Crampes and Léautier \[2023\]](#). They are simulated as a “private” subsidy defined according to the sale price of the energy certificates. The amount of the subsidy to energy efficiency is defined for each operation by an amount of savings updated cumulative energy (kWh cumac per m²) multiplied by a CEE price (€/kWh cumac). More precisely, the subsidy per m² for the switch from EPC i to EPC j , during year t , is equal to $m(i, j) \times p_{cee}/100$, with the values $m(i, j)$ defined in [Table 19](#) and $p_{cee} = 4$ from 2012 to 2016 (5 in 2017 then increases at the rate of 8% per year from 2018 included). The amount of this subsidy is multiplied by 2 if the household is precarious.³²

Financial assistance from Anah. Anah can grant financial aid for energy renovation work on housing, adaptation to loss of autonomy, etc. The amount of aid is linked to income, family composition and region. This aid is intended for households belonging to the first two quintiles of income per CU. It is simulated as a subsidy rate defined as follows:

$$\frac{s_1 + s_2}{I_0 \times a}, \quad (4)$$

where a is the area of the housing and s_1 and s_2 differ according to the quantile of income per CU (see [Table 20](#)).

Knowing that the renovation decision depends on the aid that can be allocated to the household and that these depend on the EPC score of its housing before and after renovation as well as its income per CU (more precisely in the modeling of its membership in an income quantile per CU, Y_{cu}), the household profile is therefore defined by the EPC of its home before and after and its income per CU.

³²Precariousness is defined as belonging to the first quintile of income per CU.

2.5 The new thermal renovation block

The most important stages of the program concerning the energy renovation block are summarized in Appendix B.5 (Figure 12) and consider the following reasoning for the renovation decision-making of owner-occupied households.

The homeownership household knows the initial financial amount needed for the renovation. It considers the subsidies it can claim (subject to information). The amount of subsidies is defined either on the basis of a given subsidy rate or on the basis of the modeling of different public policies. It calculates the actual amount it will have to pay for the renovation. This amount is the discounted sum of consumer credit repayments over 4 years at the rate of 4%. Recall that the household funds the work through loans and grants. The maximum indebtedness is by default 33% of income. As a result, all of the renovations that can be carried out correspond to renovations for which the notional amount reimbursed each year (by default $N/10\text{-rate}\times N$) is less than 33% of annual disposable income, corrected for accumulated renovation debts (for more details, see Annex B.6).

The household knows the evolution of energy prices for the year preceding its renovation decision and the evolution of its income (fixed growth rate). It adapts its energy consumption according to this information without changing technology. Indeed, the model does not currently take into account the evolution/change of technology.³³ The household studies all the renovation possibilities (jump from EPC band) according to their cost (material, intangible), possible subsidies and the expected effects on the energy bill of the EPC score changes. Assuming that the heterogeneity parameter, ν is known, then all the information needed to calculate the probability that an owner household will renovate its dwelling so that its EPC score varies from i to j (see (2)) is available.

For tenant households, the renovation decision is exogenous. It mainly depends on the lessor. Assuming that the works are “light”, that is to say that they generate only one EPC score jump at a time, it is possible to calculate renovation objectives to achieve the distribution given by Merly-Alpa et al. [2020]. In the tenant housing renovation module, it is assumed that the renovation rates by EPC score are constant over time. Thus, each year, a tenant household has a fixed probability (which depends on the initial score - see Table 3) of benefiting from a renovation.

B	C	D	E	F	G
3.4%	3.8%	6.1%	12.7%	11.45%	5.6%

Table 3: Probability of renovation of tenants’ dwellings according to their EPC score

The user-modifiable model input variables based are summarized in Table 4.

³³This will be the next improvement.

Variation in electricity price	Variation in gas price
Variation in heating oil price	Variation in butane price
Variation in wood price	Variation in charcoal price
Elasticity value for electricity consumption	Elasticity value for gas consumption
Elasticity value for heating oil consumption	Elasticity value for butane consumption
Elasticity value for wood consumption	Elasticity value for charcoal consumption
Variation in the disposable income of households	Variation in social aids received by households
Threshold for the fuel poverty ratio	Unemployment rate, initial year and final year
Intangible costs	Subsidy rate
Term of the loan	Loan interest rate
Household discount rate	Life of an investment
Maximum borrowing rate (constraint)	EPC Band Change cost $I_{i,j}$
Expected reduction in the bill $\Delta_{i,j}$	Annual renovation target for tenants by EPC score

Table 4: Parameters for a simulation

3 Simulations

In this section, the impacts in France of aid/subsidies for housing EERs on the rate of energy renovation and on fuel poverty are studied. For this, the microsimulation model presented in the previous section and which is based on ENL2013 is used. The lockdown periods in the context of the COVID-19 pandemic,³⁴ and the development of remote work that followed, had an impact on the behaviors/decisions of households. Moreover, “*at the end of 2022, in a context of almost continuous price increases throughout the year, more than two-thirds of households say they have changed their consumption habits due to inflation*” INSEE [Mars 2023]. Therefore, the pre- and post-Covid periods must be separated. The databases used in this study relate to the period prior to Covid, so the simulations do not go beyond the year 2019. Two simulations are carried out. The target year of the first simulation is 2017, which makes it possible to calibrate the heterogeneity parameter of owner households faced with the renovation of their principal residence, i.e., ν , as well as the cost matrix of change of EPC band. The target year of the second simulation is 2019. The values of the parameters for the simulation of fuel poverty in 2017 and 2019 are in Table 21 in Appendix C.

Some information needed for simulation and calibration is extracted from Giraudet et al. [2020], Energies Demain et al. [2018], Merly-Alpa et al. [2020].

³⁴In France, the lockdown periods were as follows: from March 17 to May 10, 2020; from October 30 to December 14, 2020; and from April 3 to May 2, 2021.

3.1 Calibration and benchmark of the model

The first simulations are carried out to calibrate certain parameters of the renovation block, in particular the heterogeneity parameter and the intangible costs.

3.1.1 Housing renovation

Some parameters of the renovation block have already been mentioned in 2.2.1 and are summarized in Table 5.

Household discount rate	10%
Investment life	30 years
Loan constraint	33% of income
Interest rate of the loan	4%
Duration of the loan	10 years

Table 5: Value of certain parameters of the renovation block

Rebound effect. When deciding whether to renovate its home, the household does not take into account the rebound effect. Thereafter, two effects of the renovation (improved EPC) are considered (theoretical effect and real effect) and two tables are included in the model. The first is the matrix of expected (or theoretical) effects of an EPC score transition. The values in this matrix are used by owner-occupiers to make their renovation decision. The second (that of the real effects) is used to update household bills for the post-renovation years.

The theoretical effects of a renovation are defined as the effects of the different EPC scores on household energy bills, all other things being equal. Their value can be estimated from a regression of the logarithm of the annual household bill on the characteristics of the dwelling, those of the household and on the EPC score (see Appendix C.2). This estimate (see Table 23) made with data from the ENL2013EPC database shows the limits of the pairing mentioned in Subsection 2.1. Ideally, in the ENL survey, the “good” EPC score of the dwellings of the households surveyed would have been mentioned. Thus, even if the EPCs from the ADEME database were not contestable, the estimate could be biased due to the existence of at least one unobservable variable that acts on the energy bill and is correlated with the EPC score. Moreover, this estimate of the theoretical effect of the renovation assumes that the renovation work carried out is of good quality. Specifically, there is no difference between the theoretical energy efficiency of the efficient renovation (allowing the change in EPC score) and the difference on household energy bills between these two scores.

The presence of a rebound effect may indicate that before the improvement in housing quality, the household was under stress (constraint), financial or psychological. The decrease in the theoretical bill due to the change in EPC score allows a relaxation of this constraint. Based on this assumption, the rebound effect is estimated as follows. Initially, the theoretical rate of effort after renovation denoted T_1 , defined as the ratio between its theoretical energy expenditure and its income, is calculated. This household

expenditure ratio is then compared to the median expenditure ratio corresponding to the new EPC score and the income class per CU (Y_{cu}) to which the household belongs, denoted \bar{T}_{EPC,Y_c} (See Table 6). More precisely, the rate of effort after taking into account the rebound effect, T_1^r , is

$$T_1^r = \begin{cases} \frac{k+1}{2} \times \bar{T}_{EPC,Y_{cu}} & \text{if } \exists k \in \{1, 2, 3\} \text{ such as } \frac{2T_1}{\bar{T}_{EPC,Y_{cu}}} \in [k, k + 1[, \\ T_1 & \text{otherwise.} \end{cases} \quad (5)$$

EPC Scores \ Y_{cu}		1	2	3	4	5
		A	1.71%	1.15%	0.63%	0.51%
B	3.36%	2.33%	1.69%	1.28%	0.80%	
C	4.99%	3.23%	2.51%	2.01%	1.46%	
D	7.07%	4.45%	3.42%	2.71%	1.90%	
E	9.52%	5.64%	4.41%	3.38%	2.51%	
F	12.86%	7.70%	5.72%	4.53%	3.21%	
G	15.74%	10.59%	7.50%	6.09%	4.13%	

Table 6: Median effort rate by household profile (EPC score, Y_{cu})

Illustration: If the median rate of energy effort concerning the profile of the household (defined by the EPC score of its dwelling and its income per CU) is 7%, and if its theoretical rate of effort after renovation is 10% then the rebound effect of this household will be equal to 3/2 of the median rate.

According to (5), if the rate of energy expenditure after renovation (T_1) is greater than twice the median (\bar{T}_{EPC,Y_c}), there is no rebound effect. This situation arises when the improvement of the household's financial situation takes precedence over the improvement of its comfort.

Public policies promoting housing renovation. The new renovation block allows two public policy modeling options. The first consists in considering them separately (as in Subsection 2.4) and the second in grouping them together. In the second, public aid is modeled with an aggregate subsidy rate ($g_{q,i}$ in (1)), different for the EPC score/quintile of income per consumption unit (Y_{cu}). This makes it possible to simplify the model and to overcome multiple hypotheses (parameterization of public aid, probability of access to specific aid, independence between the latter, increase in the common information rate, etc.). A first simulation of the model makes it possible to calculate what is then considered **the maximum subsidy rate for each household profile**. It is determined assuming that households use all the aid granted to them. The value of this maximum rate depending on the household profile will be given after calibration of the model. The use of these maximum subsidy rates makes it possible to check the sensitivity of the model to public aid and to study the effect of targeting according to scores and income categories via a redeployment of the envelopes obtained.

For calibration, the first option is retained, and the following assumptions are made. The aids obtained are independent of each other and households can use one or more aids. Each household has a probability of having access to these aids depending on whether it is informed of their existence. According to the TREMI survey, only 15% of households having carried out work were informed [Energies Demain et al., 2018]. The renovation block of EPEEr is calibrated on this rate and not on 0 or 100% information. The distribution of aid is shown in Table 7.

PTZ	CITE	CEE	TVAR	ANAH
8.3%	18.3%	13.3%	75.0%	13.3%

Table 7: Likelihood of getting financial aid

What is the cost of renovation work to move from one EPC score to another?

Information on these costs is scarce. Admittedly, it is possible to have a price range for different types of work (e.g., floor insulation, changing windows, heating systems), but for these data to be useful, it is necessary to know the condition and number of “equipment” likely to be replaced/renovated. However, this information is not available in the ENL2013 database. While it is possible with ADEME’s EPC database to estimate the gain resulting from a change in EPC, the same is not true of the associated cost. However, there is at least one EPC score transition cost matrix which is defined by [Giraudet et al., 2020]. Even if its elaboration is obscure, in the absence of other data, this matrix, I (defined by Table 24 in the Appendix), is retained for the rest of the study.³⁵

What value should be taken for the heterogeneity parameter of household preferences? Giraudet et al. [2018] point out that there are no data allowing a precise estimate of this parameter (ν). They set it equal to 8, and mention that “*analyses carried out in the past have shown that the energy consumption simulated by the model³⁶ was not very sensitive to this parameter*”. Thereafter, $\nu = 8$.

Intangible costs.³⁷ Data/information to quantify these intangible costs are scarce. Chaton and Zitouni [2023] use the TREMI survey to extract a value. They consider that the intangible costs can be separated into two: δ_d representing the inconvenience suffered during the work and δ_u representing satisfaction after the work. They obtain $\delta_u = 0.225$ and $\delta_d = 0.06$. Therefore, if the discount factor is 0.1 and the lifetime of the investment is 30 years, then the intangible costs add up to 0.18. However, as the authors point out, this may differ from household to household. It is also very likely that this cost depends on the housing EPC score before work. Indeed, intuitively, the more energy intensive the dwellings are, the more the interest in energy renovation outweighs the work of beautifying the dwelling. Additionally, δ_d should grow with the improvement of the EPC. In the absence of information/data to estimate these intangible costs, they are deducted from the calibration. Under the assumption that I is the real EPC score improvement transition cost matrix and that 8 is the true

³⁵However, in view of the simulation results, another matrix is also considered in Appendix C.5.

³⁶i.e. the Res-IRF model.

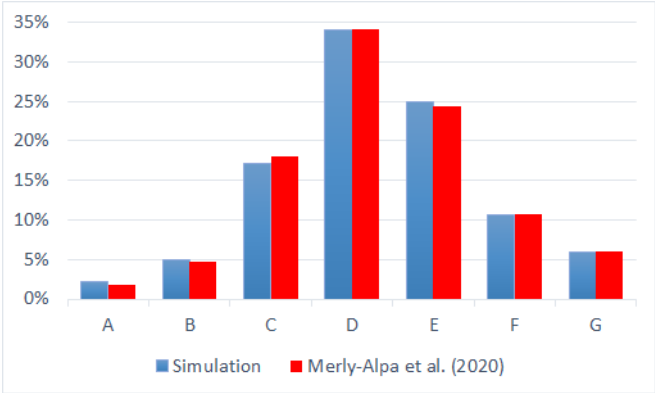
³⁷ α_i in (1).

heterogeneity parameter value, then the difference between the distribution of dwellings according to their EPC score resulting from the simulation when the costs intangible costs are nil and the “actual distribution” (that of Merly-Alpa et al. [2020]) gives the value of these intangible costs. Consequently, if this is not the case (which is highly probable in this study), the value of the intangible costs thus calculated incorporates any errors in the transition costs and the heterogeneity parameter considered. This does not affect the rest of the study. It should not be forgotten that the value of the intangible costs and the heterogeneity parameter (ν) are linked to that of the I matrix and to the structure of the real estate stock considered in 2013 (this is, i.e., from the ENL2013EPC database) and that of the end of 2017. Taking as intangible costs those in Table 8, the distribution by EPC score of the simulated housing stock is shown in Figure 3. This distribution comes from a simulation (hereinafter called **reference simulation**) among hundreds carried out considering these intangible costs.³⁸ It is close to that of Merly-Alpa et al. [2020].³⁹ Consequently, in the remainder of this study, these costs are retained.

B	C	D	E	F	G
0.72	0.85	0.825	0.671	1.18	2.659

Note: These costs have been approximated. They may include errors due to the inclusion of erroneous renovation costs.

Table 8: Intangible costs according to the EPC score of the dwelling before renovation



Note: In blue (red), the distribution of dwellings according to their EPC after the simulation (according to Merly-Alpa et al. [2020]).

Figure 3: Distribution of dwellings on 1 January 2018 according to their EPC score

³⁸In Appendix C.4, Figure 14 gives the minimum, maximum, median and average of each EPC score from these simulations.

³⁹In Appendix C.4, the distributions according to the EPC score of the dwellings of tenants and owner-occupied dwellings from the simulation are compared to that of Merly-Alpa et al. [2020] (see Figure 15). Obviously, if the heterogeneity parameter ν is modified, all other things being equal, the distribution of EPCs simulated at the end of 2017 is not the same. Figure 13 in Appendix C.3 gives this distribution for several values of ν . In view of these distributions, one can wonder about the low sensitivity of the renovation decision to the ν parameter.

3.1.2 Fuel poverty

As in [Chaton and Gouraud \[2020\]](#), the following four indicators are used to quantify the percentage of households in fuel poverty in mainland France:

1. The rate of energy effort, which must not exceed 8% for the three lower deciles of income per consumption unit (8%EER).⁴⁰ According to this indicator, also used by the ONPE, a household is in energy poverty if the ratios
 - (energy expenditure)/(household income) > 10% and
 - (household income)/(consumption units) < 3rd decile.

According to the ONPE [[Devalière et al., 2018](#)], 13.8% of French households in 2013 were in a situation of fuel poverty according to this indicator.

2. Two other indicators are the French versions of the Low Income, High Cost indicator [[Hills, 2011](#)], i.e., a household is in fuel poverty if its income is below the relative poverty line⁴¹ and if its declared energy expenditure exceeds the median energy expenditure. Two versions of the LIHE indicator are used: LIHE_{m²} and LIHE_{CU}. In the first, energy expenditure is divided by the surface area of the dwelling; in the second it is divided by consumption units.
3. As these three indicators target populations that partially overlap, the indicator taking into account all of these precarious households, denoted GFP, is also retained.

3.1.3 Dynamics of energy renovation of housing and fuel poverty in 2017

Some results of the simulation for the period 2013–2014 to the end of 2017 are given in this part. They are based on the value of the parameters defined previously, i.e. taking into account public housing renovation policies. They serve as a reference to study the impact of these policies in subsection [3.2](#).

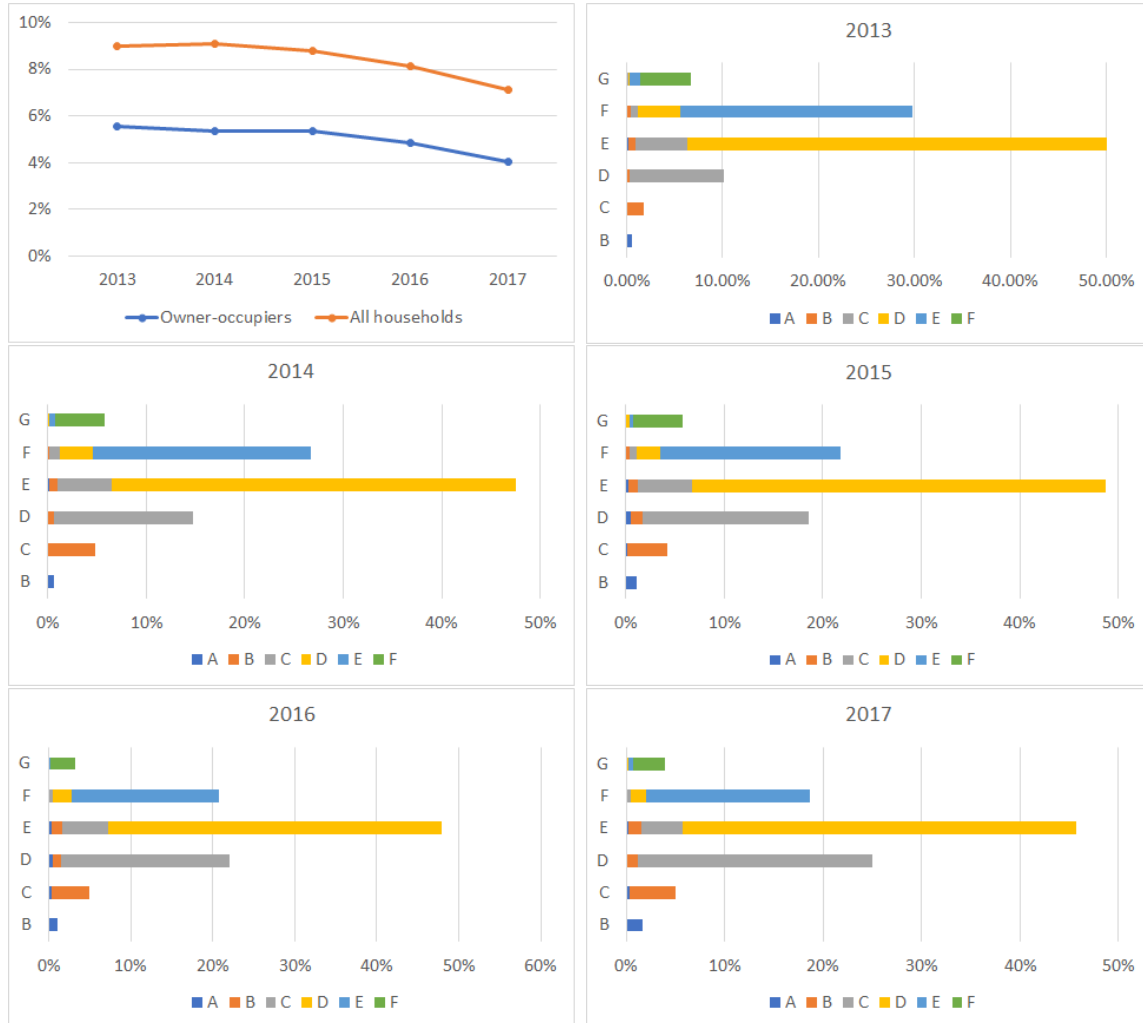
Figure [4](#) gives the percentage of dwellings renovated each year (from 2013 to 2017) in the reference simulation.⁴² In addition to the renovation parameters listed and quantified in [3.1.1](#), this percentage depends on energy prices before the renovation year, as well as household income. It varies from one EPC to another. However, each year, the renovated dwellings are mainly EPC E dwellings (between 43.7% and 51%). Dwellings rated F take second place with a percentage that decreases over time. Thus in 2013, 29.8% of renovated homes had an F score. In 2017, this percentage was 19.8%. On the other hand, the share of dwellings benefiting from score D in renovation increases over time (like those rated B). More than 86.4% of homes that are renovated are only for a score jump. A maximum of 11.18% of renovations (in 2013) allow a jump of more than one score (see [Table 9](#)). Renovations generating a jump of more than one EPC

⁴⁰Note that Chaton and Gouraud considered a rate of 8%.

⁴¹The relative poverty line is set at 60% of the national median income after housing costs and energy costs are deducted.

⁴²Figure [16](#) gives the minimum, maximum, median and average percentages of housing renovated each year obtained from around a hundred simulations.

score are necessarily homeowner renovations. Indeed, it is assumed that the renovation of tenant housing generates only one EPC score jump at a time (see 2.5).



Note: The first graph (top left) gives the percentage of homes renovated each year between 2013 and 2017. The other graphical representations give the percentage renovated each year according to the EPC scores. Thus in 2013, 49.36% of renovated dwellings were classified as EPC E. In 2013, 44.22% of dwellings were dwellings ranging from score E to score D; 4.12% from E to C, 0.95% from E to B and 0.07% from E to A.

Figure 4: Housing renovation rate over time and breakdown by initial EPC score and final EPC score

	2013	2014	2015	2016	2017
A jump from an EPC score	88.60%	88.21%	89.72%	87.41%	89.80%
A jump of two EPC score	7.97%	8.49%	8.15%	9.94%	7.80%
A jump of three and more EPC score	3.43%	3.30%	2.13%	2.65%	2.40%

Table 9: Percentage of renovation according to the number of EPC score jumps

The distribution of renovations between tenants and owners occupying their accommodation is given in Table 10.⁴³

	2013	2014	2015	2016	2017
Owners occupying their homes	59.32%	59.30%	59.46%	59.27%	53.34%
Tenants	40.68%	40.70%	40.54%	40.73%	46.66%

Table 10: Percentage of renovation according to occupancy status

According to the simulation, the percentage of owner-occupier households who renovate their dwelling is between 12.4% and 15.8% (see Table 11). Over the period studied, according to the simulation, well over 3/4 of owner-occupied housing renovations allow a single class jump (see Figure 5). This is consistent with the type of renovations completed, where only a few were global renovations. However, staged renovation is not the most effective for obtaining classified housing BBC⁴⁴ (see ADEME [2021] and Chaton and Zitouni [2023]).

2013	2014	2015	2016	2017
15.70%	15.84%	15.34%	14.19%	12.41%

Table 11: Percentage of owner-occupiers who renovate their home

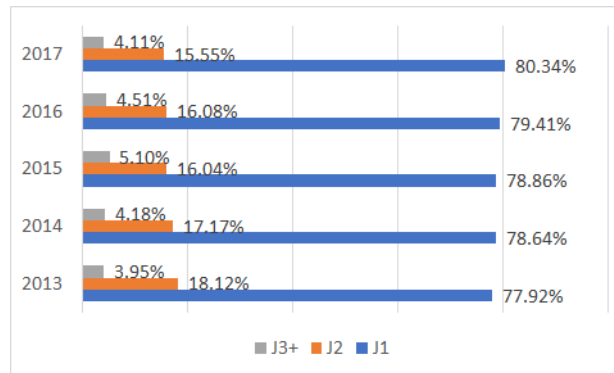


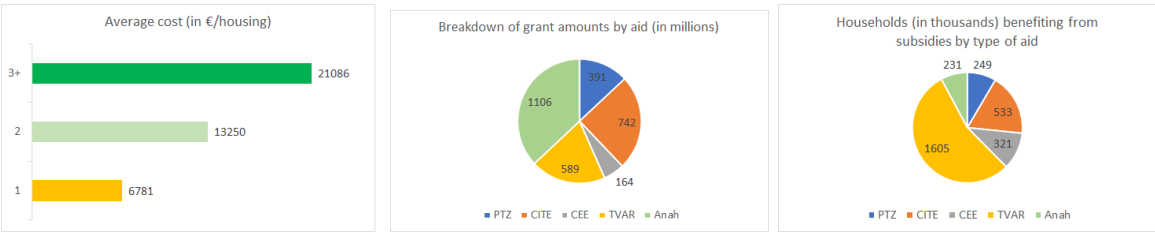
Figure 5: Distribution of renovations of owner-occupier housing according to the number of EPC score jumps

Figure 6 reports, over the period 2013-2017, the average cost of energy efficiency work in owner-occupied housing as well as the average amount of the various subsidies received, according to the number of EPC score jumps. Nearly half of the envelope is devoted

⁴³Recall that 57.4% of households own their home.

⁴⁴BBC: low energy consumption building.

to financial aid from Anah (37%), while only 7.9% of owner-occupiers who receive aid for effectively renovating their housing benefit from the aid of Anah. On the other hand, 54.6% of owner-occupiers benefit from a VAT reduced (rVAT) to 5.5%, which represents 19.7% of the total amount of aid considered in this study. Compared to the result of the TREMI 2017 survey (Energies Demain et al. [2018]), the average costs in euros from the simulation are much lower. Indeed, while with the simulation the average expenditure per accommodation amounts to €8,486, according to TREMI it is €11,750. This cost difference is higher if we look at the average cost in euros per accommodation allowing one or more EPC score jumps. This cost difference is more significant if we consider the average cost in euros per accommodation allowing one or more jumps in EPC scores. Thus, while in simulation this cost is €6,781 (€14,880) for a score jump (at least two score jumps), according to Energies Demain et al. [2018] it is €15,900 (€25,900). Certainly the TREMI 2017 survey only concerns individual houses as main residences (private and social housing) over the period 2014 and 2016, but is this sufficient to explain the difference in cost? We can therefore question the accuracy of the values of the I matrix retained⁴⁵. Consequently, in Appendix C.5, a sensitivity analysis with respect to this matrix is carried out.



Note: The graph on the left gives the average cost of work carried out in owner-occupied dwellings according to the EPC score jump they generate. The graph on the right gives the average amount in euros of the various subsidies granted according to the number of EPC score jumps (1, 2 or 3 and more).

Figure 6: Average cost (in euros) and average grants for work carried out from 2013 to 2017

Figure 17 in Appendix C.4 gives the average amount of aid received according to the type of aid and the jumps in EPC class generated by the energy renovation. The amounts confirm that Anah’s aid is on average higher than that of other aid.

If over time, the total amount of aid increases, the same cannot be said for the total cost of energy renovations⁴⁶ (see Table 12).

⁴⁵Recall that I is defined by Table 24.

⁴⁶Recall that by assumption renovation costs are constant over time (same transition matrix to move from one EPC to another).

	2013	2014	2015	2016	2017
Amount of aid paid	0.331	0.378	0.577	0.691	0.729
Total cost of all energy efficiency retrofits	12.359	11.862	11.416	11.188	9.079

Table 12: Amount of annual aid and energy renovation costs (in billions of euros)

Table 13 provides information on the average household income, the average energy bill and the fuel poverty rate according to the 4 indicators mentioned in 3.1.2 for the period 2012–2014 and the year 2017. The percentage of households in fuel poverty according to the 8%EER indicator resulting from the reference simulation (11.99%) is between that obtained by the Prometheus model (11.6%)⁴⁷ and Chaton and Gouraud [2020] (13.02%).⁴⁸ The energy renovation of housing is not the main cause of the reduction in energy poverty between 2012/2014 and 2017. Indeed, it is also explained by the increase in the disposable income of households associated with a decrease in prices at the consumption (including taxes) of natural gas, heating oil and butane.

	2013 – 2014	2017
Average annual gross income (€)	39,283	41,495
Average annual energy expenditure (€)	1,578	1,454
Percentage of fuel poor households		
8%EER	14.06 %	11.99%
LIHE _{m²}	13.67 %	13.81 %
LIHE _{cu}	10.06 %	10.01 %
GFP	19.48 %	18.61 %

Table 13: Income, energy bill and fuel poverty ratios (calculated for 2013/2014 and simulated for 2017)

3.1.4 The maximum subsidy rate for each household profile

The value of this maximum rate defined in 3.1.1 is given in Table 14. This maximum subsidy rate decreases with the income decile. Contrary to intuition, this rate does not strictly decrease with improvement in energy performance.

⁴⁷See Devalière et al. [2018].

⁴⁸Table 25 gives the minimum, maximum, average and median percentages of households in fuel poverty based on around a hundred simulations.

		Y_c				
		1	2	3	4	5
EPC Scores	B	79.5%	72.8%	27.8%	28.8%	28.8%
	C	83.8%	74.4%	30.0%	30.0%	30.2%
	D	87.8%	72.8%	32.4%	32.0%	31.6%
	E	79.5%	68.8%	32.7%	34.0%	33.3%
	F	91.3%	75.2%	31.3%	35.6%	37.5%
	G	99.3%	72.9%	37.7%	39.2%	41.9%

Table 14: Maximum effort rate by household profile (EPC score, Y_{cu})

3.2 Impact of subsidies for housing EERs on renovation and on fuel poverty

As with the initial model (EPEE), it is possible with EPEEr to study the impact on the energy poverty rate of variations in the price of energy, the unemployment rate, income and energy renovation. However, this is not done in this study because the emphasis is on the novelty, namely the study of the impact on the one hand of public aid for energy renovation and on the other hand information on such aid on fuel poverty. Subsequently, the following four scenarios are studied.

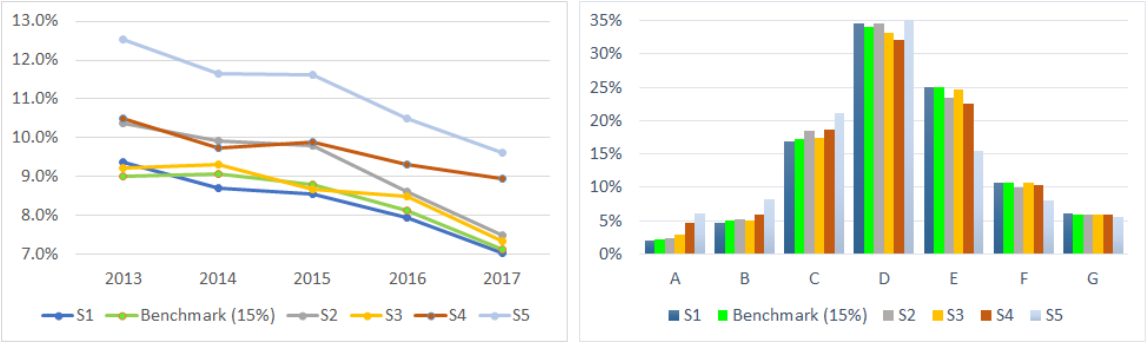
- S1: absence of public aid for the energy renovation of housing;
- S2: perfect information on aid;
- S3: policy targeted at the first income quintile;
- S4: policy targeted at the first two income quintiles;
- S5: targeted policy on housing with EPC score E to G.⁴⁹

Figure 7 shows for the different scenarios the dynamics of the energy renovation of housing as well as their distribution at the end of 2017 according to the EPC. Obviously, perfect information on aid (scenario S2) leads to more renovations than in the case of the benchmark (reference simulation) where only 15% of households having carried out work were informed of the aid. It also appears that the percentage of renovated housing is lower without renovation aid (S1). Compared to the benchmark, it is certainly preferable from the point of view of the thermal quality of housing to target aid on “leaky houses” (S5). This type of targeting, which concerns the energy quality of housing, does not seem to have been implemented in the past. It is true that today it is easier to have information on household income than on the energy class of their home.⁵⁰ Targeting aid to the first income quintile (S3) also reduces the number of “leaky

⁴⁹If the objective of renovation policies is to eliminate “leaky houses”, why not only help owners of EPC score E to G housing?

⁵⁰In fact, owner-occupiers who do not wish to sell or rent their home are not encouraged to have an energy performance diagnosis carried out for their home.

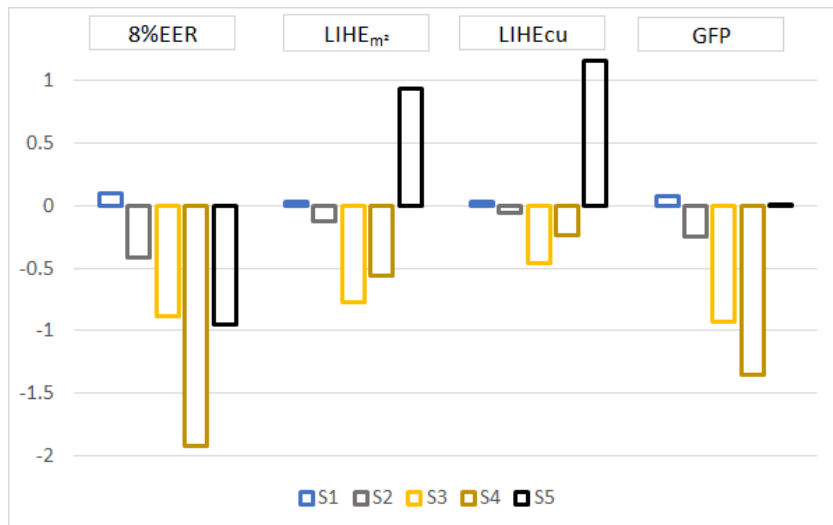
houses” compared to the benchmark. However, this reduction is greater if the targeting is on the first two income quintiles (S4). Certainly this reduction is less significant than in scenario S5. But among the scenarios considered, which contributes the most to reducing fuel poverty?



Note: The graph on the right gives the percentage of homes renovated each year between 2013 and 2017 according to the different scenarios considered: S1: no public aid for the energy renovation of homes; S2: perfect information; S3 (S4): policy targeted at the first (the first two) income quintile(s) and S5: targeted policy on housing with EPC scores E to G. The graph on the left gives the percentage of dwellings by EPC score at the end of 2017 for each scenario.

Figure 7: Impact of aid on the renovation dynamic and on the distribution of EPC at the end of 2017

Public aid for housing EERs should help reduce fuel poverty. However, is this always the case? According to the simulations, greater information on aid contributes to reducing energy poverty (i.e., S2 versus Benchmark – see Figure 8). Among the scenarios considered, targeting the first two income quintiles (S4) makes it possible to reduce fuel poverty the most. This reduction is 1.92 (1.35) percentage point (pp) compared to the benchmark if the 8%EER (GFP) indicator is used. If we know (see, for example, [Chaton and Gouraud \[2020\]](#)) that LIHEs are not very sensitive to variations in energy prices and income because they are calculated with variable thresholds (medians), Figure 8 shows that these indicators are sensitive to the targeting of renovation aid. Thus, targeting aid to the first income quintile contributes to reducing fuel poverty compared to the reference of 0.77 pp (0.46 pp) according to the $LIHE_{m^2}$ ($LIHE_{cu}$). This is all the more convincing if we look at the S5 scenario. If we use the global indicator (i.e., GFP) as the indicator of fuel poverty, targeting aid on “leaky houses” does not contribute to reducing fuel poverty. Thus, although scenario S5 is the most effective in terms of reducing the “leaky houses”, it is not in terms of reducing fuel poverty. Worse, compared to the aid system of the reference scenario, this could worsen the situation (if indicators LIHEs or GFP are considered).

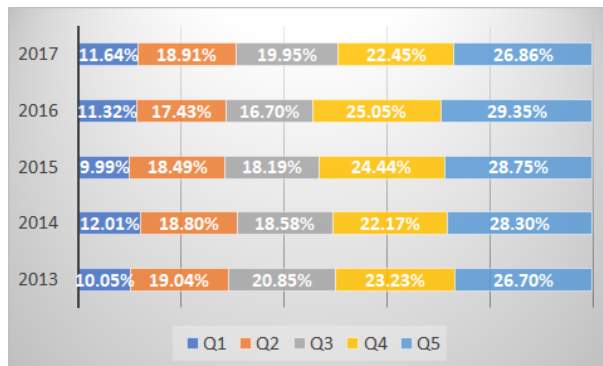


Note: The bars represent the variations in percentage points of fuel poverty according to the 4 indicators retained compared to the benchmark for the 4 scenarios considered. Thus, if scenario 1 (S1) is considered (i.e. no aid for energy renovation), fuel poverty according to 8%EER increases by 0.1 pp compared to the benchmark.

Figure 8: Variation in fuel poverty at the end of 2017 due to changes in aid

Without aid (scenario S1), there would have been 4.30% more owner-occupiers living in “leaky houses” (EPC score E to G) and 6.98% fewer in low-energy buildings (EPC score A and B). On the other hand, without aid the percentage of households in fuel poverty would have increased very little. However, can we deduce from this that owner-occupier households who renovate their homes have few financial difficulties?

Certainly, if we refer to the percentages in Figure 9. In fact, the percentage of owner-occupant households who renovate and who belong to the first income quintile is much lower than that of owner-occupant households belonging to the other quintiles. More than half of owner-occupied housing renovations are initiated by households in the top two income quintiles.

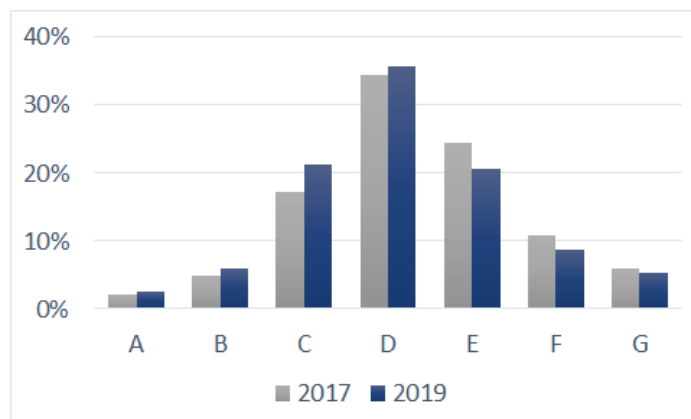


Note: The graph above shows the distribution of home renovations by owner-occupiers each year by income quintile. The number of renovations of these housing units is for 2013: 1.49 million; 2014: 1.43 million; 2015: 1.43 million; 2016: 1.31 million; 2017: 1.09 million.

Figure 9: Distribution of renovations of owner-occupied housing by income quintile

3.3 Simulation for the year 2019

Figure 10 gives the simulated distribution of the real estate stock in mainland France according to the EPC for the end of 2017 and the end of 2019.



Note: In gray (blue), the distribution of dwellings according to their EPC after the simulation in 2017 (2019).

Figure 10: Distribution of dwellings according to their EPC score

The improvement in the energy efficiency of certain homes has offset the increase in energy prices between 2017 and 2019 (see Table 21). Thus, the average annual energy expenditure⁵¹ increased very little between 2017 and 2019. In fact, this increase is €33 (see Tables 13 and 15). This increase in the energy bill was on average more than offset by the increase in income⁵², leading to a reduction in energy poverty between 2017 and 2019. Thus, according to the simulations, in 2017 (2019), 18,61% (18.29%) of households in mainland France are in fuel poverty as defined by the GFP indicator. Considering the 8%ERR indicator in 2019 this rate is 11.6%. This value is close to that mentioned by the ONPE. Indeed, [ONPE \[2023\]](#) underlines that in 2019, 11.4% of households were in fuel poverty according to 8%EER. This rate is 11.9% if it is corrected for climate.

⁵¹The projection of the annual energy bill according to the surface area of the dwelling is given in Table 28.

⁵²The average annual gross income in 2017 (2019) is €41,495 (€42,688).

	2019
Average annual gross income (€)	42,688
Average annual energy expenditure (€)	1,487
Percentage of fuel poor households	
	8%EER 11.6%
	LIHE _{m²} 13.64%
	LIHE _{cu} 10.1%
	GFP 18.29%

Table 15: Income, energy bill and fuel poverty ratios
(Simulated for 2019)

If for each income decile over the period 2012-2014 (ENL2013), the rate of fuel poverty decreased between 2012-2014 and 2019, it nevertheless remains excessively high for the first deciles. Thus, in 2019, nearly 74% (more than half) of households that belonged to the first (second) income decile during the period 2012-2014 are in fuel poverty according to the GFP indicator (see Table 16). Almost 10% of households belonging to the fifth income decile are in fuel poverty in 2019. The EPEER model makes it possible to determine the percentage of households leaving or entering fuel poverty between the period 2012-2014 and the simulation year. Thus, when 2019 is the simulation year, 2.18% (6.22%) of households in the first income decile enter (exit) in fuel poverty (see Table 29).

	D1	D2	D3	D4	D5
2012-2014	78.00%	54.49%	25.99%	19.23%	10.15%
2019	73.97%	51.69%	23.89%	17.17%	9.91%
	D6	D7	D8	D9	D10
2012-2014	4.29%	1.89%	0.42%	0.23%	0.11%
2019	3.82%	1.76%	0.38%	0.22%	0.11%

Table 16: Percentage of households in fuel poverty (GFP) according to their status
(income decile) in 2012-2014

More than half of households where the household reference person (HRP) is outside the labor market or homemaker are in fuel poverty considering GFP as the indicator of fuel poverty (see Table 30). The reduction in fuel poverty between the two periods was greatest for households where the reference person was unemployed.

4 Conclusion

If the French National Housing Survey (ENL) seems to be the only source of data rich enough to accurately measure fuel poverty in mainland France, it has the defect of not being carried out closely. Thus, nearly a decade has elapsed between the last two surveys and data from the last survey (ENL2020) were not available at the time of the development of the EPEER model.⁵³ Thus, as mentioned in [Les cahiers Louis Bachelier \[2019\]](#), “*obtaining recent data is a real problem... To calculate detailed up-to-date figures on fuel poverty, we have to make use of a model or obtain new data at national level, because the ENL is too widely spaced over time.*” Thus, the ONPE monitors the evolution of fuel poverty in France through the 8%EER indicator estimated with the Prometheus microsimulation model. Insofar as this indicator does not consider all households in fuel poverty, the ONPE also uses a subjective indicator based on the feeling of household members in terms of thermal comfort. The EPEE model quantifies fuel-poor households with the Reduced Cold indicator⁵⁴, but as projections using a logit model give counterintuitive and unreliable results, this subjective indicator is not used. We can obviously wonder about the fuel poverty indicator(s) to be used to qualify households as fuel poor. But others have already done it (e.g. [Castaño-Rosa et al. \[2019\]](#)). One solution could be, as [Chaton and Guillerminet \[2023\]](#) suggest, to consider that a household is in fuel poverty if it does not have sufficient income to acquire a minimum amount of energy and other essential goods (food, housing, clothing, etc.). The difficulty is then to quantify this minimum level that depends on the one hand on the characteristics of the dwelling (surface area, energy efficiency, etc.) and on the other hand on the composition of the household and its habits (number of individuals, time spent in housing, etc.). This could be an extension/a block to add to the EPEER microsimulation model, used in this study, which makes it possible to quantify households in fuel energy poverty from 8%EER, LIHE_{m²} and LIHE_{cu} indicators as well as from the global indicator (GFP).

The EPEER model allows, among other things, to study the impact of aid encouraging building EERs on the evolution (in terms of EPC score) of the French real estate stock, and on fuel poverty. However, the calibration and simulations are based on a transition cost matrix from one EPC to another. However, the impact of this matrix is not negligible (see Appendix C.5). It would therefore be useful to have information to develop this matrix. In addition, given the increase in material prices, it should be updated for analyzes beyond 2019.

The model EPEER was calibrated by considering the distribution at the end of 2017 of the main residences of owner-occupiers and tenants. This could be improved by differentiating the type of accommodation (apartment/house) to take into account the constraints weighing on owners of collective housing. These constraints are expected to contribute to different intangible costs depending on the type of housing.

⁵³ENL2013 was conducted between June 2013 and June 2014 and ENL2020 (available since summer 2023) between October 2019 and April 2022.

⁵⁴A household whose income per CU is less than the third decile is considered fuel poor according to the Reduced Cold indicator if it declares suffering from cold because of one of the following reasons: 1) Insufficient heating installation; 2) Poor insulation of the dwelling; 3) Self-heating restriction due to the cost.

This model, which certainly has weaknesses, mainly due to the lack of data, is the only one to my knowledge that can be used to evaluate the impact of aid for housing EERs on fuel poverty in France. To do this, the matrix of gains resulting from the transition from one EPC to another (independent of transition costs) was estimated (see Table 22). Since non-precarious homeowner households are not necessarily protected from falling into fuel poverty, subsidizing the energy renovation of their homes can prevent them from falling into this state. Targeting households in the first two income quintiles contributes to reducing fuel poverty. If aid focuses on the worst EPC housing, it is not certain that energy poverty will decrease. Indeed, according to the simulations if the chosen indicator is 8%EER there is a reduction in energy poverty, on the other hand it increases if indicators LIHEs are considered. Consequently, helping only with the renovation of “leaky home” does not necessarily imply the reduction of fuel poverty. One of the benefits of this assistance is to encourage owner-occupiers to have an energy performance diagnosis carried out for their home.⁵⁵ Certainly, living in more energy-efficient housing reduces energy consumption, but to avoid falling into fuel poverty, you must still have sufficient income to purchase a decent level of energy and decent levels of other goods essential (housing, food, health expenses, etc.).

References

- ADEME. La rénovation performante par étape. Technical report, ADEME, dorémi and ENERTECH, 2021.
- H. Allcott and M. Greenstone. Is there an energy efficiency gap? *Journal of Economic Perspectives*, 26(1):3–28, 2012.
- E. Aydin, N. Kok, and D. Brounen. Energy efficiency and household behavior: The rebound effect in the residential sector. *The Rand Journal of Economics*, 48(3): 749–782, 2017.
- R. Best and K. Sinha. Fuel poverty policy: Go big or go home insulation. *Energy Economics*, 97, 2021.
- S. Borenstein. A microeconomic framework for evaluating energy efficiency rebound and some implications. *The Energy Journal*, 36(1):1–21, 2015.
- P. Bouisset, R. Benda, and A. Bornstein. Are low-income households sensitive to tax incentives for energy efficiency investments? evidence from french tax credit schemes. Technical Report 2023/1, Direction générale du Trésor, 2023.
- R. Castaño-Rosa, J. Solís-Guzmán, C. Rubio-Bellido, and M. Marrero. Towards a multiple-indicator approach to energy poverty in the european union: A review. *Energy and Buildings*, 193:36–48, 2019.
- R. Caumont, T. Merly-Alpa, and J.-P. Rathle. La rénovation énergétique des maisons individuelles : résultats de l’enquête tremi 2020, in La rénovation énergétique des logements bilan des travaux et des aides entre 2016 et 2019. Technical report, ONRE, 2022.

⁵⁵This diagnosis is currently mandatory for the sale or rental of accommodation.

- C. Chaton and A. Gouraud. Simulation of fuel poverty in France. *Energy Policy*, 140:111434, 2020.
- C. Chaton and M.-L. Guillerminet. Coverage for fuel poverty. Available at SSRN: <https://ssrn.com/abstract=4479746> or <http://dx.doi.org/10.2139/ssrn.4479746>, 2023.
- C. Chaton and S. Zitouni. To invest or not in the energy renovation of one’s home? Technical report, WP FiME, 2023.
- C. Crampes and T.-O. Léautier. Les certificats d’économie d’énergie entre économie et politique. *Revue économique*, 74:51–80, 2023.
- I. Devalière, M. Clément, and F.-X. Dussud. Suivi annuel de la précarité énergétique : un nouvel enjeu pour l’onpe. Technical report, Observatoire National de la Précarité Energétique, 2018.
- S. Ebrahimiagharehbaghi, Q. K. Qian, F. M. Meijer, and H. J. Visscher. Unravelling dutch homeowners’ behaviour towards energy efficiency renovations: What drives and hinders their decision-making? *Energy Policy*, 129:546–561, 2019.
- Energies Demain, Kantar Public, and Pouget Consultants. Enquête TREMI : Travaux de rénovation énergétique des maisons individuelles, campagne 2017. Technical report, ADEME, 2018.
- M. Fowlie, M. Greenstone, and C. Wolfram. Do energy efficiency investments deliver? evidence from the weatherization assistance program. *The Quarterly Journal of Economics*, 133(3):1597–1644, 2018.
- M. Frondel and C. Vance. Heterogeneity in the effect of home energy audits: Theory and evidence. *Environ Resource Econ*, 55:407–418, 2013.
- K. Gillingham and K. Palmer. Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence. *Review of Environmental Economics and Policy*, 8(1):18–38, 2014.
- L.-G. Giraudet, C. Bourgeois, P. Quirion, and D. Glotin. Evaluation prospective des politiques de réduction de la demande d’énergie pour le chauffage résidentiel. Technical Report 2023/1, CIREN CNRS; école des ponts paristech. (hal-01955954v2), 2018.
- L.-G. Giraudet, C. Bourgeois, and P. Quirion. Efficacité économique et effets distributifs de long-terme des politiques de rénovation énergétique des logements. *Économie & prévision*, 27(1):43–63, 2020.
- J. Healy and J. Clinch. Fuel poverty, thermal comfort and occupancy: results of a national household-survey in ireland. *Appl. Energy*, 73(329-343):105195, 2002.
- J. Hills. Fuel poverty: the problem and its measurement. Technical report, CASEREport, 69. Department for Energy and Climate Change, London, UK, 2011.

- R. B. Howarth and A. H. Sanstad. Discount rates and energy efficiency. *Contemporary Economic Policy*, 13(3):101–109, 1995.
- INSEE. La croissance résiste, l’inflation aussi. Technical report, Note de conjuncture (SSN 2726-6176 ISBN : 978-2-11-162385-9), Mars 2023.
- W. S. Jevons. *The coal question. An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-Mines*. London: Macmillan and Co., 1866.
- Le médiateur national de l’énergie. Baromètre énergie-info 2022. Technical report, Médiateur national de l’énergie, 2022.
- R. Le Saout, B. Mesqui, and J.-P. Rathle. Le parc de logements par classe de performance énergétique au 1er janvier 2022. Technical report, Observatoire national de la rénovation énergétique, Commissariat général au développement durable, Service des données et études statistiques, 2022.
- Les cahiers Louis Bachelier. Measuring fuel poverty in real time. *Les cahiers Louis Bachelier*, 33:14–15, 2019.
- A. M. Matos, J. M. P. Q. Delgado, and A. S. Guimarães. Linking energy poverty with thermal building regulations and energy efficiency policies in portugal. *Energies*, 15(329), 2022.
- T. Merly-Alpa, N. Riedinger, and M. Baudry. Le parc de logement par classe de consommation. Technical report, Ministère de la transition écologique, 2020.
- ONPE. Tableau de bord de la précarité énergétique 2022. Technical report, Observatoire National de la Précarité Énergétique, 2023.
- P. C. Stern. Blind spots in policy analysis: What economics doesn’t say about energy use. *Journal of Policy Analysis and Management*, 5(2):200–27, 1986.
- D. G. Woodward. Life cycle costing—theory, information acquisition and application. *International Journal of Project Management*, 15:335–344, 1997.
- Z. Xiang, Y. Yin, and Y. He. A microeconomic methodology to evaluate energy efficiency by consumption behaviors and strategies to improve energy efficiency. *Sustainability*, 10(11):4327, 2018.

Appendix: for online publication

A The French EPC label, “Energy Performance Diagnostic, DPE”

The French EPC label provides information on the energy consumption and greenhouse gas emissions of a dwelling and estimates the amount of the annual energy bill of the household that resides in this dwelling. Specifically, it reflects the consumption in primary energy as expressed in kWh_{pe} per m² and per year for heating, domestic hot water, and cooling. The primary energy accounts both the final energy, that is, the energy used by a house (gas, electricity, heating oil, etc) plus all the energy needed to extract, transport, store, and produce them. Depending on the estimated level of energy consumption, a label score is assigned from A (the most efficient) to G (the most mediocre). Table 17 shows thresholds for primary energy consumption for all label scores. Thus, for a dwelling whose primary energy consumption is between 151 kWh_{pe}/m²/year and 230 kWh_{pe}/m²/year, it is assigned a D score.

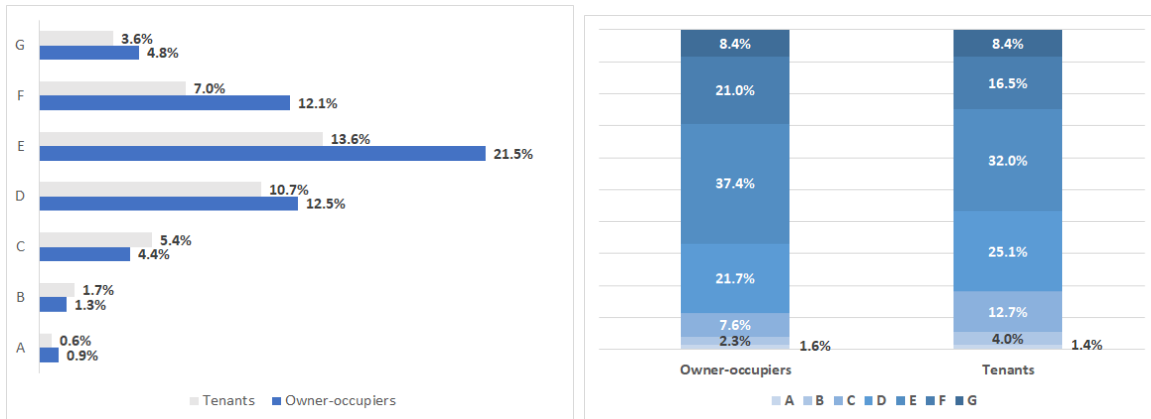
A	B	C	D	E	F	G
50	90	150	230	330	450	–

Table 17: Thresholds for primary energy consumption (kWh_{pe}/m²/year)

B Supplement to Section 2

B.1 ENL2013EPC database

The distribution of EPC scores by tenant or homeowner status is shown in Figure 11.



Note: The figures above give the distribution of EPC scores according to household status (owner occupiers and tenants). Thus, in the ENL2013EPC database, 21.5% of households (13.6%) are owner-occupiers (tenants) living in a dwelling with an EPC E score (left figure). These 21.5% (13.6%) represent 37.4% (32%) of the owner-occupier (tenant) population.

Figure 11: Distribution of EPC scores according to household status (owner occupiers and tenants).

B.2 Statistics on the ENL2013

Statistics	Mean	St. Dev.
Total energy expenditure (€)	1,461	1,031
Energy expenditure per m ² (€/m ²)	18.88	10.62
Energy expenses + rental charges	1,617	977
Housing cost (€)	19,561	5,101
Total annual income (€)	39,959	47,427
Total income per consumption unit (CU)	25,376	29,111
Income net of housing costs	35,142	46,630
Income net per CU	22,008	29,074
CU	1.62	0.57
Age of household reference person	53.90	16.80
Household dwelling area	91.88	42.85
The owners	0.56	0.50
Tenants	0.38	0.49

Table 18: Some statistics about the ENL2013

B.3 CEE: Subsidy per kWh cumac/m² per label transition

The amount of cumulative energy discounted gains following an improvement in EPC is given for the various transitions in the following table.

EPC Scores	A	B	C	D	E	F
B	171					
C	534	363				
D	1126	955	592			
E	1982	1811	1448	856		
F	3202	3031	2669	2077	1220	
G	5337	5166	4803	4211	3355	2135

Source: [Giraudet et al. \[2018\]](#)

Table 19: Savings cumulative energy discounted for each EPC score jump (KWh cumac/m²)

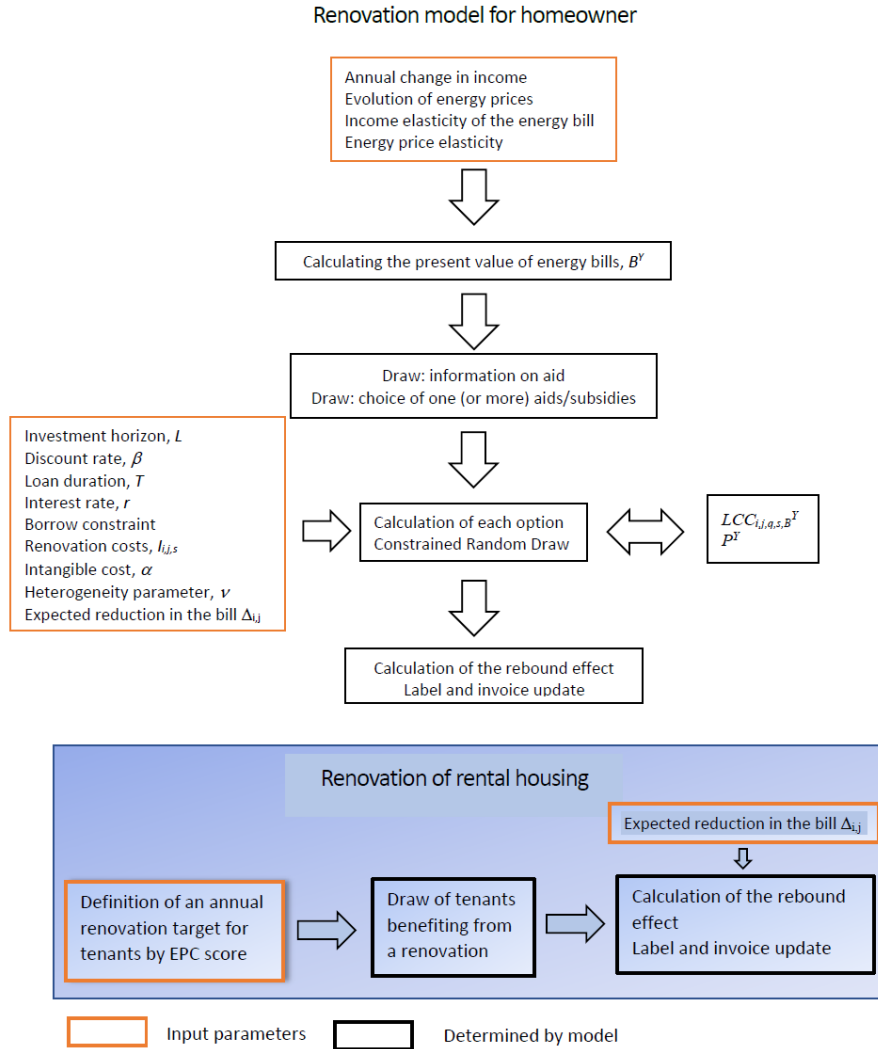
B.4 Financial assistance from Anah

The determining parameters of the amount of payment of the Anah aid (see formula 4), s_1 and s_2 are defined in Table 20.

	s_1	s_2
Quintile 1	$\min(0.5 \times I_0, 10000)$	$\min(0.1 \times I_0, 2000)$
Quintile 2	$\min(0.35 \times I_0, 7000)$	$\min(0.1 \times I_0, 1600)$

Table 20: Anah aid disbursement parameters

B.5 Renovation block of EPEEr model



Note: The renovation block is not the same whether the household owns or rents its main dwelling. The likelihood that a homeownership household will renovate their home and switch EPC bands depends on the life-cycle cost of the investment needed for this switch. This probability depends for tenants on an annual renovation objective.

Figure 12: Structure of the renovation block of the microsimulation model

B.6 Impact of household debt on disposable income

The impact of indebtedness due to renovation investments is taken into account in the model. For the sake of simplification, each year, only the obligation of the following year is taken into account. This is greater than the obligations for future years since, on the one hand, the amount to be paid will be less the following year, and on the other hand, the income will not have decreased. The renovation module does not take status changes into account. A household that invests in year $t = 0$ receives the amount of subsidies in year $t = 1$. These grants enable it to repay part of its debt. Grants never exceed the amount borrowed. Future interest is calculated on the remainder to be repaid. Thus, by denoting N the notional amount borrowed, D_k the stock of debt at period k (before detachment of the coupon), S the amount of subsidies, then if a household renovates at $t = 0$, its debt at $t = k$ will be equal to

$$D_k = \max\left(\frac{T-k}{T}N - S, 0\right). \quad (6)$$

The coupon paid each year is equal to $C_k = 1(D_k > 0) \times \min(N/T, D_k)$ and the interest is equal to $i_k = \pi \times D_k$. Consequently, having contracted a loan at $t = 0$, the disposable income of the household at period k is reduced by $C_k + I_k$. As a result, assumptions were made. The household repays part of its loan before the usual due date. The banker only looks at the current situation of the household, in other words, he only looks at the deadline for the year of the potential work to grant or not a loan.

C Supplement to Section 3

C.1 Parameter values for simulations

The model is tested with projections of thermal renovation of housing and fuel poverty projections in 2017 and 2018. The ENL2013 survey was conducted from June 2013 to June 2014, so the parameters for the initial year are averages over this period: the growth rates of prices energy prices are calculated from the average of the prices between June 2012 and June 2014 and the initial unemployment rate as well as the initial disposable income are the average of the figures for 2013 and 2014. The variation of energy prices is the percentage of variation between the mean price June 2012 to June 2014 and the mean price for the projection year (January to December). Thus, the initial year for the simulation is the period of survey submission and the projection year goes up to the end of 2017 or 2018.

C.2 Theoretical effects of renovation

Table 23 gives the result of estimating the logarithm of the energy bill.

Label of the parameter	2017	2019
Variation in electricity price	9%	9%
Variation in gas price	-9%	3%
Variation in heating oil price	-18%	2%
Variation in butane price	-1%	10%
Variation in wood price	-5%	-4%
Variation in charcoal price	2%	2%
Elasticity value for electricity consumption	-0.31	
Elasticity value for gas consumption	-0.28	
Elasticity value for heating oil consumption	-0.24	
Elasticity value for butane consumption	-0.24	
Elasticity value for wood consumption	-0.24	
Elasticity value for charcoal consumption	-0.24	
Variation in the disposable income of households	5.6%	8.5%
Variation in social aids received by households	5.6%	8.5%
Threshold for the fuel poverty ratio	8%	
Unemployment rate, initial year	9.83%	
Unemployment rate, final year	9.07 %	8.73%

Table 21: Value of the parameters for the 2017 and 2019 simulations

Label of the parameter	Estimate	Std. Error	t value	Pr(> t)
Intercept	5.620186	0.037007	151.867	< 2e-16 ***
Ln(income total)	0.022724	0.002766	8.216	< 2e-16 ***
Consumption units	0.059116	0.004080	14.489	< 2e-16 ***
Shops far	0.002453	0.004686	0.524	0.600621
Work car motorbike ^(a)	-0.002140	0.004747	-0.451	0.652159
Usufructuary owner				
“Hosted” = free lodging	-0.003645	0.007420	-0.491	0.623263
Tenant hlm ^(b)	-0.037567	0.006045	-6.215	5.23e-10 ***
Tenant no hlm	-0.024335	0.005290	-4.600	4.23e-06 ***
Retired				
Employed	-0.016892	0.005624	-3.004	0.002671 **
Unemployed person	-0.023904	0.008478	-2.819	0.004816 **
Homemaker	0.006837	0.015198	0.450	0.652825
Out-off the labor market	-0.014879	0.011467	-1.298	0.194446
More than 8 hours ^(c)				
Less than 3 hours (H)	0.021905	0.005263	4.162	3.16e-05 ***
From 3H to 8H	0.007377	0.004920	1.499	0.133813
Less than 25 m ²				
From 25 to 40 m ²	0.362034	0.016544	21.882	< 2e-16 ***
From 40 to 70 m ²	0.671581	0.015727	42.702	< 2e-16 ***
From 70 to 100 m ²	0.890449	0.016086	55.356	< 2e-16 ***
From 100 to 150 m ²	1.089636	0.016685	65.308	< 2e-16 ***
More than 150 m ²	1.426571	0.017722	80.499	< 2e-16 ***
Detached house/farm				
Semi-detached house	-0.025640	0.004898	-5.235	1.67e-07 ***
Building – 2 flats or fewer	0.004804	0.016966	0.283	0.777068
Building – Between 2 and 9 flats	-0.013223	0.015550	-0.850	0.395148
Building – More than 10 flats	-0.023074	0.015461	-1.492	0.135618
Leaky home	0.130296	0.058954	2.210	0.027104 *
Other type of dwelling	-0.123291	0.020284	-6.078	1.23e-09 ***

.../...

(a): Commuting to work or home by car or motorbike.

(b): HLM = housing at moderate rent.

(c): Periods during which the home is unoccupied.

Label of the parameter	Estimate	Std. Error	t value	Pr(> t)
.../...				
Leaks	0.001669	0.004890	0.341	0.732897
No bath	-0.067121	0.028713	-2.338	0.019412 *
No toilets	-0.168858	0.053178	-3.175	0.001498 **
Humidity detected	0.001190	0.004614	0.258	0.796460
Production of renewable energy	-0.029142	0.007577	-3.846	0.000120 ***
Swimming pool	0.089627	0.009155	9.790	< 2e-16 ***
Air conditioning	0.013486	0.008002	1.685	0.091913 .
Construction after 1990				
From 1975 to 1989	-0.007126	0.005512	-1.293	0.196103
Before 1974	0.021681	0.004858	4.463	8.11e-06 ***
Uses natural gas				
Uses natural gas	0.070141	0.012421	5.647	1.65e-08 ***
Uses fuel oil	0.212974	0.012401	17.174	< 2e-16 ***
Uses butane	0.013442	0.004407	3.050	0.002290 **
Uses wood	0.022433	0.005354	4.190	2.80e-05 ***
Uses coal	0.036737	0.010832	3.391	0.000696 ***
All electricity	0.026187	0.012588	2.080	0.037507 *
Use collective energy source	0.118311	0.011745	10.074	< 2e-16 ***
No heating system				
Individual boiler	0.087634	0.009019	9.717	< 2e-16 ***
Independent devices	-0.004866	0.005871	-0.829	0.407164
Collective central heating	0.004628	0.014022	0.330	0.741344
Mixed heating	0.041435	0.028805	1.438	0.150321
Heating individual electric	0.046832	0.008462	5.534	3.16e-08 ***
Others heating	-0.015713	0.012822	-1.225	0.220429
Collective roof insulation				
Recent	-0.027242	0.014755	-1.846	0.064867 .
Old but sufficient	-0.004534	0.014725	-0.308	0.758145
Old but insufficient	0.005734	0.015356	0.373	0.708822
Non-existent	-0.003782	0.016875	-0.224	0.822675
.../...				

Label of the parameter	Estimate	Std. Error	t value	Pr(> t)
.../...				
Poor window insulation	0.011220	0.004639	2.419	0.015578 *
Good wall insulation				
Unknown wall insulation	0.013418	0.017076	0.786	0.432014
Average wall insulation	0.010892	0.004195	2.596	0.009432 **
Poor wall insulation	0.022755	0.006138	3.707	0.000210 ***
Climate zone : Mediterranean				
Oceanic	-0.016069	0.007600	-2.114	0.034503 *
Fresh oceanic	0.025741	0.006889	3.737	0.000187 ***
Altered oceanic	0.036913	0.005935	6.220	5.06e-10 ***
Semi-continental	0.040922	0.007275	5.625	1.87e-08 ***
Mountain climate	0.016575	0.007230	2.293	0.021881 *
EPC Score D				
EPC Score A	-1.895977	0.014376	-131.884	< 2e-16 ***
EPC Score B	-0.781013	0.010564	-73.930	< 2e-16 ***
EPC Score C	-0.351735	0.006524	-53.913	< 2e-16 ***
EPC Score E	0.276089	0.004633	59.597	< 2e-16 ***
EPC Score F	0.531487	0.005466	97.233	< 2e-16 ***
EPC Score G	0.823100	0.007151	115.105	< 2e-16 ***
Residual standard error: 8.739 on 26197 degrees of freedom				
Multiple R-squared: 0.8112, Adjusted R-squared: 0.8107				
F-statistic: 1705 on 66 and 26197 DF, p-value: < 2.2e-16				

Table 22: Energy bill estimate

From the value of the estimated parameters given in Table 22, we deduce the theoretical (estimated) effects of an improvement in the energy efficiency of the dwelling on the energy bill (see Table 23).

EPC Scores	A	B	C	D	E	F
B	-67.21%					
C	-78.65%	-34.90%				
D	-84.98%	-54.21%	-29.65%			
E	-88.61%	-65.25%	-46.62%	-24.13%		
F	-91.17%	-73.09%	-58.66%	-41.23%	-22.54%	
G	-93.41%	-79.89%	-69.11%	-56.09%	-42.13%	-25.29%

Table 23: Theoretical effect (estimate) of a change in EPC score on the energy bill

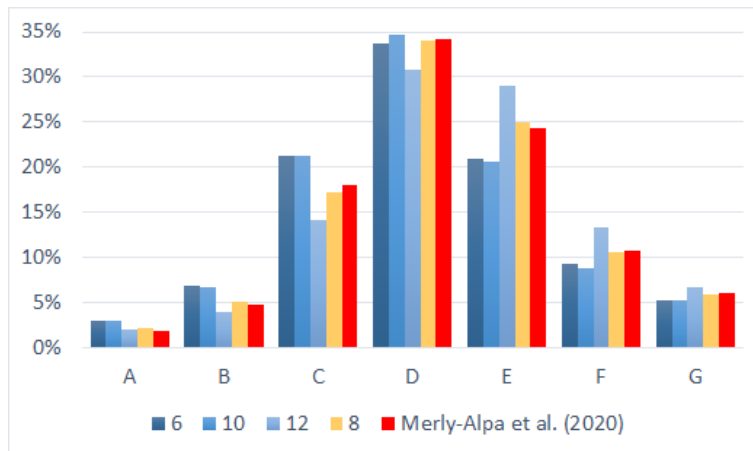
C.3 Retrofit costs and heterogeneity parameter

Table 24 gives the cost matrix of switching from one EPC score to another (I) used by [Giraudet et al. \[2018\]](#). There is no difference in cost depending on the type of housing (individual and collective housing, private and social housing).

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

Source: [Giraudet et al. \[2020\]](#)

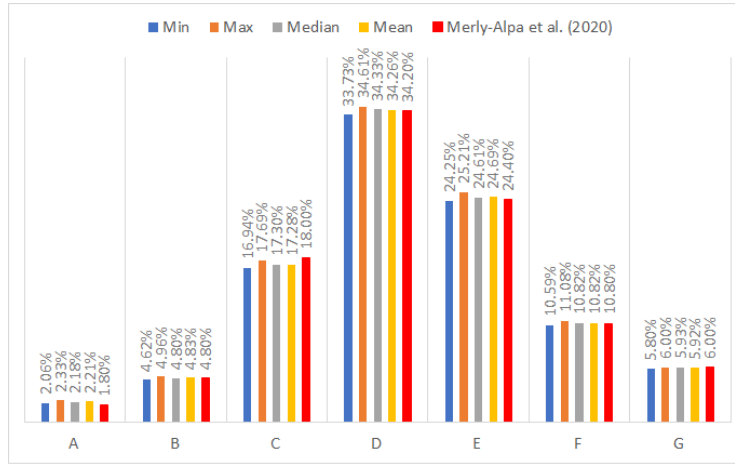
Table 24: Average cost per m² of renovation work for a EPC score jump



Note: In red, the distribution of housing according to their EPC score on January 1, 2018 according to [Merly-Alpa et al. \[2020\]](#). In blue (yellow) those resulting from the simulation for the following values of the heterogeneity parameter: $\nu = 6; 10; 12$ ($\nu = 8$), when the transition costs from one EPC score to another is given in Table 24, the intangible costs are those given in Table 8 and the other parameters of the renovation module are those in Table 5.

Figure 13: Comparison of the results of the energy renovation simulations before calibration with those of [Merly-Alpa et al. \[2020\]](#).

C.4 Benchmark (simulation)



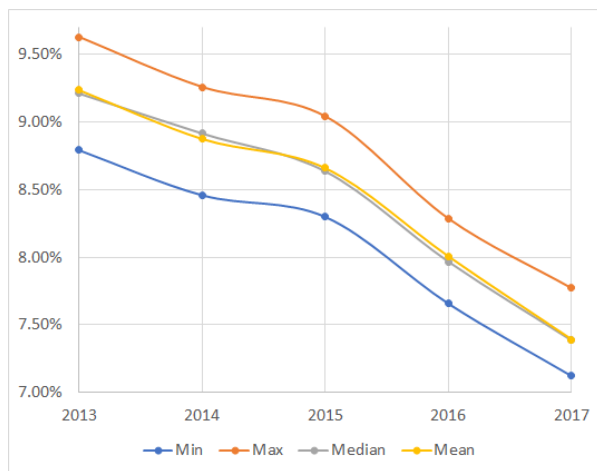
Note: The figure above gives the minimum, maximum, median and average values of the different EPC scores from around a hundred simulations. In red, the distribution of Merly-Alpa et al. [2020].

Figure 14: Distribution of dwellings according to their EPC score (at the end of 2017)



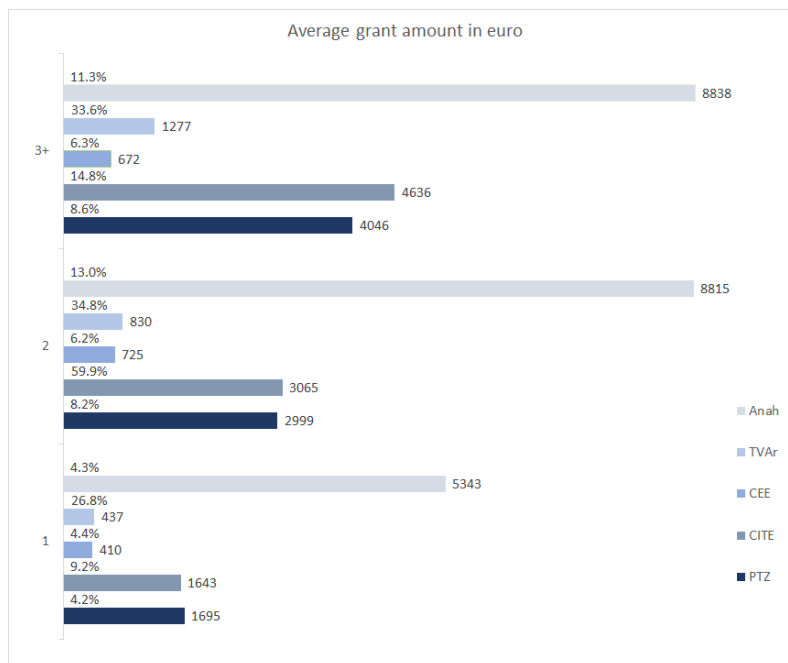
Note: The figure on the left (on the right) compares the distribution of tenants' homes (owners occupying their homes) according to the EPC scores obtained via the simulation and those from Merly-Alpa et al. [2020].

Figure 15: Distribution of dwellings according to their EPC score (at the end of 2017)



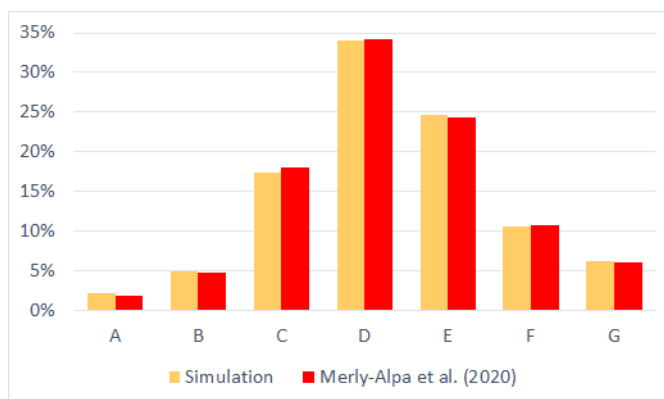
Note: The figure above gives the minimum, maximum, median and average percentages of housing renovated each year obtained from around a hundred simulations.

Figure 16: Percentage of renovated housing



Note: The bars represent the average amount in euros of the various aids received according to the number of EPC score jumps (1, 2 and 3 and more). Above the bars representing this amount is a percentage. This represents, among owner-occupier households who renovate their homes, the share of those who receive the subsidy.

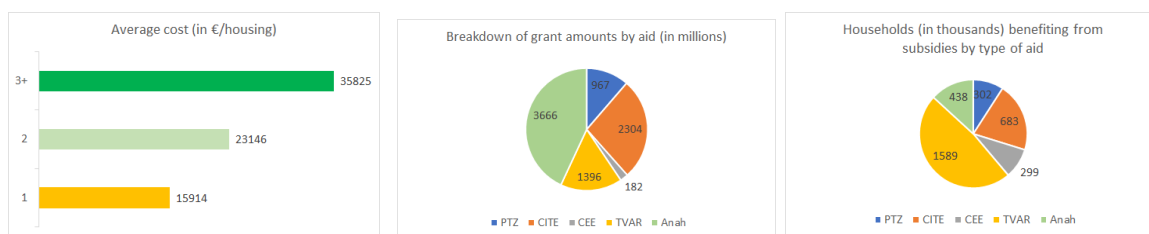
Figure 17: Average amount in euros of aid distributed



Note: In yellow (red), the distribution of dwellings according to their EPC after the simulation (according to Merly-Alpa et al. [2020]).

Figure 18: Distribution of dwellings on 1 January 2018 according to their EPC score (transition cost matrix = IC^m)

Figure 19 reports, over the period 2013-2017, the average cost of energy efficiency work in owner-occupied housing as well as the average amount of the various subsidies received, according to the number of EPC score jumps. Average costs are slightly higher than those of TREMI2017. Indeed, for a jump in DPE score (two jumps or more), the cost resulting from the simulations is €15,914 (€26,213) while they are €15,900 (€26,213) in TREMI2017. The distribution of aid/subsidies is approximately similar to that obtained by considering the I matrix (see Table 27).



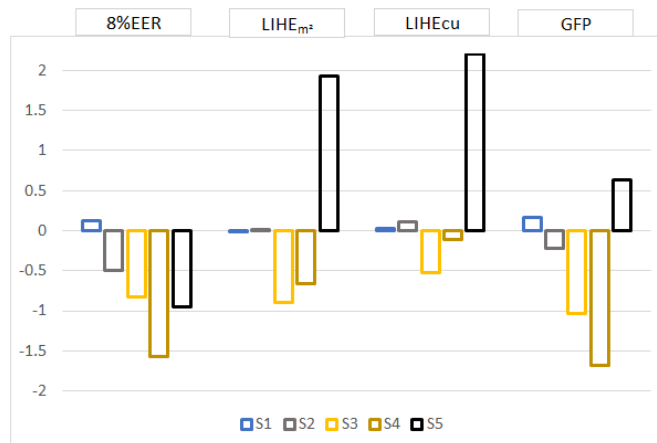
Note: The graph on the left gives the average cost of work carried out in owner-occupied dwellings according to the EPC score jump they generate. The graph on the right gives the average amount in euros of the various subsidies granted according to the number of EPC score jumps (1, 2 or 3 and more).

Figure 19: Average cost (in euros) and average grants for work carried out from 2013 to 2017 (transition cost matrix = IC^m)

	PTZ	CITE	CEE	TVAR	Anah
Breakdown of grant amounts by aid	11% (13%)	27% (25%)	2% (5%)	16% (20%)	43% (37%)
Distribution of households benefiting from subsidies by type of aid	9% (8%)	21% (18%)	9% (11%)	48% (55%)	13% (8%)

Table 27: Distribution of aid/subsidies simulated by considering the I^m matrix (simulations with the I matrix in parentheses)

The impact of aid/subsidies on fuel poverty is similar to that obtained by considering the I matrix (see Figure 8). Thus, among the scenarios considered, to reduce fuel poverty, it seems preferable to target the first two income quintiles rather than only targeting **leaky homes** (see Figure 20).



Note: The bars represent the variations in percentage points of fuel poverty according to the 4 indicators retained compared to the benchmark for the 4 scenarios considered. Thus, if scenario 1 (S1) is considered (i.e. no aid for energy renovation), fuel poverty according to 8%EER increases by 0.1 pp compared to the benchmark.

Figure 20: Variation in fuel poverty at the end of 2017 due to changes in aid (transition cost matrix = IC^m)

C.6 The year 2019

< 25 m ²	25 to 40 m ²	40 to 70 m ²	70 to 100 m ²	100 to 150 m ²	>150 m ²
690	777	1,093	1,413	1,762	2,381

Table 28: Average of the annual energy bill according to the surface area of the dwelling for 2019 (in euros) – projection

	D1	D2	D3	D4	D5
Households becoming Fuel Poor (FP)	2.18%	4.35%	2.82%	1.83%	1.50%
Households leaving FP	6.22%	7.15%	4.92%	3.89%	1.74%
	D6	D7	D8	D9	D10
Households becoming Fuel Poor (FP)	0.53%	0.21%	0.04%	0.04%	0.00%
Households leaving FP	1.00%	0.35%	0.08%	0.05%	0.00%

Table 29: Percentage of households entering and exiting fuel poverty (GFP) between 2012-2014 and 2019

HRP	2012-2014	2019
Homemaker	60.17%	54.69%
Unemployed person	57.86%	47.14%
Employed	16.45%	14.59%
Out-off the labor market	62.67%	57.01%
Retired	19.07%	15.67%

Table 30: Percentage of households in fuel poverty (GFP) in each status concerning the household reference person (HRP)